1

Megafans as Major Continental Landforms

M. JUSTIN WILKINSON and YANNI GUNNELL

Abstract

Discovery of the significance of fluvial megafans came about in the mid to late twentieth century. We suggest reasons why appreciation of their existence came late in the history of Earth science, even after the advent of space-based observation of planetary landscapes. The reasons are partly cultural: megafans are uncommon in the historic cradles of modern geology (Europe, North America). Reasons are also partly theoretical: rivers have been conceptualised chiefly as sediment bypass systems terminating in deltas, rather than as aggradational systems in their own right. Reasons are also perceptual: just as the megaflood origin of channeled scablands was held in disbelief, the inordinate size of megafans has stood in the way of accepting (i) the sheer magnitude of their unit-size and also (ii) their existence as active systems in modern landscapes, rather than just as stratigraphic features in the rock record. Post-1990, scientific activity around megafans accelerated and involved global mapping, classification, and regional investigations into patterns and processes. An overview of this take-off period is provided as a partial introduction to the remaining 17 chapters of this book, which are briefly outlined.

1.1 Outline, Purpose, and Scope

Megafans are fluvial sedimentary landforms of very low gradient and fan-shaped planform, with radial lengths of several tens, and up to hundreds of kilometres – i.e., significantly larger than the well-known smaller, mountain-front alluvial fans, but still much smaller than giant submarine fans such as the Indus and Bengal. However, megafans have long been poorly recognised in the literature on subaerial geomorphology and sedimentology. These landforms now require scientific attention, not only for reasons of fundamental Earth science understanding, but because of their importance as landscape elements occupied by major population centres around the world.

Our driving concern in this volume is to derive generalisations from the relatively limited total global population of ~270 identified megafans (as documented by remote means (Wilkinson and Currit, Ch. 2) compared with the thousands of examples of small alluvial fans detectable from the air, and many more in the near-surface Neogene geological record. The geomorphic and tectonic settings for megafans on each continent raise different kinds of research problems and approaches to solving them. Thus, in South America, the active Andean orogen has given rise to a large number of currently active megafans. By contrast, the Indo-Gangetic basin displays not only some active megafans but also others that are significantly incised and appear as successions of terraces. Cratonic Africa and Australia show patterns of isolated fans. Five chapters deal with groups of megafans (Africa, Asia, Central Europe, South America), the rest with more detailed studies of one or two megafans. The studies include megafans situated in basins of all major tectonic styles. Antarctica displays no subaerial megafans, and North America is excluded because so few modern examples exist and because of space limitations in this volume.

There seems little doubt about the importance of megafans as landforms on which very large human populations subsist – what Geddes (1960:253) termed the ‘alluvial plains of profound significance [. . .] that have tended to be almost completely ignored in geomorphology, instead of providing a central theme for physical study. . .’. Fortunately, Geddes’s (1960:258–259) comment of six decades ago (‘even a general study of the world’s plains is lacking (. . .) in spite of their immense environmental significance’) has begun to be reversed. While focusing on northern India, he also suggested that perspectives from the Gangetic Plains might well apply to the study of similar alluvial settings in South America, North America, and parts of Europe, as is attempted in this volume. The vast agricultural potential of such plains, the relative ease of constructing irrigation and transport systems on their remarkably flat surfaces, and their associated vulnerability to extensive flooding – as witnessed in 2008 (and almost annually since 2013) by the Kosi River megafan in northern India (hereafter megafans are named simply after their formative rivers) – all argue for further study, scrutiny, and public awareness. Vast expanses of megafan terrain in African and South America (particularly the Chaco) are coveted for setting up irrigation projects, plantations, or tourism ventures. Water grabs in Mali (Niger megafan), and recent warfare over land in oil- and groundwater-rich South Sudan have also been prominent in current affairs (Pearce 2013). Until recently desolate, untamed and untenured, a number of megafans are among the last frontiers of this planet.

1.2 Expanding Perspectives on Megafans

1.2.1 Earlier Perspectives: Limited Recognition Pre-1990

Before space-based observation of Earth’s landscapes was available, a few megafans had been described. Prime examples are the Kosi in India, which remains probably the most cited example (e.g., Geddes 1960; Parkash et al. 1983; Wells and Dorr 1987a, b; Gohain and Parkash 1990; Mohindra et al. 1992; Richards et al. 1993; Singh et al. 1993; Sinha and Friend 1994; Shukla et al. 2001; Goodbred 2003); the Okavango (for numerous early references, see historical review in McCarthy 2013); and megafans in the Andean foreland (Cordini 1947, and early references in Iriondo 1993; Horton and DeCelles 2001; Latrubesse et al. 2012) and in the Pantanal region of SW Brazil (Klammer 1982; Tricart 1982; Souza et al. 2002; Assine 2005). In francophone literature, the ‘inland delta’ of the Niger River, in the Sahel region of Mali, was studied by Urvoy (1942) and later by Gallais (1967) prior to awareness of the fluvial megafan idiom *sensu hic*. This early recognition of deltas and large fans in continental interiors by isolated pioneers displays parallels in the history of science with other very large landforms such as megaflood scars in the Pacific Northwest of the United States (Bretz 1923) – in this case erosional rather than predominantly depositional landforms. At first critiqued by incredulous detractors (see review about the Channeled Scablands of the NW USA in Baker 1978), ‘scablands’ have now not only been validated, but also detected outside their type area by means of satellites and underwater sonar technology – from the very doorstep of modern geology’s European homebase (the English Channel: Gupta et al. 2017) to remote regions such as Siberia and other areas in the solar system such as Mars (Burr et al. 2009).

