Slope and bifurcation on braided distributive fluvial systems

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SLOPE AND BIFURCATION ON BRAIDED DISTRIBUTIVE FLUVIAL SYSTEMS

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THESIS

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SLOPE AND CHANNEL BIFURCATION ON BRAIDED DISTRIBUTIVE FLUVIAL SYSTEMS

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ABSTRACT

Much of the current literature on ancient fluvial systems is based on studies of modern rivers, but fails to differentiate between degradational and aggradational systems. That is a problem because degradational systems are not preserved and therefore are not representative of fluvial systems found in the rock record. Current research is attempting to rectify this shortcoming by exploring distributive fluvial systems (DFS) in active sedimentary basins, which have the highest likelihood of being preserved. DFS are sediment deposits that occur when rivers exit the confinement of mountain valleys and become laterally mobile in broad sedimentary basins. They are characterized by a radial pattern of channels from an apex of channel networks. The main mechanisms through which channel networks on DFS evolve are bifurcation and avulsion. Instabilities in river channels that lead to bifurcation and avulsion are related to the 1) slope of the river channel, 2) the slope of the ground perpendicular to the channel, and 3) the ratio of the slope of the floodplain or valley perpendicular to the channel-belt, relative to the down-stream or down–valley slope of the existing channel (Mackey and Bridge, 1995; Jones and
Schumm, 1999; and Karssenberg and Bridge, 2008). This study sought to find a correlation between bifurcation and slope on large (>30 km) braided DFS by measuring long-profile slopes, cross-profile slopes, and slope ratios along active distributive channels. Using digital elevation models and Landsat images, a database of 1,253 long-profile slope values, 1,245 cross-profile values, and 1,112 slope ratios along 98 large DFS was compiled to gain a better understanding of slope relationships along large braided DFS and to determine if there is a correlation between bifurcation and slope. This study found a high statistically significant difference between slope ratios of non-bifurcating and bifurcating areas. Non-bifurcating areas were also found to have shallower gradients than bifurcating areas. Cross-profile slope is greater for non-bifurcating areas in proximal regions of the DFS and greater for bifurcating areas in the medial regions, indicating a change from avulsion-dominated channel migration to bifurcation-dominated migration across these regions. Further work needs to be carried out to look at the role incision plays on slope ratios on DFS, particularly in proximal regions. Additionally, a small number of long-profile slopes had positive values. More research is needed to determine what is causing these positive slope values and to what extent they interfere with the study of the relationship between slope and bifurcation.
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I. INTRODUCTION

Facies models used to interpret ancient fluvial stratigraphy are largely based on modern fluvial systems. These studies, such as those carried out my Miall (1996) and Bridge (2006) emphasize the small-scale architecture of degradational rivers, specifically channel-scale facies. However, large scale alluvial architecture of depositional fluvial systems-- size, shape, and relationship of channel-belt deposits within floodplain deposits-- fundamentally control pore fluid movement, such as oil and water, through sedimentary sequences (Allen, 1978). Alluvial architecture is affected by deposition rate and frequency and location of channel bifurcation (Karssenberg and Bridge, 2008).

The term “bifurcation” is used to mean the process by which a portion of a river's flow is diverted out of an established channel and into a new course on the adjacent floodplain resulting in a parent channel and a distributary, or daughter channel that coexist together (Jones and Schumm, 1999; Slingerland and Smith, 2004). If discharge in the parent channel falls below a critical value, the channel is abandoned and the bifurcation develops into an avulsion (Jones and Schumm, 1999; Stouthamer and Berendsen, 2007). For this study, bifurcation does not mean short-term flow switching that is associated with braided channels and meander bends, but major diversions that result in new channel belts.

In order for fluvial deposits to be preserved, sediment must be subsided below the point of incision and removal (Blum and Törnqvist, 2000). Therefore, only deposits in active sedimentary basins have the potential for long-term preservation.
Weissmann et al. (2010) established that most rivers used to develop facies models (e.g. Miall, 1996; Bridge, 2006) are degradational tributaries, are confined in valleys, and/or are not in active sedimentary basins, thus they have minimal preservation potential and, therefore, do not represent what is seen in the rock record.

