

1 Recognition and importance of amalgamated sandy meander  
2 belts in the continental rock record

3 **Adrian J. Hartley<sup>1</sup>, Amanda Owen<sup>1</sup>, Alistair Swan<sup>1</sup>, Gary S. Weissmann<sup>2</sup>, Barbara I.**  
4 **Holzweber<sup>1,\*</sup>, John Howell<sup>1</sup>, Gary Nichols<sup>3</sup>, and Louis Scuderi<sup>2</sup>**

5 *<sup>1</sup>Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen, AB24 3UE,*  
6 *UK*

7 *<sup>2</sup>University of New Mexico, Department of Earth and Planetary Sciences, MSC03 2040,*  
8 *Albuquerque, New Mexico 87131-0001, USA*

9 *<sup>3</sup>Nautilus Ltd., Ashfields Farm Industrial Estate, Priors Court Road, Hermitage, Berkshire,*  
10 *RG18 9XY, UK*

11 *\*Current address: ERCL, Dragon Court, 15 Station Road, Henley-on-Thames, Oxon, RG9 1AT,*  
12 *UK*

13 **ABSTRACT**

14 Meandering fluvial channels and their meander belts are common in modern continental  
15 sedimentary basins, yet compose a minor constituent of the reported fluvial rock record. Here we  
16 document exhumed amalgamated meander belt deposits from the upper Jurassic Morrison  
17 Formation, Utah (United States). The size of the amalgamated meander belt (9000 km<sup>2</sup>)  
18 is significantly larger than any documented previously and comparable in size to those from  
19 modern sedimentary basins. We describe a representative outcrop of sandy point bar deposits  
20 that shows features considered characteristic of both braided and meandering fluvial systems.  
21 Lateral accretion sets compose <5% of the outcrop area, yet point bar morphology is clearly  
22 visible in plan view. We suggest that difficulties in the identification of sandy, amalgamated

23 meander belt deposits indicate that they have gone largely unrecognized in the rock record. Their  
24 recognition has important implications for basin-scale reconstructions of fluvial systems and  
25 interpretation of tectonic setting.

## 26 **INTRODUCTION**

27 Recognition of fluvial channel plan form in the rock record is important because it is thought to  
28 control sandstone body shape, dimensions, connectivity, and internal heterogeneity (e.g., King,  
29 1990; Bridge, 1993). For example, it is generally considered that braided rivers produce laterally  
30 extensive, amalgamated, sheet-like sandstone bodies with limited internal heterogeneity (e.g.,  
31 Moody-Stuart, 1966; Cant, 1982; Allen, 1983; Friend, 1983; Gibling, 2006), whereas  
32 meandering channels produce relatively small, isolated to poorly connected sandstone bodies  
33 with a high degree of internal heterogeneity (Cant, 1982; Galloway and Hobday, 1996). The  
34 distinction between braided and meandering channel types is commonly made in the  
35 sedimentological literature, and many text books recognize these two types as distinct end  
36 members with characteristic facies and facies associations (Galloway and Hobday, 1996).  
37 However, others have recognized a continuum between channel types and considerable overlap  
38 in facies (Jackson, 1978; Bridge, 1985).

39

40 Gibling (2006), in an extensive review of fluvial deposits, concluded that braided channel  
41 deposits dominate the rock record and that meandering river deposits form only a minor  
42 constituent. This braided river dominance of the rock record is somewhat surprising given that  
43 close to 50% of large distributive fluvial systems (DFSs) in modern sedimentary basins are  
44 dominated by meandering channels (Hartley et al., 2010). In addition, axial river systems in  
45 many sedimentary basins display a meandering plan form (e.g., Paraguay-Paraná Basin, South

46 America; Po River, Italy; Rhine River, Europe; Ebro River, Spain), as do most marine connected  
47 coastal plain and distributary channels, particularly along passive margins (e.g., Zambezi and  
48 Niger Rivers, Africa; Volga and Ural Rivers, Russia; Gulf of Mexico, North America). This  
49 suggests that either modern channel plan form types within actively aggrading sedimentary  
50 basins are not representative of the rock record or that meandering channel systems are not  
51 recognized.