Studies of individual megafans, however, often overlooked wider suites of neighbouring megafans, and thus the broader subregional-scale megafan setting. For example, the Okavango megafan in the Kalahari Basin of southern Africa, visually prominent in aerial imagery, has claimed perhaps even the bulk of attention for the past century. However, it is now known to be only one of a group of at least ten megafans in the region (Wilkinson et al., Ch. 4). Thus, only four multi-fan landscapes benefited from published studies prior to 1990, namely the Indo-Gangetic plains of northern India (Geddes 1960), the Chaco plains of Argentina and Paraguay (Iriondo 1984, 1987), the Pantanal (Tricart 1982; Tricart et al. 1984) in southwestern Brazil, and the Hungarian Plains (Borsy 1990). These studies were necessarily idiosyncratic to their local basins, with Geddes (1960:262) noting that some major Himalayan rivers such as the Ghaghara failed to display ‘great alluvial fans or cones’ compared with the continuous set of active megafans generated by major rivers in central South America. Experience from megafan landscapes of one continent was only tenuously transferred to other continents, partly because of language barriers and slow diffusion of the studies, and partly through the assumption that such landscapes were unusual or simply not representative of planetary landforms.

The widely held view of megafans as rare landforms was supported by the small number of known examples and by the scant scientific attention directed to these features, leading to cursory treatment in reference works – mostly as large end members of the spectrum of piedmont alluvial fans. Schumm's explicit opinion – in his influential 1977 book The Fluvial System – that large 'wet' fans [i.e., megafans] must have been widespread during pre-vegetation times probably reinforced the view that few such fans should be expected in modern landscapes. Experienced field geologists have noted that the very low slopes and occasionally immense size have made large fans difficult to recognise in modern landscapes (N. Cameron and R. Miller, pers. comm. to MJW). Lack of recognition was likely reinforced by the age of many megafans, as drainage patterns and fluvial morphology are progressively overprinted in remotely sensed imagery by eolian features, incision and terracing, and vegetation patterns. This has been especially the case within a broad geological mindset that had assumed that vast alluvial landscapes are specifically connected to coastlines in the form of deltas. This view still dogs research into fluvial landscapes and sediments on Mars (Wilkinson et al., Ch. 16).

A cultural component probably also played a part. Megafans are presently almost non-existent or inconsequential in the landscapes of Europe and North America, where Earth science matured as a modern discipline during the twentieth century. This coincidence has probably conditioned the pervasive view that incisional fluvial regimes, so dominant in these continents, are the norm on all continents. Thus, Schumm's (1977) classic three-zone model of the drainage system is based on the topographic sequence mountain–valley-confined floodplain–coastal delta, with the Mississippi drainage clearly in mind. This model reinforces the concept of rivers as sediment-bypass systems rather than as potentially aggradational systems in their own right, and implicitly excludes the vast megafan-dominated landscapes that are now attracting growing attention.

1.2.2 Accelerated Scientific Activity since ~ 1990: Global Mapping, Approaches, and Definitions

As mentioned above, a few examples of megafans were known before the 1990s. Blair and McPherson (1994) had specifically excluded large fluvial fans from the alluvial-fan designation. In their view, megafans belonged in the class of typical valley-confined floodplains, to be distinguished from short-radius, higher-gradient piedmont alluvial fans. Blair and McPherson (1994) reasserted the original definition of alluvial fans, namely as coarse-grained features with relatively steep slopes, of the type classically associated with the small desert alluvial fan less than 15–20 km in length, and distinguishable from larger river systems also in terms of sedimentary processes and products. Their view is interesting because they gave little validity to fanlike morphology, which is otherwise the overwhelmingly dominant approach.

Following widely held views, Miall (1996) took instead an inclusive stance of grouping large fans within a more broadly defined alluvial-fan class. However, large known megafans at that time, such as the Kosi megafan of northern India, the Chaco megafans, and the Pantanal, were not included by Miall (1996) (See Wilkinson, Ch. 17, Section 17.3). In a more detailed analysis, Stanistreet and McCarthy (1993) also took a more inclusive view, classifying all sizes of fan-like fluvial landforms as alluvial fans, with categories based on process and included small alluvial fans, braided fans, and the largest, so-called losimean (i.e., low sinuosity and meandering) Okavango type (150 km long).

Simultaneously, the increasing availability of satellite remote sensing products started to open up new potential for the identification of megafans worldwide. For example, starting in 1988 at the Johnson Space Center, astronaut-handheld imagery of continental surfaces revealed what may have been the first global perspective on megafans. It rapidly provided evidence of more than 150 examples, with some components of these inventories presented at conferences or in grey literature (e.g., Wilkinson 2001, 2005, 2006; Wilkinson et al. 2002, 2006, 2010; Sounny-Slitine and Latrubesse 2014).