A worldwide database of over 700 active continental sedimentary basins developed by the Fluvial Systems Research Group¹ (FSRG) is attempting to rectify this shortcoming in the existing literature because it explores aggradational systems in sedimentary basins, which have the highest likelihood of being preserved. The basins identified cover compressional, extensional, strike-slip, and cratonic tectonic settings. An assessment of these basins shows that the rivers within them are (1) distributive, (2) axial, or (3) confined to valleys between adjacent distributive systems in the interfan area. While the significance of distributive systems in the sedimentary rock record is presently being debated (e.g., Fielding et al., 2012), distributive fluvial systems (DFS) are the dominant river pattern in every modern sedimentary basin (Weissmann et al., 2010, Weissmann et al., 2011). Distributive planforms belong to a spectrum of braided-, meandering-, and debris-flow dominated patterns (Stanistreet and McCarthy, 1993). Braided planforms are the dominant pattern of large DFS with lengths >30 km, making up ~73% of the DFS seen (Hartley et al., 2010). They are characterized by laterally mobile rivers with concave upward long-profiles whose channel networks evolve through channel bifurcation on ~ 80% or the rivers and abandonment (avulsion) on the remaining ~ 20%. Channel patterns of braided distributive fluvial systems (DFS) differ from

¹ FSRG (Fluvial Systems Research Group) is a collaboration between Gary Weissmann and Louis Scuderi at
those of their confined counterparts. In particular, DFS are characterized by a network of channels that evolves through bifurcation.

The hypothesis of this study is that bifurcations occur on areas of DFS with lower long-profile and cross-profile slopes and avulsions occur on areas of DFS with higher long-profile and cross profile slopes. To test this hypothesis, this study focused on detecting a correlation between the ratio of long-profile and cross-profile slopes and channel bifurcation on large braided DFS. Detecting a quantifiable boundary between slope ratios that lead to bifurcation and those that do not will help our understanding of river channel network patterns and evolution in sedimentary basins.

Although it is beyond the scope of this study, understanding how slope relates to bifurcation is important because it may be that the type of channel switching associated with bifurcations and avulsions affect the preservation of floodplain material. In addition, it appears that floodplain preservation potential is higher where channels evolve through bifurcation instead of avulsion.

To test this hypothesis, Shuttle Radar Topography Mission (SRTM) based digital elevation models (DEMs) and decadal Landsat satellite imageries were used to identify what areas on the DFS are dominated by bifurcation vs. avulsion. Digital elevation data were then used to find the cross section and profile slopes of large (>30 km) braided DFS surfaces. These measures were then compared between bifurcating portions and non-bifurcating channeled (avulsion-dominated) portions of the DFS in an attempt to better quantify the relationship between slope and bifurcation type. It is also important to note that sediment supply, size, discharge,
and vegetation can control bifurcation and avulsion, however, the data are not presently available to differentiate these variables.

The knowledge gained from understanding the controls slope has on bifurcation on large DFS in active continental sedimentary basins can help researchers better understand channel evolution processes in distributive systems. This knowledge can also be applied to understanding large-scale architectures and geometries of fluvial systems and can give researchers insights into paleoslopes. Understanding the geometries of fluvial systems also aids in the detection of petroleum reserves, fresh-water aquifers, and current and past fluvial processes.

1.1 Braided Fluvial Systems

Fluvial facies models are common tools for understanding ancient fluvial systems, and are a reflection of their depositional environments. Miall (1996), for example, describes the channel architectural characteristics of common modern and ancient fluvial styles based on lithofacies assemblage. Of Miall’s 16 facies models, 7 describe braided depositional systems. Miall (1996) characterizes braided rivers as having broad, shallow, relatively straight, bedload dominated channels. These channels are composed of a series of smaller channels that interweave, or braid, around sand bars and islands that migrate down river. These differ from meandering systems, which are composed of single suspension-load dominated channels that are more narrow and deep than their braided counterparts. Meandering rivers move in a highly sinuous, or snaking pattern across their valleys as a result of erosion on the outer, or concave, bank of a bend and the lateral accretion of sediment, known as point bars, on the inner, or convex, bank of a bend.
that is the result of the migration of a thalweg (the fastest line of flow in a river channel).

