Geology

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Geology 2005;33;289-292
doi: 10.1130/G21228.1

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ABSTRACT

In certain cases, the rivers draining mountain ranges create unusually large fan-shaped bodies of sediment that are referred to as fluvial megafans. We combine information from satellite imagery, monthly discharge and precipitation records, digital elevation models, and other sources to show that the formation of fluvial megafans requires particular climatic conditions. Specifically, modern fluvial megafans in actively aggrading basins are produced by rivers that undergo moderate to extreme seasonal fluctuations in discharge that result from highly seasonal precipitation patterns. The global distribution of modern megafans is primarily restricted to 15°–35° latitude in the Northern and Southern Hemispheres, corresponding to climatic belts that fringe the tropical climatic zone. No relationship exists between megafan occurrence and drainage-basin relief or area. The tendency of rivers with large fluctuations in discharge to construct megafans is related to the instability of channels subject to such conditions. Because of the correlation between seasonal precipitation and megafan occurrence, the recognition of fluvial megafan deposits in ancient stratigraphic successions may provide critical information for paleoclimate reconstructions.

Keywords: fluvial, megafan, paleoclimate, sedimentation, monsoon, avulsion.

INTRODUCTION

Fluvial megafans form as rivers exit the topographic front of a mountain belt, migrate laterally in the adjacent basin, and deposit large fan-shaped bodies of sediment (DeCelles and Cavazza, 1999; Fig. 1). Although they share some characteristics with alluvial fans, fluvial megafans are distinct geomorphic features, distinguishable from stream-dominated alluvial fans by their unusually large area (areas of 10^3–10^5 km^2 for fluvial megafans vs. generally <100 km^2 for alluvial fans), low gradient (fluvial megafans, generally ~0.1°–0.01°; alluvial fans, ~1°–4°), sedimentary texture (sediments in fluvial megafans vary from boulders at the apex to predominantly silt and mud at their toes), and depositional processes (fluvial megafans are devoid of sediment gravity flows) (DeCelles and Cavazza, 1999; Horton and DeCelles, 2001; and references therein). Fluvial megafans play an integral role in the dispersal and deposition of sediment in tectonically active areas. The deposits of these features serve as primary repositories for information on climatic conditions and rates of tectonic uplift and erosion in both young and ancient mountain belts. Fluvial megafan deposits have been recognized in stratigraphic successions in the Cordillera of the western United States and Canada (Eisbacher et al., 1974; Lawton et al., 1994; DeCelles and Cavazza, 1999), the Andes (Horton and DeCelles, 2001), the Pyrenees (Hirst and Nichols, 1986), and the Himalaya (Willis, 1993; DeCelles et al., 1998). Characteristics of these deposits have been used to support a number of contentious hypotheses pertaining to basin dynamics and the structural evolution of mountain belts (cf. Love, 1973; Schmitt and Steidtmann, 1990; Lawton et al., 1994; Janecke et al., 2000).

One of the most important unresolved issues related to fluvial megafans, and one with ramifications for tectonic, paleoclimatic, geomorphic, and sedimentary studies, centers on the fact that only a limited number of fluvial megafans exist today despite the multitude of sizeable rivers around the world that cross faults, exit topographic highlands, and enter basins. Is there something unique about rivers that create fluvial megafans? Studies have focused on fluvial megafan facies, morphologies, and the relationship of megafans to drainage-basin development (Wells and Dorr, 1987a, 1987b; Iriondo, 1993; Stanistreet and McCarthy, 1993; Singh et al., 1993; Sinha and Friend, 1994; Gupta, 1997; DeCelles and Cavazza, 1999; Horton and DeCelles, 2001; Shukla et al., 2001), but the underlying factors governing megafan formation and distribution along individual mountain systems and around the globe remain unknown. We studied the characteristics of rivers that form, and do not form, fluvial megafans in order to address the fundamental questions that surround the con-