The task of identifying from remote sensing products the global population of all medium and large fans (i.e., > 30 km long) was complemented by Weissmann et al. (2010, 2011), Hartley et al. (2010a, b) and Davidson et al. (2013), resulting in an overarching classification of fan-like fluvial deposits based on 415 examples. These authors applied the innovative term distributive fluvial systems (DFS) ‘to encompass fluvial and alluvial distributive landforms at all scales’ (Weissmann et al. 2015:189), in the attempt to circumvent the semantic issues associated with the definition of alluvial fans. Their purpose was first to identify modern DFS and describe what they deemed the important aspects of their morphology and structural setting; and then, given that they saw DFS to be the areally dominant landforms in present-day continental basins, to propose these as the basis for an ‘alternative interpretation for much of the fluvial rock record’ (Weissmann et al. 2010, 2011:329). These authors drew a major distinction between ‘tributary’ drainage patterns (Weissmann et al. 2011:329; also ‘tributive’ in Weissmann et al. 2015:214), which they saw as typical of regional degradational landscapes even though such landscapes include some of the largest and most active river floodplains in the world; and ‘distributive’ drainage patterns, which are typical of many landscapes of regional extent that are dominated by fan-like fluvial deposits of all dimensions.

Global data surveys supported the notion of a genetic continuum for these landforms, earlier demonstrated by Saito (2003), Saito and Oguchi (2005), and Hashimoto et al. (2008). The continuum questioned the ‘natural depositional slope gap’ that Blair and McPherson (1994) had argued must exist between alluvial fans and floodplains, and they reclassified megafans as ‘rivers [i.e., floodplains] or river deltas’ (Blair and McPherson 1994:457). Confusion was thus compounded because the slope gap does not exist between debris-flow-dominated ‘torrential’ fans and fluvial megafans, even though a *process* gap between these features does exist—given that smaller debris cones and alluvial fans are shaped by supercritical flow (and some even by non-Newtonian flow), whereas megafans are dominated by fluvial processes under a critical or subcritical flow regime.

The potential climatic conditions for the development of megafans has been another controversial topic. Earlier claims by Leier et al. (2005) are often quoted to support a climatic explanation for the distribution of megafans. Results from different parts of the world demonstrate that megafans can be generated under a broad spectrum of climatic conditions, which range from periglacial to arid, semiarid and temperate climates. Some writers still invoke aridity or pronounced seasonality as an explanation for the existence of megafans (e.g., Fielding et al. 2012; Rossetti et al. 2014; Plink-Björklund 2015). This might also include equatorial regions covered today by dense tropical rainforest such as the Amazon.

The chapters in this volume thus address the following four dimensions in the study of megafans: (i) two-dimensional space, and thus the characterisation of present-day sky-view morphologies and other visually detectable patterns; (ii) process, by exploring the spectrum from less well understood local autogenic controls to wider allogenic controls such as tectonic setting, catchment geology, and climate; (iii) time, providing constraints on the age of deposits and landform assemblages; and (iv) stratigraphy, spanning the subsurface from shallow depths to depths of hundreds of metres. Due to disparities in documentation and purpose, it would be impossible for each chapter to address all these dimensions, but the list gives a sense of the approaches used thus far in the study of these large sedimentary bodies.

The present renewed attention to modern fluvial landscapes and their dominant fluvial styles, with potential for preservation in the geological record, has led to more detailed comparisons with large, but nevertheless confined floodplains (Fielding et al. 2012), and with related types of landform such as major avulsive fluvial systems, or MAFS (Latrubesse 2015), and large accretionary fluvial systems, or LAFS (R. Nanson, pers. comm. to MJW) (see Wilkinson, Ch. 17, Section 17.6.1).

Based on the universality of larger fans in modern sedimentary basins, Weissmann et al. (2010: 41) emphasised the extensive areal scale and distribution of ‘DFS deposits [that] are probably more common than previously recognised in continental strata, and may form the bulk of the continental fluvial record’. This statement highlighted a critical distinction between rivers in long-term degradational settings (on which most facies and architectural models for fluvial deposits are based), and rivers in aggrading settings, the latter being heavily represented by DFS in modern landscapes. Weissmann et al. (2011) argued that DFS deposits have a particularly high preservation potential in the rock record. Hartley et al. (2010b) agreed that the many models based on converging river patterns at the channel scale 'provide a very valuable body of literature' (Weissmann et al. 2015:214), but citing scale considerations they noted that 'what we believe is missing in the literature on fluvial systems is an understanding of the larger-than-channel belt and basinal context in which fluvial systems are developed'.