Most of the modern rivers used by Miall (1996) to describe braided rivers are confined degradational systems that are not in sedimentary basins and have no possibility of being preserved (Table 1). Of the three braided systems that are distributive, two are examples of debris-flow and sheet-flow dominated systems. Internal characteristics of channels, such as mid-channel bars, dominate all of the facies models described, yet they show very little floodplain sediment. The use of facies models derived from confined rivers in degradational settings is inconsistent with what is seen in the geologic record.

Because most of the fluvial systems used in modern studies are degradational, the question must be asked, *Are these systems true analogs of the fluvial systems seen in the rock record?* If they are not, then any knowledge applied to large-scale architectures based on these studies is incomplete and does not capture the full range. This leads to the questions, *What are the dominant river patterns that get preserved?* and *How does fluvial morphology change in aggradational systems that exist in active continental sedimentary basins?* This study of braided distributive rivers in continental sedimentary basins is part of a larger study evaluating fluvial patterns in aggradational settings.
### Table 1. Common braided fluvial styles described by Miall (1999) and the types of modern rivers from which they are based.

<table>
<thead>
<tr>
<th>fluvial style</th>
<th>modern river</th>
<th>modern location</th>
<th>river setting</th>
<th>DFS</th>
<th>references</th>
</tr>
</thead>
<tbody>
<tr>
<td>gravel-bed braided river with sediment-gravity-flow deposits</td>
<td>Trollheim fan</td>
<td>Death Valley, CA</td>
<td>fan</td>
<td>yes</td>
<td>Hooke (1967)</td>
</tr>
<tr>
<td>shallow, gravel-bed braided river</td>
<td>Scott fluvio-glacial outwash river</td>
<td>Alaska</td>
<td>fan</td>
<td>yes</td>
<td>Boothroyd and Ashley (1975); Boothroyd and Nummedal (1978)</td>
</tr>
<tr>
<td>deep, gravel-bed braided river</td>
<td>Donjek River</td>
<td>Yukon Territory, Canada</td>
<td>incised valley</td>
<td>no</td>
<td>Williams and Rust (1969)</td>
</tr>
<tr>
<td>low-sinuosity braided river with alternate bars</td>
<td>Platte River</td>
<td>Colorado/ Nebraska</td>
<td>incised valley</td>
<td>no</td>
<td>Crowley (1983)</td>
</tr>
<tr>
<td>shallow, perennial, sand-bed braided river</td>
<td>Platte River</td>
<td>Colorado/ Nebraska</td>
<td>incised valley</td>
<td>no</td>
<td>Miall (1977); N.D. Smith (1970, 1971, 1972); Blodgett and Stanley (1980); Crowley (1983)</td>
</tr>
<tr>
<td></td>
<td>William River</td>
<td>northern Saskatchewan</td>
<td>incised valley</td>
<td>no</td>
<td>N.D. Smith and D.G. Smith (1984)</td>
</tr>
<tr>
<td>deep, perennial, sand-bed braided river</td>
<td>South Saskatchewan River</td>
<td>southern Saskatchewan</td>
<td>incised valley</td>
<td>no</td>
<td>Cant and Walker (1976, 1978)</td>
</tr>
<tr>
<td>high-energy, sand-bed braided river</td>
<td>no modern example</td>
<td></td>
<td></td>
<td></td>
<td>Cowan (1991)</td>
</tr>
</tbody>
</table>
1.2 **Distributive Fluvial Systems**

