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

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ABSTRACT

Meandering fluvial channels and their meander belts are common in modern continental sedimentary basins, yet compose a minor constituent of the reported fluvial rock record. Here we document exhumed amalgamated meander belt deposits from the upper Jurassic Morrison Formation, Utah (United States). The size of the amalgamated meander belt (9000 km2) is significantly larger than any documented previously and comparable in size to those from modern sedimentary basins. We describe a representative outcrop of sandy point bar deposits that shows features considered characteristic of both braided and meandering fluvial systems. Lateral accretion sets compose <5% of the outcrop area, yet point bar morphology is clearly visible in plan view. We suggest that difficulties in the identification of sandy, amalgamated

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

INTRODUCTION

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

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

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

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

STUDY AREA

The Salt Wash fluvial system Morrison Formation comprises the Salt Wash and Tidwell Members of the upper Jurassic (Kimmeridgian). The deposits are exposed in south-central Utah and western Colorado (Fig. 1). They are as thick as 160 m, have low bed dips (mostly <10°) and are largely unfaulted. The succession is interpreted to represent a large DFS that flowed in a north to northeast direction (Fig. 1; Craig et al., 1956; Mullens and Freeman, 1957; Owen et al., 2015a, 2015b). The system comprises large-scale amalgamated channel belt deposits that can extend tens of kilometers laterally in the proximal region. Downstream, channel belts pass progressively into floodplain facies composed of poorly developed paleosols, ribbon channels, and minor lacustrine units (Owen et al., 2015b).

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

We describe a representative point bar complex from an outcrop north of Caineville (Figs. 1and 2), where it is possible to relate directly the preserved plan view geomorphology of a series of amalgamated point bar deposits to vertical outcrop faces. In plan view (Fig. 3A) the partially preserved scroll bar morphology is clearly visible and the paleocurrent data from trough cross-strata trend oblique to parallel to scroll bar edges and curve for more than 180°. Trough cross-strata dominate the plan view perspective, accounting for >95% of the exposure. Scroll bar contacts are represented by erosion surfaces that dip between 5° and 20° in either a downstream, orthogonal, or upstream direction relative to the direction of immediately adjacent trough cross-strata.

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

The outcrop (Fig. 3) is interpreted to record the development of a bank-attached bar with trough cross-strata representing unit bars. Arcuate paleoflow trends that are close to parallel to the erosional bounding surfaces indicate that the unit bars form part of larger scale scroll bars defined by erosional bounding surfaces. The bounding surfaces are interpreted to record periods when point bar accretion was modified during waning flood and low-flow stage. Sandstone packages paralleling the erosion surfaces are interpreted as lateral accretion deposits.

DISCUSSION

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

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

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

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

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

Analysis of satellite imagery from modern sedimentary basins (Table 1; Fig. 4) reveals a range of amalgamated meandering channel belts with dimensions that are comparable to those of the Salt Wash Member example. We document 16 examples here, located primarily in foreland basins, but also in rift (Okavango, East Africa) and passive margin (Ganges, India) settings, as well as valley confined systems developed along passive margins (Paraná, South America; Mississippi, USA). The amalgamated meander belts occur as part of distributive fluvial or axial fluvial systems, where meander belt deposits on DFS display a laterally extensive amalgamated form that results from channel-belt switching across the DFS (e.g., Weissmann et al., 2013). The location of the majority of these meander belts within actively subsiding sedimentary basins suggests that they have significant preservation potential at a basin scale. The possibility that sheet-like sandstones can be formed by amalgamated meander belts some distance from the basin margin has important implications for basin-scale reconstructions of fluvial systems.

CONCLUSIONS

An exhumed amalgamated meander belt can be mapped over an area of 9000 km2 in the Salt Wash DFS of the Morrison Formation in southeastern Utah. This represents one of the largest known exhumed amalgamated meander belts and is comparable in size to amalgamated meander belts from modern sedimentary basins. Outcrop studies illustrate the difficulty in distinguishing between sandy meandering and braided fluvial systems. The planform view of the outcrop allows recognition of a series of amalgamated point bar deposits recording the lateral and downstream migration of a meandering fluvial system. Vertical sections show a lack of a well-developed fining-upward motif, dominance of cross-strata, internal erosion surfaces, and presence of mudstone intraclasts, features characteristic of both coarse-grained braided and meandering systems. Lateral accretion deposits compose <5% of the total outcrop area and display dip directions similar to those of adjacent trough cross-strata. Consequently, without a plan view perspective it would be difficult to identify these sandstones as point bar deposits, and they will be difficult to identify in many outcrops and particularly in the subsurface.

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

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REFERENCES CITED

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

Best, J.L., Ashworth, P.J., Bristow, C.S., and Roden, J.E., 2003, Three-dimensional sedimentary architecture of a large, mid-channel Sand Braid Bar, Jamuna River, Bangladesh: Journal of Sedimentary Research, v. 73, p. 516–530, doi:10.1306/010603730516.

Bridge, J.S., 1985, Paleochannel patterns inferred from alluvial deposits: A critical evaluation: Journal of Sedimentary Petrology, v. 55, p. 579–589.

Bridge, J.S., 1993, The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers, *in* Best, J.L., and Bristow, C.S., eds., Braided Rivers: Geological Society of London, Special Publication 75, p. 13–71.