The claim for a potentially dominant representation of DFS in the geological record was considered controversial or even rejected (Sambrook Smith et al. 2010; Fielding et al. 2012; Ashworth and Lewin 2012; Latrubesse 2015). The ensuing conversation refocused attention on the dimensions of very wide floodplains and their distinctiveness compared with DFS, especially megafans – a discussion ultimately aimed at the larger question of fluvial sedimentation styles and their preservation potential in the subsurface. Miall (2014), in particular, considered the debate on tributary vs. radial drainage patterns to be important because of its bearing on 'the mappability and predictability of fluvial systems in the subsurface' (p. 281). Such patterns are investigated in some detail in chapters in this book. Echoing the critique of Fielding et al. (2012), however, Miall (2014:281) stated that 'the most important counter argument to the importance of DFS [in dominating depositional patterns in active continental sedimentary basins] is the abundant documentation of the deposits of large rivers in the rock record'. This important and complex consideration, that of ultimate burial and preservation of fluvial sediment bodies (see especially Miall 2014, his chapters 2 and 6; and Miall et al. 2021), is a topic beyond the scope of this volume. Citing the Amazon, Paraná, and Magdalena rivers, Latrubesse (2015) has given evidence that very large axial rivers all display larger areas of active sedimentation than the largest megafans in central South America – illustrating the capacity of large rivers, even in erosional settings, to give rise to very significant zones of deposition. Latrubesse (2015) argued that some sub-environments of foreland tectonic depressions are inimical to preservation of DFS because they promote the erosional destruction of sediment bodies such as megafans due to the effects of tectonics-driven erosion.

Contrary to claims by Weissmann et al. (2011), Miall (2014) argued that bedforms and macroforms of facies models cannot serve as a basis for differentiating between degradational vs. aggradational (i.e., DFS-type) geomorphic systems because the processes that apply to these features operate in all rivers – whether valley-confined floodplains or unconfined megafan rivers. Miall (2014:280) reasoned that the difference in the setting was 'irrelevant' because bedforms and macroforms develop over time periods and scales small enough to operate in rivers of similar discharge range.

Over the last several years, a growing number of studies have nonetheless documented DFS successions in stratigraphic records from various ages and on all continents (Sáez et al. 2007; Latrubesse et al. 2010; Trendell et al. 2013; Gulliford et al. 2014; Klausen et al. 2014; Owen et al. 2015; Astini et al. 2018), and one chapter of this volume addresses these issues (Ventra and Moscariello, Ch. 14). We note that it is extremely difficult to differentiate in the geologic record between megafans and other large avulsive fluvial systems that are not DFS (Latrubesse et al. 2010; Valente and Latrubesse 2012, 2015). The existence of DFS in the rock record is not, however, the main focus of this volume, which is directed primarily at modern and submodern fans at the large end of the fan continuum. Nevertheless, because of the importance of the topic, four chapters are devoted partly or mainly to the deeper stratigraphy of surface megafan deposits (Ch. 8, Ch. 9, Ch. 11, and Ch. 15).

This volume is also an attempt to present the variety of research aims and ensuing methodologies that have been employed in the study of megafans. For example, significantly different results are derived from morphological mapping as opposed to geological mapping. In the former case, distal convergent drainage patterns have been excluded from the computation of area, either explicitly (Hartley et al. 2010a) or implicitly (Horton and DeCelles 1997; Barnes and Heins 2009); whereas geological mapping includes the entire unconfined zone occupied by fluvial landforms and sediments of the feeder river (e.g., Assine et al. 2014; Latrubesse et al. 2012, and chapters in this volume).

Scientific study of megafans has involved a variety of entry points. The most prominent has been their morphological similarity to alluvial fans, perhaps because the planform view had become so familiar in the voluminous literature on alluvial fans, with overviews presented by many authorities (e.g., Lecce 1990; Stanistreet and McCarthy 1993; McCarthy and Cadle 1995; Cooke et al. 2006). Stanistreet and McCarthy (1993) classified fans primarily by planform with a ternary subdivision by process, namely the elementary alpine debris cone (small range-front 'alluvial fan'), the braided fluvial fan, and a low-sinuosity/meandering (Okavango) type, a subdivision broadly followed by Miall (1996). The literature nonetheless reveals other approaches. Applying a more strictly sedimentological approach, as noted earlier, Blair and McPherson (1994) simply grouped megafans as a type of landform constructed by fluvial aggradation, in contrast to the processes dominant on piedmont alluvial fans. By retaining the morphological and facies approaches to different degrees, classifications with many nuances and even contradictions have arisen.

Despite the attention paid to features of fan-like planform, the recognition of the full dimensions of many megafans was not immediately obvious. With the long tradition of geomorphic and geological research directed at small alluvial fans, and the relatively small Kosi and Okavango as examples of the few well-known megafans (both ~150 km long), simple dimensional attributes were often thought to be smaller than they are now known to be. For example, Horton and DeCelles (2001) gave significantly smaller dimensions for what they termed megafans in the northern Chaco Plains (which included the largest-known on the planet), compared with dimensions ascertained by Iriondo (1993), Weissmann et al. (2011) or Latrubesse et al. (Ch. 5). Under present climatic conditions, most Chaco Plains fan-forming rivers cease to flow hundreds of kilometres upstream of the megafan toe at the trunk Paraná River (Cafaro et al. 2010; Latrubesse et al. 2012). This led Horton and DeCelles (2001) to consider that river end points mark the distal margins of the megafans. Consequently, the areas they obtained for the Río Grande, Parapetí, and Pilcomayo megafans were much smaller than those now considered to be representative: ~12,600 km^2, ~5,800 km^2, and ~22,600 km^2, respectively, compared with 58,140 km^2, 59,656 km^2, and 216,210 km^2 measured for the full extent of the cones (Latrubesse, Ch. 5).