52

53 Here we map the lateral extent of an amalgamated meander belt in the Salt Wash fluvial system  
54 of the Morrison Formation, Utah (western USA), using satellite imagery and outcrop field  
55 studies. The system is significantly larger than any previously documented amalgamated  
56 meander belt and is similar in size to those of modern continental sedimentary basins. We  
57 describe a representative outcrop of the meander belt that allows both plan form and vertical  
58 facies relationships of a laterally extensive, sandy, amalgamated meandering channel complex to  
59 be determined. Plan form observations provide clear evidence for deposition from a meandering  
60 system, but the characteristics of vertical outcrop faces match previous descriptions of deposits  
61 by a braided fluvial system.

62

### 63 **STUDY AREA**

64 The Salt Wash fluvial system Morrison Formation comprises the Salt Wash and Tidwell  
65 Members of the upper Jurassic (Kimmeridgian). The deposits are exposed in south-central Utah  
66 and western Colorado (Fig. 1). They are as thick as 160 m, have low bed dips (mostly  $<10^\circ$ ) and  
67 are largely unfaulted. The succession is interpreted to represent a large DFS that flowed in a

68 north to northeast direction (Fig. 1; Craig et al., 1956; Mullens and Freeman, 1957; Owen et al.,  
69 2015a, 2015b). The system comprises large-scale amalgamated channel belt deposits that can  
70 extend tens of kilometers laterally in the proximal region. Downstream, channel belts pass  
71 progressively into floodplain facies composed of poorly developed paleosols, ribbon channels,  
72 and minor lacustrine units (Owen et al., 2015b).

73

74 The meander belt is exposed on both flanks of the San Rafael Swell and extends south into the  
75 Henry Mountain area (Fig. 1). Outcrop locations displaying meander belt features in plan view  
76 are shown in Figures 1 and 2. Meander belt deposits are identified in plan view on the basis of a  
77 combination of (1) curvature of beds between 90° and 180° that display geometries indicative of  
78 scroll bars such as internal truncation and subtle thickening and thinning, (2) curved beds  
79 dipping at an oblique angle to regional bedding, and (3) curved bed dips truncated against either  
80 adjacent scroll or channel deposits. Identification is restricted to relatively flat and planar bed  
81 surfaces in order to avoid ambiguity associated with outcrops modified by erosion. The majority  
82 of the preserved meander bend deposits occur within the upper 10 m of the Salt Wash Member,  
83 and although they cannot be constrained to be time equivalent, they probably represent  
84 individual channel belts that have become amalgamated both vertically and laterally through  
85 time. Although subject to post-depositional erosion, it seems reasonable to assume that the  
86 amalgamated meander belt deposits extended across this entire part of the DFS (140 km long, 80  
87 km wide), covering at least 9000 km<sup>2</sup>.

88

89 We describe a representative point bar complex from an outcrop north of Caineville (Figs. 1 and  
90 2), where it is possible to relate directly the preserved plan view geomorphology of a series of

91 amalgamated point bar deposits to vertical outcrop faces. In plan view (Fig. 3A) the partially  
92 preserved scroll bar morphology is clearly visible and the paleocurrent data from trough cross-  
93 strata trend oblique to parallel to scroll bar edges and curve for more than 180°. Trough cross-  
94 strata dominate the plan view perspective, accounting for >95% of the exposure. Scroll bar  
95 contacts are represented by erosion surfaces that dip between 5° and 20° in either a downstream,  
96 orthogonal, or upstream direction relative to the direction of immediately adjacent trough cross-  
97 strata.