DFS are the result of sediment deposition that occurs when rivers exit the confinement of mountain valleys and become laterally mobile in broad sedimentary basins (Weissmann et al., 2010; Hartley et al., 2010). They are characterized by a radial pattern of channels from an apex of channel networks that evolve through channel bifurcation and avulsion. DFS are roughly fan-shaped lobes of sediment that are convex upward across the system and concave upward down the system (Troeh, 1965). This long-profile results as slope adjusts to transport the supplied sediment load (Stock et al., 2007). The steepness of the long-profile slope correlates with the size of the DFS (Stanistreet and McCarthy, 1993). The largest systems (with areas of $\sim 10^3$ to $10^5$ km$^2$) have shallow slopes, $\sim 0.1^\circ$ to $0.01^\circ$, while the smallest systems ($<100$ km$^2$) have steeper slopes, $\sim 1^\circ$ to $4^\circ$ (Stanistreet and McCarthy, 1993; DeCelles and Cavazza, 1999; and Leier et al., 2005). DFS also have an intersection point where above which the river or alluvial system is incised in its floodplain and below which the river spreads out across the active sediment deposits. These features have been noted in modern settings (Hooke, 1967; Boothroyd and Ashley, 1978; Kelly and Olsen, 1993; Stanistreet and McCarthy, 1993; Blair and McPherson, 1994; DeCelles and Cavazza, 1999; Weissmann et al. 2002, 2005; Leier et al., 2005) as well as ancient settings (Friend, 1978; Nichols, 1987; Nichols, 1989).

DFS occur at different scales as well, and while they can be subdivided based on commonalities, it is important to recognize that they are all part of a continuum (Hartley et al., 2010). Stanistreet and McCarthy (1993) created a triangular classification for subaerial fans with three end members that include large-scale low
sinuosity/meandering (losimean) fluvial fans with axial lengths ≥ 150 km, mid-scale braided fluvial fans ≤ 120 km, and small-scale alluvial fans ≤ 10 km. Leier et al. (2005) divide DFS between fluvial megafans defined as greater than 30 km and alluvial fans defined as less than < 30 km.

Using Google Earth, Hartley et al. (2010) indentified 415 large (>30 km) DFS. They found that large DFS display six major planform types (Table 2). These large DFS exist in many climatic zones, including drylands, tropical, subtropical, continental, and polar zones. While many catchments are located in one climatic zone, some, especially the larger ones, occur in as many as four. Much like climate, the large DFS span different tectonic settings, of which, the four most general are (1) extensional, (2) compressional, (3) strike-slip, and (4) cratonic. This study focused on the first three planforms of this database.

<table>
<thead>
<tr>
<th>Planform Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>a single braided channel that bifurcates downstream into braided/straight channels</td>
</tr>
<tr>
<td>2</td>
<td>a single braided channel</td>
</tr>
<tr>
<td>3</td>
<td>a single dominant braided channel which becomes sinuous downstream and often bifurcates</td>
</tr>
<tr>
<td>4</td>
<td>a major sinuous channel system</td>
</tr>
<tr>
<td>5</td>
<td>a single sinuous channel that bifurcates into smaller sinuous channels downstream</td>
</tr>
<tr>
<td>6</td>
<td>multithread sinuous channels where no single sinuous channel dominates the DFS surface</td>
</tr>
</tbody>
</table>
1.3 BIFURCATION

The main mechanisms through which channel networks on DFS evolve are bifurcation and avulsion. Bifurcation studies include investigation of modern and Holocene bifurcations (Slingerland and Smith, 2004; Jones and Schumm, 1999; and Stouthamer and Berendsen, 2007), flume experiments (Ashworth et al., 2004, 2006), numerical modeling (Mackey and Bridge, 1995; Slingerland and Smith, 1998; and Karssenberg and Bridge, 2008), and interpretations of the geologic record (Jones and Hajek, 2007).