As commentary by Latrubesse (2015) reveals, overemphasis on planform as a unifying criterion has also diverted attention from the different sets of processes active on fans of different sizes.

1.3 Chapter Outlines

In the continuation of Part I, Introduction, Wilkinson and Currit (Ch. 2) provide a new map showing the distribution of 272 megafans (defined as fans with lengths greater than 80 km) worldwide, a total that more than doubles the number of features of similar dimension in a previously published distribution (Hartley et al. 2010a). The extreme variability by continent is apparent (one in North America, 87 in Africa), and the different tectonic styles are briefly mentioned. Building the map provided the raw material for the broad discussion in Chapter 17, Megafans in World Landscapes, which also concludes with an overview of possible future research directions.

Part II, Regional Studies, deals with the continents. Chapter 3 begins with mapping the megafans of the African continent and placing them in tectonic context; eighty-seven megafans are shown to be connected directly to the swells of Africa's unique basin-and-swell geomorphology. In Chapter 4, Wilkinson et al. identify ten megafans in the northern Kalahari Basin where until now only one was thought to exist, namely the well-known Okavango 'inland delta'. They show that six of these megafans sit astride basin divides such that the discharges of the six feeder rivers have flowed at times into two different basins. Three chapters are devoted to South America, where megafans are most widely developed and cover the largest contiguous area on the planet. Latrubesse et al. (Ch. 5) give a regional study of the Chaco megafans that stretch from central Bolivia to central Argentina through Paraguay, in which the discharge of the different fan-forming rivers is analysed and the several contributing allogenic controls are examined. In a similar study of somewhat smaller megafans of the Pantanal in southwest Brazil, Santos et al. (Ch. 6) map the intricately nested pattern of megafans and examine the relationship between catchment basin geology and megafan size. Avulsions are a key process on megafans, but their occurrence is sufficiently infrequent that little is known of their periodicity. On that topic, May et al.

(Ch. 7) document a detailed chronology of recent avulsions on the Rio Grande megafan of central Bolivia and discuss its possible connections with the Amazon.

In Europe, Fontana and Mozzi (Ch. 8) describe in detail the evolution of two major groups of fans, namely the largest five on the southern piedmont of the Alps in Italy, and those that have developed on the Pannonian Basin. The tributaries of the Danube River, feeding in from the Carpathian Mountains, reveal the effects of glaciation in the case of the Po Basin fans and the lack of glaciation effects in the Pannonian Basin. Gunnell (Ch. 9) gives a full history of the large Loire megafan in central France, from evolution of the shallow receiving basin, to the deposition of its major units, to the subsequent regional incision by major and minor rivers. Furthermore, the Loire River has acted as a 'divide megafan', flowing at different times westwards to the Atlantic and northwards through the Paris Basin towards the English Channel.

In southern Asia, Sinha et al. (Ch. 10) explore the major geomorphic difference between the incised western Gangetic Plains and the aggradational megafan country of the eastern Gangetic Plains. Sinha et al. (Ch. 11) update many aspects of the geomorphology of this well-known fan and map the detail of the modern course. In Australia, Lane et al. (Ch. 12) give a brief overview of the distribution of megafans on that continent, then illustrate the behaviour of a megafan on the coast of the Gulf of Carpentaria that enters the shallow marine realm. They map the greater number of avulsions near the present-day coastline and suggest the term megafan-delta for such features. Kapteinis et al. (Ch. 13) use radiometric satellite imaging to identify three megafans for the first time in Australia's state of Victoria. The flatness of the landscape has led to an apparent coalescence of the two larger megafans in the distal reaches, a comparatively unusual geomorphic occurrence.

In Part III Applications in Other Sciences, Ventra and Moscariello (Ch. 14) and Miller et al. (Ch. 15) report on subsurface fluvial sediments and stratigraphy, the former in a wide-ranging review of continental basins, the latter on the Cubango megafan in northern Namibia. The recent drilling of this megafan came about as a direct result of the identification of the megafan from a mapping study reported in Part I, Chapter 2. Wilkinson et al. (Ch. 16) for the first time apply patterns seen in megafan landscapes to the kilometre-thick layered rocks in the Sinus Meridiani part of planet Mars. This new approach is based on a growing understanding of aggradational landscapes encapsulated in the 'megafan analogue'.

In Part IV, Megafans in World Landscapes, Wilkinson (Ch. 17) attempts a summary of the major attributes of continental megafans, especially of the drainage networks and large aggradational landscapes, which are so different from those of the more familiar 'dendritic' drainage patterns and valley-dominated morphologies of erosional landscapes. In the final chapter (Wilkinson and Gunnell, Ch. 18) broader conclusions are drawn from what proves to be a rich haul of future research topics, such as the still blurred divide between autogenic and allogenic controls over megafan evolution.

References

Ashworth, P. J. and Lewin, J. (2012). How do big rivers come to be different? *Earth-Science Reviews*, 114, 84–107.

Assine, M. L. (2005). River avulsions on the Taquari megafan, Pantanal wetland, Brazil. *Geomorphology*, 70, 357–371.