98  
99 Figure 3 shows a single 6–8-m-thick story that cuts into underlying strata. The basal erosion  
100 surface is overlain by a pebble lag, often with mudstone intraclasts, that is in turn overlain by a  
101 series of pebbly and coarse- to medium-grained, poorly sorted sandstone displaying trough cross-  
102 strata with set heights of as much as 1 m. Sets are normally close to horizontal, although some  
103 dip 5°–10° in the same direction as the trough cross-strata. In the vertical panels occasional  
104 large-scale erosion surfaces (4–6 m in height) truncate packages of trough cross-strata and are  
105 often overlain by parallel-dipping packages of sandstone as much as 1 m thick that scale to the  
106 same height as the story. Each erosion-surface bounded package comprises trough cross-strata,  
107 which show systematic changes in paleoflow of >180° when traced laterally around the outcrop  
108 (Fig. 3). The difference in direction between the dip of the erosion surface and the dip of the  
109 trough cross-strata varies from 0° to 35°.

110  
111 The outcrop (Fig. 3) is interpreted to record the development of a bank-attached bar with trough  
112 cross-strata representing unit bars. Arcuate paleoflow trends that are close to parallel to the  
113 erosional bounding surfaces indicate that the unit bars form part of larger scale scroll bars

114 defined by erosional bounding surfaces. The bounding surfaces are interpreted to record periods  
115 when point bar accretion was modified during waning flood and low-flow stage. Sandstone  
116 packages paralleling the erosion surfaces are interpreted as lateral accretion deposits.

117

## 118 **DISCUSSION**

119 The ability to relate vertical sections and planform exposures on the described outcrop highlights  
120 difficulties in recognizing sandy meandering fluvial systems using standard vertical sedimentary  
121 logging techniques. The lack of a well-developed fining-upward motif, dominance of cross-  
122 strata, internal erosion surfaces, presence of mudstone intraclasts, and lack of interbedded mud  
123 are widely recognized characteristics of both coarse-grained meandering (Jackson, 1978; Bridge,  
124 1985) and braided (Cant, 1978; Bridge, 1985) channel deposits. Distinction between the two  
125 planform types based on vertical logs is particularly difficult. As noted by Davies and Gibling  
126 (2010), the key criterion for distinction between braided and meandering systems is the  
127 recognition of lateral accretion sets. If these cannot be identified, then an interpretation of a  
128 meandering channel deposit is difficult to justify.

129

130 Lateral accretion deposits make up <5% of the total Caineville outcrop area and are represented  
131 by strata that show no significant grainsize change and display a dip direction similar to that of  
132 adjacent trough cross-strata, features normally considered characteristic of braid bar deposits  
133 (e.g., Bristow, 1993; Best et al., 2003). Even with exceptional vertical exposure, without  
134 a plan view perspective it would be difficult to identify these sandstones as point bar deposits.  
135 Previous interpretations of the Salt Wash Member from this and adjacent study areas have  
136 suggested a braided system (Peterson, 1984; Robinson and McCabe, 1998).

137

138 Given the problems of recognizing sandy meandering fluvial deposits in outcrop, it will be  
139 particularly difficult to recognize these systems in the subsurface (Fralick and Zaniwski, 2012).  
140 Core-based studies and borehole imaging techniques are unlikely to be able to identify the large-  
141 scale dipping surfaces that would allow recognition of lateral accretion sets. Consequently,  
142 it is likely that meandering channel systems are misinterpreted and significantly  
143 underrepresented in subsurface studies of sandy fluvial systems that are restricted to core,  
144 wireline, and borehole image data. Meandering fluvial channel geometries can sometimes be  
145 differentiated on seismic horizon slice amplitude displays (e.g., Carter, 2003), but documented  
146 examples are encased within floodplain sediments and contain significant proportions of  
147 mudstone.

148

149 It is commonly assumed that amalgamated sheet-like sandstone bodies are formed by braided  
150 fluvial systems (e.g., Allen, 1983; Robinson and McCabe, 1998; Gibling, 2006). For example,  
151 Gibling (2006) considered that mobile-channel belts are mainly the deposits of braided and low-  
152 sinuosity rivers, and suggested that their overwhelming dominance throughout geological time  
153 reflects their link to tectonic activity, exhumation events, and high sediment supply. In contrast,  
154 Gibling (2006) noted that meandering river bodies are normally <38 m thick and <15 km wide,  
155 and considered the organized flow conditions necessary for their development to have been  
156 unusual, because they do not appear to have built basin-scale deposits. This appears at odds with  
157 observations from many modern continental sedimentary basins that are dominated by  
158 meandering fluvial systems, particularly in their more distal parts (Davies and Gibling, 2010;

159 Hartley et al., 2010). This evidence suggests that the deposits of meandering fluvial systems  
160 could potentially form a significant proportion of the sedimentary record if preserved.