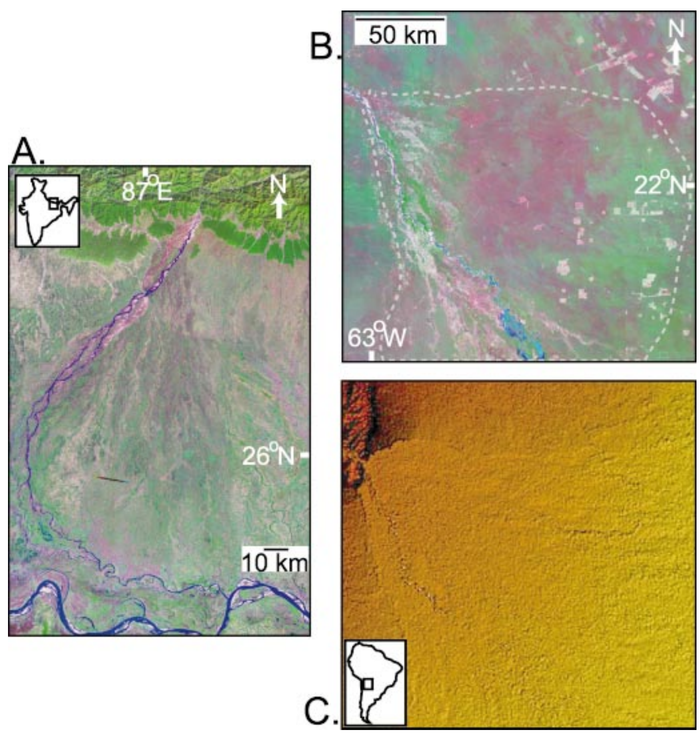

Figure 1. Images of modern fluvial megafans. A: Kosi fluvial megafan forms as Kosi River exits Himalaya. B: Pilcomayo fluvial megafan (outlined by dashes) forms as Pilcomayo River exits Andes. C: Digital elevation model of Pilcomayo megafan (100 times vertical exaggeration). Field of view matches that in B.

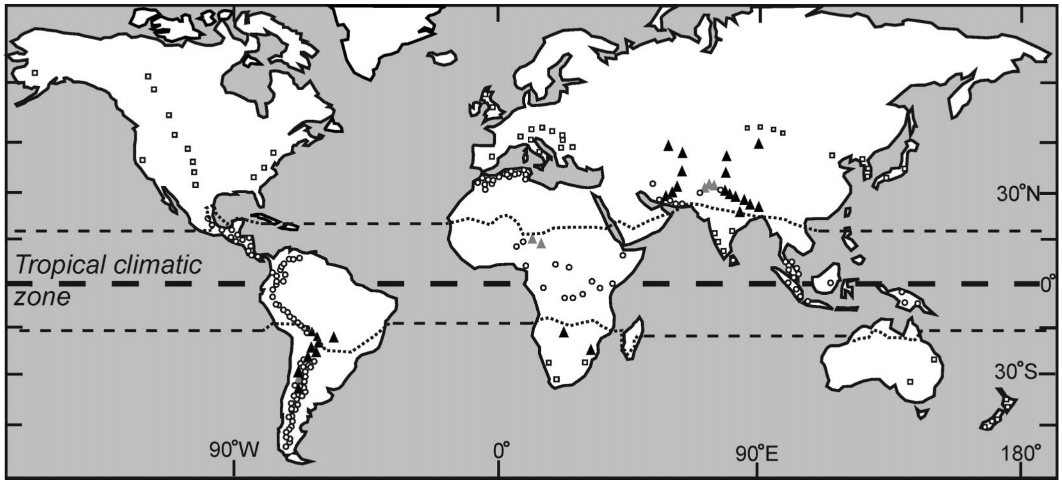

Figure 2. Location of studied rivers and the tropical climatic zone according to Köppen's classification (de Blij and Muller, 1996). Black triangles—megafan rivers; gray triangles—possible megafan rivers; open circles—nonmegafan rivers used in comparisons; open squares—nonmegafan rivers examined, but omitted from comparisons. Fluvial megafans are most prevalent in latitudinal belts that fringe tropical climate zone, corresponding to regions with seasonal precipitation.

struction of these features. Our results show that fluvial megafans are produced by rivers that undergo large seasonal fluctuations in discharge that result from seasonal or monsoonal precipitation. The same association between seasonal precipitation and fluvial megafans is present in ancient stratigraphic successions, suggesting that fluvial megafan deposits may be useful paleoclimate indicators.