Assine, M. L., Corradini, F. A., Pupim, F. N., and McGlue, M. M. (2014). Channel arrangements and depositional styles in the São Lourenço fluvial megafan, Brazilian Pantanal wetland. *Sedimentary Geology*, 301, 172–184.

Astini, R. A., Martini, M. A., Oviedo, N. d. V., and Álvarez, A. (2018). El paleocañon de Tuc Tuca (Cordillera Oriental, Noroeste argentino); reconocimiento de una "zona de traspaso sedimentario" Cenozoic entre el interior cordillerano y un megaabanico en la región subandina. *Revista de la Asociación Geológica Argentina*, 75, 482–506.

Baker, V. R. (1978). The Spokane flood controversy. In V. R. Baker, and D. Nummedal, eds., *The Channeled Scabland, A Guide to the Geomorphology of the Columbia Basin*. NASA, Washington, D.C., 3–16.

Barnes, J. B. and Heins, W. A. (2009). Plio-Quaternary sediment budget between thrust belt erosion and foreland deposition in the central Andes, southern Bolivia. *Basin Research*, 21, 91–109.

Blair, T. C. and McPherson, J. G. (2009). Process and forms of alluvial fans. In A. J. Parsons, and A.D. Abrahams, eds, *Geomorphology of Desert Environments*. Springer, Berlin, 2nd edn., 354–402.

Borsy, Z. (1990). Evolution of the alluvial fans of the Alföld. In A. H. Rachocki, and M. Church, eds., *Alluvial Fans: A Field Approach*. Wiley, Chichester, 229–248.

Bretz, J. H. (1923). The channeled scabland of the Columbia plateau. *Journal of Geology*, 31, 617–649.

Burr, D. M., Baker, V. R., and Carling, P. A., eds. (2009). *Megaflooding on Earth and Mars*. Cambridge University Press, Cambridge, 330 pp.

Cafaro, E., Latrubesse, E., Ramonell, C., and Montagnini. M. D. (2010). Channel pattern arrangement along Quaternary fans and mega-fans of the Chaco plain, central South America. In M. Garcia, E. Latrubesse, and G. Perillo, eds., *River Coastal and Estuarine Morphodynamics, Vols. 1 and 2*, CRC Press, Netherlands, 349–354.

Cooke, R. U., Warren, A., and Goudie, A. S. (2006). *Desert Geomorphology*, University College London Press, London, 2nd edn, 526 pp.

Cordini, R. (1947). *Los Ríos Pilcomayo en la Región del Patiño*. Anales I, Dirección de Minas y Geología (Buenos Aires), 82 pp.

Fielding, C. R., Ashworth, P. J., Best, J. L., Prokocki, E. W., and Sambrook Smith, G. H. (2012). Tributary, distributary and other fluvial patterns: What really represents the norm in the continental rock record? *Sedimentary Geology*, 261–262, 15–32.

Gallais, J. (1967). Le delta intérieur du Niger et ses bordures, étude morphologique. Paris, Éd. du CNRS, 155 pp. (with 1:200 000 scale geomorphological maps).

Geddes, A. (1960). The alluvial morphology of the Indo-Gangetic plains. *Transactions of the Institute of British Geographers*, 28, 253–276.

Gohain, K., Parkash, B. (1990). Morphology of the Kosi megafan. In A. H. Rachocki, and M. Church, eds., *Alluvial Fans: A Field Approach*. Wiley, Chichester, 151–178.

Goodbred, S. L. (2003). Response of the Ganges dispersal system to climate change: a source-to-sink view since the last interstade. *Sedimentary Geology*, 162, 83–104.

Gulliford, A. R., Flint, S. S., and Hodgson, D. M. (2014). Testing applicability of models of distributive fluvial systems or trunk rivers in ephemeral systems: reconstructing 3D fluvial architecture in the Beaufort Group, South Africa. *Journal of Sedimentary Research*, 84, 1147–1169.

Gupta, S., Collier, J. S., Garcia-Moreno, D., et al. (2017). Two-stage opening of the Dover Strait and the origin of island Britain. *Nature Communications*, DOI: 10.1038/ncomms15101.

Hartley, A. J., Weissmann, G. S., Nichols, G. J., and Warwick, G. L. (2010a). Large distributive fluvial systems: characteristics, distribution, and controls on development. *Journal of Sedimentary Research*, 80, 167–183.

Hartley, A. J., Weissmann, G. S., Nichols, G. J., and Scuderi, L. A. (2010b). Fluvial form in modern continental sedimentary basins: distributive fluvial systems: reply. *Geology*, 38, e231.

Hashimoto, A., Oguchi, T., Hayakawa, Y., et al. (2008). GIS analysis of depositional slope change at alluvial-fan toes in Japan and the American Southwest. *Geomorphology*, 100, 120–130.

Horton, B. K. and DeCelles, P. G. (1997). The modern foreland basins system adjacent to the Central Andes. *Geology*, 25, 895–898.

Horton, B. K. and DeCelles, P. G. (2001). Modern and ancient fluvial megafans in the foreland basin system of the central Andes, southern Bolivia: implications for drainage network evolution in fold-thrust belts. *Basin Research*, 13, 43–63.

Iriondo, M. H. (1984). The Quaternary of northeastern Argentina. *Quaternary of South America*, 2, 51–78.