Bristow, C.S., 1993, Sedimentology of the Rough Rock: A Carboniferous braided river sheet sandstone in northern England, *in* Best, J.L., and Bristow, C.S., eds., Braided Rivers: Geological Society of London, Special Publication 75, p. 291–304.

Cant, D.J., 1978, Development of a facies model for sandy braided river sedimentation: Comparison of the South Saskatchewan River and the Battery Point Formation, *in* Miall, A.D., ed., Fluvial Sedimentology: Canadian Society of Petroleum Geologists Memoir, v. 5, p. 627–639.

Cant, D.J., 1982, Fluvial facies models and their application, *in* Scholle, P.A., and Spearing, D., eds., Sandstone Depositional Environments: American Association of Petroleum Geologists, Memoir 31, p. 115–137.

Carter, D.C., 2003, 3-D seismic geomorphology: Insights into fluvial reservoir deposition and performance, Widuri field, Java Sea: The American Association of Petroleum Geologists Bulletin, v. 87, p. 909–934, doi:10.1306/01300300183.

Craig, L.C., Holmes, C.N., Cadigan, R.A., Freeman, V.L., Mullens, T.E., and Weir, G.W., 1955, Stratigraphy of the Morrison and related formations Colorado Plateau Region: Geological Survey Bulletin 1009-E, p. 1–52.

Davies, N.S., and Gibling, M.R., 2010, Cambrian to Devonian evolution of alluvial systems: The sedimentological impact of the earliest land plants: Earth-Science Reviews, v. 98, p. 171–200, doi:10.1016/j.earscirev.2009.11.002.

Fralick, P., and Zaniewski, K., 2012, Sedimentology of a wet, pre-vegetation floodplain assemblage: Sedimentology, v. 59, p. 1030–1049, doi: 10.1111 /j .1365 -3091 .2011 .01291.x.

Friend, P.F., 1983, Towards the field classification of alluvial architecture or sequence, *in* Collinson, J.D., and Lewin, J., eds., Modern and Ancient Fluvial Systems: International Association of Sedimentologists, Special Publication 6, p. 345–354.

Galloway, W.E., and Hobday, D.K., 1996, Terrigenous Clastic Depositional Systems: Applications to Fossil Fuel and Groundwater Resources: Berlin, Springer-Verlag, 489 p.

Gibling, M.R., 2006, Width and thickness of fluvial channel bodies and valley fills in the geological record: A literature compilation and classification: Journal of Sedimentary Research, v. 76, p. 731–770, doi:10.2110/jsr.2006.060.

Hartley, A.J., Weissmann, G.S., Nichols, G.J., and Warwick, G.L., 2010, Large distributive fluvial systems: Characteristics, distribution, and controls on development: Journal of Sedimentary Research, v. 80, p. 167–183, doi:10.2110/jsr.2010.016.

Jackson, R.G., 1978, Preliminary evaluation of lithofacies models for meandering alluvial streams, *in* Miall, A.D., ed., Fluvial Sedimentology: Canadian Society of Petroleum Geologists, Memoir 5, p. 543–576.

King, P.R., 1990, The connectivity and conductivity of overlapping sand bodies, *in* Buller, A.T., et al., eds., North Sea oil and gas reservoirs—II: London, Graham and Trotman, p. 353–358, doi: 10.1007 /978 -94 -009 -0791 -1_30.

Moody-Stuart, M., 1966, High- and Low-sinuosity Stream Deposits, with Examples from the Devonian of Spitsbergen: Journal of Sedimentary Petrology, v. 36, p. 1102–1117, doi:10.1306/74D71609-2B21-11D7-8648000102C1865D.

Mullens, T.E., and Freeman, V.L., 1957, Lithofacies of the Salt Wash Member of the Morrison Formation, Colorado Plateau: Geological Society of America Bulletin, v. 68, p. 505–526, doi:10.1130/0016-7606(1957)68[505:LOTSWM]2.0.CO;2.

Owen, A., Jupp, P.E., Nichols, G.J., Hartley, A.J., Weissmann, G.S., and Sadykova, D., 2015a, Statistical estimation of the position of an apex: Application to the geological record: Journal of Sedimentary Research, doi:10.2110/jsr.2015.16 (in press).

Owen, A., Nichols, G.J., Hartley, A.J., Weissmann, G.S., and Scuderi, L.A., 2015b, Quantification of a distributive fluvial system; The salt Wash DFS of the Morrison Formation, SW USA: Journal of Sedimentary Research (in press).

Peterson, F., 1984, Fluvial sedimentology on a quivering craton: Influence of slight crustal movements on fluvial processes, Upper Jurassic Morrison Formation, Western Colorado Plateau: Sedimentary Geology, v. 38, p. 21–49, doi:10.1016/0037-0738(84)90073-3.

Robinson, J.W., and McCabe, P.J., 1998, Evolution of a braided river system: The Salt Wash Member of the Morrison Formation (Jurassic) in southern Utah, *in* Shanley, K.W., and McCabe, P.J., eds., Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks: Society of Economic Paleontologists and Mineralogists Special Publication No. 59, p. 93–107.

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

FIGURE CAPTIONS

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

Figure 2. Examples of point bars and meander belts. Locations are shown in Figure 1. A: 38°24′21.41″N, 111°0′34.68″W. B: 38°50′9.90″N, 110°6′30.39″W. C: 39°10′15.43″N, 110° 51′ 57.86″W. D: 38°24′12.13″N, 111°2′6.59″W. Dashed box shows area of Figure 3.

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

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