METHODS

We examined 202 rivers throughout the world (Fig. 2; GSA Data Repository Table DR1[1]). The compiled database includes Landsat-5 satellite imagery, topographic maps, monthly and annual stream-discharge records, precipitation records, digital elevation models (DEMs; for South American rivers), and data published in the literature. We analyzed satellite images of basins to detect the presence or absence of fluvial megafans. Fluvial megafans were identified using the following criteria: (1) there is a distinguishable fan-shaped body of sediment; (2) the sediment fan is distinctly larger than neighboring alluvial fans (all sediment bodies designated fluvial megafans in this study are >30 km from apex to toe; e.g., Fig. 1); (3) the river associated with the megafan has distributary characteristics, bifurcating into smaller channels, or at least maintaining discharge levels in the main channel (i.e., no tributaries join the megafan river once it exits the topographic front); and (4) on the satellite images there is evidence of abandoned channels whose trends are in a divergent or arcuate disposition (indicating a recent history of radial sediment dispersal). Nonmegafan rivers display the opposite of many of these characteristics and form linear channel belts. The vast majority of the studied rivers and their associated deposits could be designated or rejected as a fluvial megafan on the basis of these criteria; however, topographic maps and DEMs (for South America) were used in some ambiguous cases to search for fan-shaped protuberances in the topography.

We compared the data of all 202 rivers, looking for qualities that discriminate megafan-forming rivers from rivers that fail to create megafans (e.g., Fig. 3A). Because fluvial megafans are depositional features, and therefore necessarily limited to actively aggrading basins, we focused on regions where rivers are obviously entering aggrading basins (Figs. 2 and 3B). Much of northern Asia is excluded, primarily because of incomplete data (e.g., few Landsat-5 images); however, those regions in northern Asia that were examined lack fluvial megafans. The areas that received more detailed study are the Andes, the Cordillera of Central America, the Himalaya, the Indonesian orogenic system, parts of sub-Saharan Africa, the Atlas and adjacent Mediterranean mountain systems, the Russo-Sino and southern Mongolian regions north of the Tibetan Plateau, and the Middle East. This omits some of the rivers that can be used in the analyses (53 of the 202 rivers), but is important for removing the noise that would otherwise be introduced by river systems that occupy nonaggradational areas where fluvial megafans cannot develop. Some of the areas deemed nonaggradational can be disputed, but our findings remain unchanged even with these data points included in the analysis. Furthermore, those basins and river systems that were closely scrutinized represent many different geological and geographical settings.

RESULTS

We identified 15 new fluvial megafans in addition to the 13 megafans documented in the literature (Fig. 2B; Table DR1 [see footnote 1]). Of the 202 rivers in active depositional basins that we surveyed, 115 have no associated megafan. The majority of river systems can be easily classified as either having megafans or not, but a few cases are ambiguous. For example, the upper Indus River displays some signs of radial dispersal, but only over a limited angle. In these cases, the rivers' deposits are classified as possible fluvial megafans.

Figure 3 illustrates the occurrence of fluvial megafans in terms of key hydrologic, geomorphologic, and climatic data. Figures 3A and 3B display discharge peakedness (the average discharge during the month with the greatest discharge, divided by the average annual discharge) plotted against the average annual discharge (reflecting river size). The lack of fluvial megafan rivers on the left side of Figure 3A indicates that a minimum river discharge (~20 m^3/s) is required to create a fluvial megafan. As a result, fluvial megafan rivers typically have moderate to large drainage basins with moderate to high relief (Figs. 3C, 3D). However, many rivers with large, high-relief drainage-basins exit mountain belts but do not produce fluvial megafans (Figs. 3C, 3D). The disconnect between megafan formation and drainage basin characteristics is most clearly shown along the eastern front of the Andes, where fluvial megafans are prevalent along parts of the mountain front but absent along other stretches, despite the fact that these rivers have nearly identical mean discharges, drainage-basin areas, and relief (Fig. 2; Table DR1 [see footnote 1]). Thus, although aggradation and large discharge and drainage area facilitate megafan formation, by themselves they are insufficient. The data indicate fluvial megafan construction requires rivers that undergo seasonal fluctuations in discharge.

Given sufficient aggradation rates and discharges, the single characteristic shared by all

[1]GSA Data Repository item 2005049, Table DR1, river data, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