Iriondo, M. H. (1987). Geomorfolgía y Cuaternario de la Provincia Santa Fé (Argentina). *D'Orbignyana* (Corrientes, Argentina), 4, 54 pp.

Iriondo, M. (1993). Geomorphology and late Quaternary of the Chaco (South America). *Geomorphology*, 7, 289–303.

Klammer, G. (1982). Die Palaeowüste des Pantanal von Mato Grosso und die pleistozäne Klimageschichte des brasilianischen Randtropen. *Zeitschrift für Geomorphologie*, 26, 393–416.

Klausen, T. G., Ryseth, A. E., Helland-Hansen, W., Gawthorpe, R., and Laursen, I. (2014). Spatial and temporal changes in geometries of fluvial channel bodies from the Triassic Snadd Formation of offshore Norway. *Journal of Sedimentary Research*, 84, 567–585.

Latrubesse, E. (2002). Evidence of Quaternary paleohydrological changes in middle Amazonia: the Aripuanã/Roosevelt and Jiparana fans. *Zeitschrift für Geomorphologie*, 129, 61–72.

Latrubesse, E. M. (2015). Large rivers, megafans and other Quaternary avulsive fluvial systems: A potential 'who's who' in the geological record. *Earth-Science Reviews*, 146, 1–30.

Latrubesse, E., Cozzuol, M., Rigsby, C., et al. (2010). The Late Miocene paleogeography of the Amazon basin and the evolution of the Amazon River. *Earth-Science Reviews*, 99, 99–124.

Latrubesse, E., Stevaux, J. C., Cremon, S., et al. (2012). Late Quaternary megafans, fans and fluvio–aeolian interactions in the Bolivian Chaco, Tropical South America. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 356–357, 75–88

Lecce, S. A. (1990). The Alluvial fan problem. In A. H. Rachoki and M. Church, eds., *Alluvial Fans: A Field Approach*. Wiley, Chichester, 151–178.

Leier, A. L., DeCelles, P. G., and Pelletier, J. D. (2005). Mountains, monsoons, and megafans. *Geology*, 33, 289–292.

McCarthy, T. S. (2013). The Okavango Delta and Its Place in the Geomorphological Evolution of Southern Africa. *South African Journal of Geology*, 116, 1–54.

McCarthy, T. S. and Cadle, A. B. (1995). Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages – Discussion. *Journal of Sedimentary Research*, A65, 581–583.

Miall, A. D. (1996). *The Geology of Fluvial Deposits*. Springer, New York, 582 pp.

Miall, A. D. (2014). *Fluvial Depositional Systems*. Springer, New York, 316 pp.

Miall, A. D., Holbrook, J. M., and Bhattacharya, J. P. (2021). The stratigraphic machine. *Journal of Sedimentary Research*, 91, 595–610.

Mohindra, R., Parkash, B., and Prasad, J. (1992). Historical geomorphology and pedology of the Gandak megafan, middle Gangetic plains, India. *Earth Surface Processes and Landforms*, 17, 643–662.

Owen, A., Nichols, G. J., Hartley A. J., Weissmann, G. S., and Scuderi L. A. (2015). Quantification of a distributive fluvial system: the Salt Wash DFS of the Morrison Formation, SW U.S.A. *Journal of Sedimentary Research*, 85, 544–561.

Parkash, B., Awasthi, A. K., and Gohain, K. (1983). Lithofacies of the Markanda terminal fan, Kurukshetra district, Haryana, India. *International Association of Sedimentology, Special Publication*, 6, 337–344.

Pearce, F. (2013). *The Land Grabbers: The New Fight Over Who Owns the Earth*. Beacon Press, Boston, 336 pp.

Plink-Björklund, P. (2015). Morphodynamics of rivers strongly affected by monsoon precipitation: Review of depositional style and forcing factors. *Sedimentary Geology*, 323, 110–147.

Richards, K., Chandra, S., and Friend, P. (1993). Avulsive channel systems: characteristics and examples. In J. L. Best and C. S. Bristow, eds., *Braided Rivers*. Geological Society of London, Special Publication, 75, 195–203.

Rosetti, D. F., Zani, H., and Cremon, E. H. (2014). Fossil megafans evidenced by remote sensing in the Amazonian wetlands. *Zeitschrift für Geomorphologie*, 58, 145–161.

Sáez, A., Anadón, P., Herrero, M. J., and Moscariello, A. (2007). Variable style of transition between Palaeogene fluvial fan and lacustrine systems, southern Pyrenean foreland, NE Spain. *Sedimentology*, 54, 367–390.

Saito, K. (2003). Model of Alluvial Fan Development Based on Channel Pattern and Gravel Size. Report of Research Project, Grant-in-Aid for Scientific Research, 138 (in Japanese).

Saito, K. and Oguchi, T. (2005). Slope of alluvial fans in humid regions of Japan, Taiwan and the Philippines. *Geomorphology*, 70, 147–162.

Sambrook Smith, G. S., Best, J. L., Ashworth, P. J., et al. (2010). Fluvial form in modern continental sedimentary basins: distributive fluvial systems: comment. *Geology*, 38, e230.

Schumm, S. A. (1977). *The Fluvial System*. Wiley, New York, 338 pp.