161  
162 Analysis of satellite imagery from modern sedimentary basins (Table 1; Fig. 4) reveals a range of  
163 amalgamated meandering channel belts with dimensions that are comparable to those of the Salt  
164 Wash Member example. We document 16 examples here, located primarily in foreland basins,  
165 but also in rift (Okavango, East Africa) and passive margin (Ganges, India) settings, as well as  
166 valley confined systems developed along passive margins (Paraná, South America; Mississippi,  
167 USA). The amalgamated meander belts occur as part of distributive fluvial or axial fluvial  
168 systems, where meander belt deposits on DFS display a laterally extensive amalgamated form  
169 that results from channel-belt switching across the DFS (e.g., Weissmann et al., 2013).

170 The location of the majority of these meander belts within actively subsiding sedimentary basins  
171 suggests that they have significant preservation potential at a basin scale. The possibility that  
172 sheet-like sandstones can be formed by amalgamated meander belts some distance from the  
173 basin margin has important implications for basin-scale reconstructions of fluvial systems.

174

## 175 **CONCLUSIONS**

176 An exhumed amalgamated meander belt can be mapped over an area of 9000 km<sup>2</sup> in the Salt  
177 Wash DFS of the Morrison Formation in southeastern Utah. This represents one of the largest  
178 known exhumed amalgamated meander belts and is comparable in size to amalgamated meander  
179 belts from modern sedimentary basins. Outcrop studies illustrate the difficulty in distinguishing  
180 between sandy meandering and braided fluvial systems. The planform view of the outcrop allows  
181 recognition of a series of amalgamated point bar deposits recording the lateral and downstream

182 migration of a meandering fluvial system. Vertical sections show a lack of a well-developed  
183 fining-upward motif, dominance of cross-strata, internal erosion surfaces, and presence of  
184 mudstone intraclasts, features characteristic of both coarse-grained braided and meandering  
185 systems. Lateral accretion deposits compose <5% of the total outcrop area and display dip  
186 directions similar to those of adjacent trough cross-strata. Consequently, without a plan view  
187 perspective it would be difficult to identify these sandstones as point bar deposits, and they will  
188 be difficult to identify in many outcrops and particularly in the subsurface.

189

190 We suggest that sandy meandering channel belts form amalgamated sheet-like sandstone bodies  
191 and that the apparent predominance of braided fluvial systems in the fluvial stratigraphic record  
192 may not be true. In addition, as recognition of braided river deposits is often used to imply  
193 proximity to source, source area uplift, and tectonic activity, the possibility that  
194 they represent amalgamated meander belts suggests that some paleogeographic models may  
195 require re-evaluation.

196

## 197 **ACKNOWLEDGMENTS**

198 This work was supported by the Fluvial Systems Research Group sponsors BG Group, BP,  
199 Chevron, ConocoPhillips, and Total.

200

201

## 202 **REFERENCES CITED**

203 Allen, J.R.L., 1983, Studies in fluvial sedimentation: Bars, bar complexes and sandstone  
204 sheets (low-sinuosity braided streams) in the Brownstones (L. Devonian), Welsh Borders:  
205 *Sedimentary Geology*, v. 33, p. 237–293, doi:10.1016/0037-0738(83)90076-3.