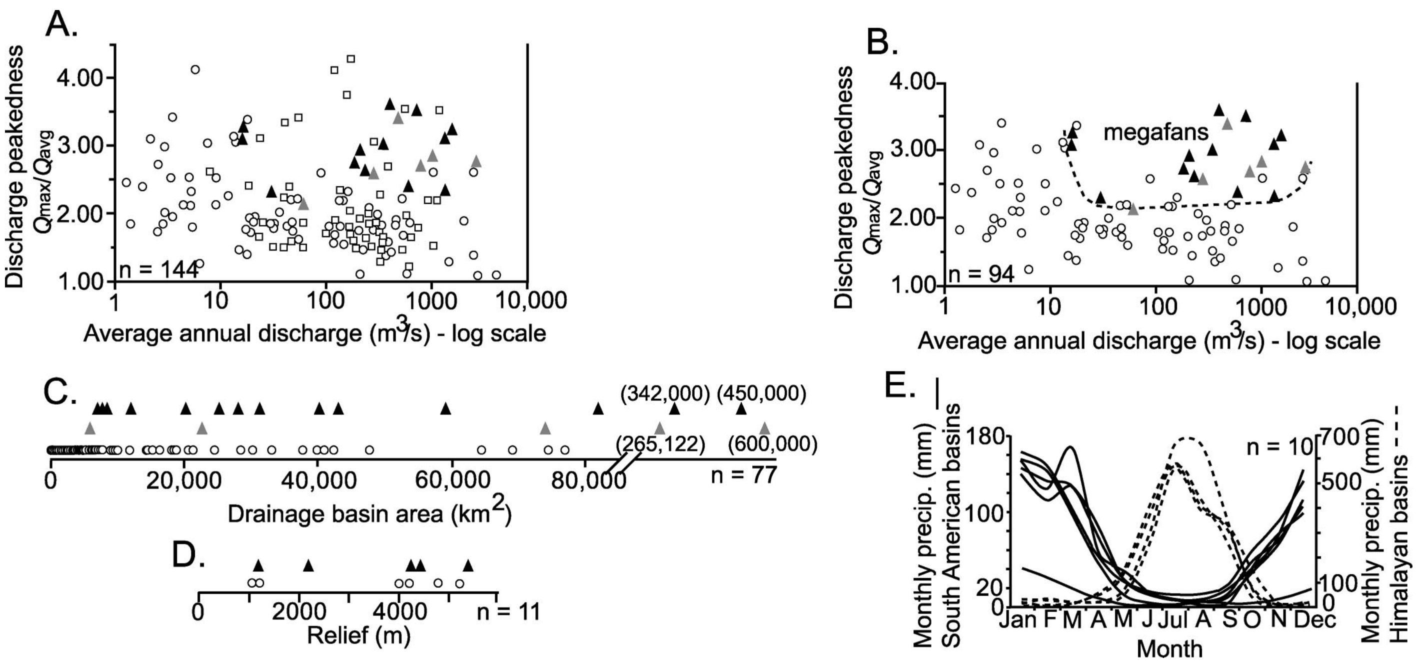

Figure 3. Comparison of rivers. Symbols described in Figure 2. A: Discharge (*Q*) peakedness (see text for details) vs. average annual discharge for all rivers examined. B: Discharge peakedness vs. average annual discharge for rivers used in comparisons. Megafan rivers have greater seasonal fluctuations than nonmegafan rivers. C: Drainage-basin area derived from digital elevation models and published data. There is no discernible break between drainage-basin area of megafan rivers and nonmegafan rivers. D: Drainage-basin relief (river elevation at mountain front subtracted from highest point in basin) of rivers in central Andes.

rivers that produce fluvial megafans is significant seasonal variation in discharge, as measured by discharge peakedness (Fig. 3B). Those rivers that produce fluvial megafans cluster in the upper half of Figure 3B, reflecting more acute peakedness. Rivers that fail to construct fluvial megafans have relatively constant discharges throughout the year (Fig. 3B), regardless of average annual discharge and drainage-basin size and relief. A few rivers in aggrading basins have discharges with relatively high peakedness but fail to form fluvial megafans, for reasons that are discussed here. The seasonal fluctuations in discharges observed in megafan-forming rivers correspond to seasonal precipitation patterns within the rivers' drainage basins (59 precipitation records; Fig. 3E). It is significant that almost all fluvial megafans are symmetrically disposed between 15° and 35° latitude in both the Northern and Southern Hemispheres (Fig. 2).

INTERPRETATION

Understanding why river systems with seasonal fluctuations in discharge are more likely to produce fluvial megafans requires an understanding of how fluvial megafans differ from typical river-channel belts. The distinctive fan-shaped sediment lobes associated with megafan rivers indicate lateral instability that promotes rapid channel migration and frequent avulsion. This tendency has been noted in previous studies of megafans (e.g., Geddes, 1960; Sinha and Friend, 1994; Horton and DeCelles, 2001) and is exemplified by the Kosi River, which drains a large part of the Himalaya in northeast India and Nepal. The Kosi River has migrated westward >113 km in just 228 yr (averaging 0.5 km/yr) (Wells and Dorr, 1987b). The overbank areas of the megafans observed in satellite images are replete with abandoned channels (Horton and DeCelles, 2001; this study).