Shukla, U. K., Singh, I. B., Sharma, M., and Sharma, S. (2001). A model of alluvial megafan sedimentation: Ganga Megafan. *Sedimentary Geology*, 144, 243–262.

Singh, H., Parkash, B., and Gohain, K. (1993). Facies analysis of the Kosi megafan deposits. *Sedimentary Geology*, 85, 87–113.

Sinha, R. and Friend, P. F. (1994). River systems and their sediment flux, Indo-Gangetic plains, Northern Bihar, India. *Sedimentology*, 41, 825–845.

Sounny-Slitine, M. A. and Latrubesse, E. M. (2014). Defining fluvial megafans through geomorphic mapping and metrics. American Geophysical Union Fall Meeting, 2014, Abstract EP51D-3551. https://ui.adsabs.harvard.edu/abs/2014AGUFMEP51D3551S/abstract

Souza, O. C., Araujo, M. R., and Mertes, L. A. K. (2002). Form and process along the Taquari River alluvial fan, Pantanal, Brazil. *Zeitschrift für Geomorphologie*, 129, 73–107.

Stanistreet, I. G. and McCarthy, T. S. (1993). The Okavango fan and the classification of subaerial fan systems. *Sedimentary Geology*, 85, 115–133.

Trendell, A. M., Atchley, S. C., and Nordt, L. C. (2013). Facies analysis of a probable large-fluvial-fan depositional system: the Upper Triassic Chinle Formation at Petrified Forest National Park, Arizona, U.S.A. *Journal of Sedimentary Research*, 83, 873–895.

Tricart, J. (1982). El Pantanal: un ejemplo del impacto geomorfologico sobre el ambiente. *Investigaciones Geográficas*, 29, 81–97.

Tricart, J., Frécaut, R., and Pagney, P. (1984). Le Pantanal (Brésil) : étude écogéographique. *Travaux et Documents de Géographie Tropicale, Bordeaux*, 52, 92 pp.

Urvoy, Y. (1942). *Les bassins du Niger : étude de géographie physique et de paléogéographie*. Larose, Paris, 134 pp.

Valente, C. and Latrubesse, E. (2012). Fluvial archive of peculiar avulsive fluvial patterns in the largest intracratonic basin of tropical South America: the Bananal basin, central Brazil. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 356, 62–74.

Weissmann, G. S., Hartley, A. J., Nichols, et al. (2010). Fluvial form in modern continental sedimentary basins: distributive fluvial systems. *Geology*, 38, 39–42.

Weissmann, G. S., Hartley, A. J., Nichols, G. J., et al. (2011). Alluvial facies distributions in continental sedimentary basins—distributive fluvial systems. In S. K. Davidson, S. Leleu, and C.P. North, eds., *From River to Rock Record: The Preservation of Fluvial Sediments and their Subsequent Interpretation*. SEPM Special Publication, 97, 327–355.

Weissmann, G. S., Hartley, A. J., Scuderi, L. A., et al. (2015). Fluvial geomorphic elements in modern sedimentary basins and their potential preservation in the rock record: A review. *Geomorphology*, 250, 187–219.

Wells, N. A. and Dorr, J. A. (1987a). Shifting of the Kosi River, northern India. *Geology*, 15, 204–207.

Wells, N. A. and Dorr, J. A. (1987b). A reconnaissance of sedimentation on the Kosi alluvial fan of India, In F. G. Ethridge, R. M. Flores, and M. D. Harvey eds., *Recent Developments in Fluvial Sedimentology*. Society of Economic Palaeontologists and Mineralogists, Special Publication, 39, 51–61.

Wilkinson, M. J. (2001). Where large fans form: interim report of a global survey. 7th International Conference on Fluvial Sedimentology, Program and Abstracts, University of Nebraska-Lincoln, Lincoln, Nebraska (USA), 6–10 August 2001, p. 282. (University of Nebraska-Lincoln, Institute of Agriculture and Natural Resources, Conservation and Survey Division, Open-file Report 60).

Wilkinson, M. J. (2005). Large fluvial fans and exploration for hydrocarbons. NASA Tech Briefs 29, 64 [NASA Tech Briefs Online, No. MSC-23424 www.nasatech.com/Briefs/ps.html 30 March 2004].

Wilkinson, M. J. (2006). 'Method for Identifying Sedimentary Bodies from Images and Its Application to Mineral Exploration' – US Patent Office, #6,851,606, issue date 01/10/2006.

Wilkinson, M. J., Cameron, N. R., and Burke, K. (2002). Global geomorphic survey of large modern subaerial fans. *Houston Geological Society Bulletin*, 44, 11–13.

Wilkinson, M. J., Marshall, L. G., and Lundberg, J. G. (2006). River behavior on megafans and potential influences on diversification and distribution of aquatic organisms. *Journal of South American Earth Sciences*, 21, 151–172.

Wilkinson, M. J., Marshall, L. G., Lundberg, J. G., and Kreslavsky, M. H. (2010). Megafan environments in northern South America and their impact on Amazon Neogene aquatic ecosystems. In C. Hoorn, F. P. Wesselingh, eds., *Amazonia, Landscape and Species Evolution: A Look into the Past*. Blackwell, London, 162–184.