- 206 Best, J.L., Ashworth, P.J., Bristow, C.S., and Roden, J.E., 2003, Three-dimensional sedimentary  
207 architecture of a large, mid-channel Sand Braid Bar, Jamuna River, Bangladesh: *Journal of*  
208 *Sedimentary Research*, v. 73, p. 516–530, doi:10.1306/010603730516.
- 209 Bridge, J.S., 1985, Paleochannel patterns inferred from alluvial deposits: A critical evaluation:  
210 *Journal of Sedimentary Petrology*, v. 55, p. 579–589.
- 211 Bridge, J.S., 1993, The interaction between channel geometry, water flow, sediment transport  
212 and deposition in braided rivers, *in* Best, J.L., and Bristow, C.S., eds., *Braided Rivers:*  
213 *Geological Society of London, Special Publication 75*, p. 13–71.
- 214 Bristow, C.S., 1993, Sedimentology of the Rough Rock: A Carboniferous braided river sheet  
215 sandstone in northern England, *in* Best, J.L., and Bristow, C.S., eds., *Braided Rivers:*  
216 *Geological Society of London, Special Publication 75*, p. 291–304.
- 217 Cant, D.J., 1978, Development of a facies model for sandy braided river sedimentation:  
218 Comparison of the South Saskatchewan River and the Battery Point Formation, *in* Miall,  
219 A.D., ed., *Fluvial Sedimentology: Canadian Society of Petroleum Geologists Memoir*, v. 5,  
220 p. 627–639.
- 221 Cant, D.J., 1982, Fluvial facies models and their application, *in* Scholle, P.A., and Spearing, D.,  
222 eds., *Sandstone Depositional Environments: American Association of Petroleum Geologists,*  
223 *Memoir 31*, p. 115–137.
- 224 Carter, D.C., 2003, 3-D seismic geomorphology: Insights into fluvial reservoir deposition and  
225 performance, Widuri field, Java Sea: *The American Association of Petroleum Geologists*  
226 *Bulletin*, v. 87, p. 909–934, doi:10.1306/01300300183.

- 227 Craig, L.C., Holmes, C.N., Cadigan, R.A., Freeman, V.L., Mullens, T.E., and Weir, G.W., 1955,  
228 Stratigraphy of the Morrison and related formations Colorado Plateau Region: Geological  
229 Survey Bulletin 1009-E, p. 1–52.
- 230 Davies, N.S., and Gibling, M.R., 2010, Cambrian to Devonian evolution of alluvial systems: The  
231 sedimentological impact of the earliest land plants: *Earth-Science Reviews*, v. 98, p. 171–  
232 200, doi:10.1016/j.earscirev.2009.11.002.
- 233 Fralick, P., and Zaniwski, K., 2012, Sedimentology of a wet, pre-vegetation floodplain  
234 assemblage: *Sedimentology*, v. 59, p. 1030–1049, doi: 10.1111 /j .1365 -3091 .2011  
235 .01291.x.
- 236 Friend, P.F., 1983, Towards the field classification of alluvial architecture or sequence, *in*  
237 Collinson, J.D., and Lewin, J., eds., *Modern and Ancient Fluvial Systems: International*  
238 *Association of Sedimentologists, Special Publication 6*, p. 345–354.
- 239 Galloway, W.E., and Hobday, D.K., 1996, *Terrigenous Clastic Depositional Systems:*  
240 *Applications to Fossil Fuel and Groundwater Resources: Berlin, Springer-Verlag*, 489 p.
- 241 Gibling, M.R., 2006, Width and thickness of fluvial channel bodies and valley fills in the  
242 geological record: A literature compilation and classification: *Journal of Sedimentary*  
243 *Research*, v. 76, p. 731–770, doi:10.2110/jsr.2006.060.
- 244 Hartley, A.J., Weissmann, G.S., Nichols, G.J., and Warwick, G.L., 2010, Large distributive  
245 fluvial systems: Characteristics, distribution, and controls on development: *Journal of*  
246 *Sedimentary Research*, v. 80, p. 167–183, doi:10.2110/jsr.2010.016.
- 247 Jackson, R.G., 1978, Preliminary evaluation of lithofacies models for meandering alluvial  
248 streams, *in* Miall, A.D., ed., *Fluvial Sedimentology: Canadian Society of Petroleum*  
249 *Geologists, Memoir 5*, p. 543–576.