The processes and conditions controlling river avulsion are complex (e.g., Jones and Schumm, 1999; Mohrig et al., 2000) and beyond the scope of this study. However, evidence suggests that large fluctuations in discharge may promote channel instability and avulsion. Floods often serve as avulsion-triggering events (Jones and Schumm, 1999), and in the case of megafan rivers, the annual flooding associated with the wet season serves as an effective, frequently recurring catalyst for avulsion. For example, the major channel shifts and avulsions of the Kosi River have occurred during the annual monsoonal floods (Wells and Dorr, 1987a). Periods of rapid channel migration also may be associated with peak annual discharges, as river banks are eroded by increased stream power (Ritter et al., 2002). The relatively high sediment yields from basins that alternate between wet and dry seasons (Wilson, 1973) may at times overtax a river's transport capacity. The high sediment yields can lead to channel aggradation and result in avulsion or rapid channel migration (e.g., Wells and Dorr, 1987a; Bryant et al., 1995). Seasonal precipitation also may influence the type and density of vegetation along the river banks, affecting bank stability and, therefore, migration rates and avulsion frequency.

CLIMATE PATTERNS AND FLUVIAL MEGAFANS

The relationship of fluvial megafans to seasonal discharges, combined with their latitudinal distributions, suggests that megafans may be primarily controlled by global climatic patterns. Fluvial megafans are absent in the tropical climatic zone (Fig. 2). Steady month-to-month rainfall totals in this area are reflected in consistent monthly discharges and a lack of fluvial megafans (e.g., Indonesia and northern South America; Fig. 2). In contrast, areas fringing the tropical climatic zone are characterized by seasonal precipitation (Fig. 3D) and have many fluvial megafans (Fig. 2). Although a small number of fluvial megafans are outside of these latitudinal belts, the outlying megafan rivers nonetheless undergo significant seasonal fluctuations in discharge. The current climatic pattern in areas of the Andes where modern megafans occur was established by early Miocene time (ca. 23–18 Ma) (Iriondo, 1993), and the South Asian monsoon has existed since at least ca. 10 Ma (Dettman et al., 2000), making it unlikely that these features are relicts of drastically different climates.

APPLICATIONS TO THE STRATIGRAPHIC RECORD

A correlation between seasonal precipitation patterns and fluvial megafan formation can be documented in ancient stratigraphic successions where paleoclimate and fluvial megafan deposits have been well studied. The Asian monsoons began, or at least intensified, between ca. 10 and 8 Ma (Dettman et al., 2000). Coevally, the deposits of the Himalayan foreland basin reflect a change from small sinuous fluvial channels to fluvial megafans (DeCelles et al., 1998). Fluvial megafans also formed in the central Andean foreland basin while seasonal precipitation patterns prevailed, similar to the present-day climate (Iriondo, 1993). Although less definitive, seasonal precipitation may have occurred in the Cretaceous Cordillera of the western United States (Glancy et al., 1993; J.T. Parrish, 1998, personal commun.); during this period, several large fluvial megafans traversed the western margin of the Cordilleran foreland basin (Lawton et al., 1994; DeCelles and Cavazza, 1999).

DISCUSSION AND CONCLUSION

All rivers that produce fluvial megafans undergo large fluctuations in discharge, but not all rivers that undergo large fluctuations in discharge form fluvial megafans. Peripheral conditions exist that can hinder the construction of fluvial megafans. The majority of factors prohibiting fluvial megafan formation are site specific. In some cases, rivers entering narrow or small basins cannot migrate laterally and therefore cannot construct fan-shaped sediment lobes. The spacing between channel outlets can also be an important factor in megafan formation. For example, the outlets of the Ravi and Chenab Rivers in the western Himalayan foreland basin are closely spaced; thus channel migration is limited by the adjacent river's deposits (Geddes, 1960) and fluvial megafan formation is inhibited.

Fluvial megafans are volumetrically important distributary systems that form adjacent to both extreme and subdued topography. Provided a sufficient aggradation rate and discharge, a river will form a fluvial megafan if it undergoes large seasonal fluctuations in discharge. Because of the correlation between seasonal precipitation and modern megafan occurrence, the presence of fluvial megafan deposits in the stratigraphic record can provide important information for paleoclimate reconstructions.

ACKNOWLEDGMENTS

This project was supported by the National Science Foundation grant EAR-9804680. We are grateful to S. DeLong, and to C. Paola and E. Wohl for helpful reviews.

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Manuscript received 27 September 2004
Revised manuscript received 22 December 2004
Manuscript accepted 26 December 2004

Printed in USA