- 250 King, P.R., 1990, The connectivity and conductivity of overlapping sand bodies, *in* Buller, A.T.,  
251 et al., eds., North Sea oil and gas reservoirs—II: London, Graham and Trotman, p. 353–358,  
252 doi: 10.1007 /978 -94 -009 -0791 -1\_30.
- 253 Moody-Stuart, M., 1966, High- and Low-sinuosity Stream Deposits, with Examples from the  
254 Devonian of Spitsbergen: *Journal of Sedimentary Petrology*, v. 36, p. 1102–1117,  
255 doi:10.1306/74D71609-2B21-11D7-8648000102C1865D.
- 256 Mullens, T.E., and Freeman, V.L., 1957, Lithofacies of the Salt Wash Member of the Morrison  
257 Formation, Colorado Plateau: *Geological Society of America Bulletin*, v. 68, p. 505–526,  
258 doi:10.1130/0016-7606(1957)68[505:LOTSWM]2.0.CO;2.
- 259 Owen, A., Jupp, P.E., Nichols, G.J., Hartley, A.J., Weissmann, G.S., and Sadykova, D., 2015a,  
260 Statistical estimation of the position of an apex: Application to the geological record:  
261 *Journal of Sedimentary Research*, doi:10.2110/jsr.2015.16 (in press).
- 262 Owen, A., Nichols, G.J., Hartley, A.J., Weissmann, G.S., and Scuderi, L.A., 2015b,  
263 Quantification of a distributive fluvial system; The salt Wash DFS of the Morrison  
264 Formation, SW USA: *Journal of Sedimentary Research* (in press).
- 265 Peterson, F., 1984, Fluvial sedimentology on a quivering craton: Influence of slight crustal  
266 movements on fluvial processes, Upper Jurassic Morrison Formation, Western Colorado  
267 Plateau: *Sedimentary Geology*, v. 38, p. 21–49, doi:10.1016/0037-0738(84)90073-3.
- 268 Robinson, J.W., and McCabe, P.J., 1998, Evolution of a braided river system: The Salt Wash  
269 Member of the Morrison Formation (Jurassic) in southern Utah, *in* Shanley, K.W., and  
270 McCabe, P.J., eds., *Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks*:  
271 *Society of Economic Paleontologists and Mineralogists Special Publication No. 59*, p. 93–  
272 107.

273 Weissmann, G.S., et al., 2013, Prograding distributive fluvial systems—Geomorphic models and  
274 ancient examples, *in* Driese, S., and Nordt, L.C., eds., *New frontiers in paleopedology and*  
275 *terrestrial paleoclimatology—Paleosols and soil surface analog systems: SEPM (Society for*  
276 *Sedimentary Geology) Special Publication 104, p. 131–147.*

277

## 278 **FIGURE CAPTIONS**

279 Figure 1. Location map showing approximate extent of Salt Wash distributive fluvial system  
280 (DFS) (Morrison Formation, southwestern USA) and identified meander belt. Yellow dots and  
281 gray letters show location of examples in Figure 2.

282

283 Figure 2. Examples of point bars and meander belts. Locations are shown in Figure 1. A:  
284  $38^{\circ}24'21.41''\text{N}$ ,  $111^{\circ}0'34.68''\text{W}$ . B:  $38^{\circ}50'9.90''\text{N}$ ,  $110^{\circ}6'30.39''\text{W}$ . C:  $39^{\circ}10'15.43''\text{N}$ ,  $110^{\circ}51'$   
285  $57.86''\text{W}$ . D:  $38^{\circ}24'12.13''\text{N}$ ,  $111^{\circ}2'6.59''\text{W}$ . Dashed box shows area of Figure 3.

286

287 Figure 3. A: Interpreted Google Earth® image of the Caineville (Utah, USA) exposure. Location  
288 is in Figure 3D. Black arrows—orientations of individual trough cross-strata; red arrows—trains  
289 of trough cross-strata. Rose diagram shows both cross-strata types. Note up-bar–verging  
290 paleoflow. White lines represent scroll bar bounding surfaces. B, C: Interpreted photopanel  
291 (locations in blue in A).

292

293 Figure 4. Examples of meander belts in modern basins. A: Digital elevation model of Beni Basin,  
294 Bolivia. B: Noa Dihing in the Himalayan foreland, Arunachal Pradesh, India. North is to top.