Bifurcation occurs when the stability of a river channel decreases past a critical threshold defined by the slope of the floodplain relative to the slope of the channel, causing a portion of its flow to diverge resulting in the formation a new channel (Jones and Schumm, 1999). Instability in river channels is primarily related to the ratio of the slope of the floodplain or valley perpendicular to the channel-belt, relative to the down-stream or down-valley slope of the existing channel (Mackey and Bridge, 1995; Jones and Schumm, 1999; and Karssenberg and Bridge, 2008). That is to say, as a floodplain or valley gets steeper than a river channel, it is likely to bifurcate the next time the river overfills its banks. Bifurcated channels will only remain stable if (1) sediment moving through the system is partitioned between the two channels in proportion to their sediment-carrying capacities, or (2) the channels are able to adjust their capacities through deposition or erosion to accommodate the sediment supplied (Slingerland and Smith, 2004; and Stouthamer and Berendsen, 2007). Avulsion occurs when one channel fails to maintain its capacity.
Figure 1 shows the model used by Karssenberg and Bridge (2008) to explain the effects that bifurcation and slope have on each other in the evolution of channel networks. If a high number of bifurcations occur in an area, the average slope ratio will be low (if slope ratio is defined as the ratio between the slope of the floodplain perpendicular to the channel-belt relative to the slope parallel to the channel-belt). This is because a high frequency of bifurcation is associated with a brief presence of channel belts, which does not allow channel-ridges to build up. A low slope ratio means that a smaller fraction of bifurcations will transform into avulsions. This, in turn, increases the average duration of bifurcation and the number of channels in the system. On the other hand, a high slope ratio indicates that bifurcations will more likely transform into avulsions. This decreases the duration of bifurcation and thus the number of channels present at that location in the system.

An interpretation of this model suggests that because DFS have concave long-profiles and convex cross-profiles, channel migration on the areas with higher slopes should be dominated by avulsions whereas channel migration on areas with lower slopes should be dominated by bifurcations. This is consistent with observations of braided DFS with Google Earth. For this study, variations in long-profile and cross-profile slopes of large-scale braided DFS were measured in an attempt to quantify the relationship between slope and types of bifurcation.
1.4 Accumulation Space

The intersection point of a DFS marks the point where accumulation space exists (Weissmann et al., 2002). A river incised up-system of an intersection point signifies negative accumulation space, while down-system of the intersection point the river aggrades, and signifies a positive accumulation space (Figure 2). Therefore, shifts up-system and down-system in the position of the intersection point in response to changes in the ratio of sediment supply to discharge, represent accumulation space change (Weissmann et al., 2002).

Allogenic processes, specifically climatic variability such as glacial and interglacial periods, affect accumulation space on DFS by changing the balance between sediment load and discharge (Figure 3) (Bull, 1991; Weissmann et al., 2002; Gibling et al., 2005; Karssenberg and Bridge, 2008). Weissmann et al. (2002) describes how glacial-interglacial cycles affect accumulation space on DFS in the following way. Decreases in the ratio of sediment supply to stream discharge occur following periods of glaciations and during interglacial periods causing the
intersection point of the DFS to shift downfan. Above this point, incision occurs and creates an incised valley with surfaces of different age and height above the active channels. Increases in the ratio of sediment supply relative to stream discharge, such as those that occur during periods of glaciation and maximum glacial recessions, result in episodes of channel aggradation, shifting the intersection point toward the apex, filling incised valleys and then leaving open fan deposits.

Additionally, tectonic uplift and subsidence control accumulation space by manipulating (1) the size, shape, and orientation of the basin and (2) the relative height of local source areas, which, in turn, contribute to local sedimentation rates (Alexander and Leeder, 1987; Karssenberg and Bridge, 2008).

**Figure 2.** Distribution of accumulation space on DFS. Above the intersection point the river is incised, indicating negative accumulation space. Below the intersection point, sediment is being deposited, indicating positive accumulation space (from Weissmann et al., 2002).

**Figure 3.** Stream equilibrium is shown as a balance between the relative ratio of driving forces (stream slope and discharge) and resisting forces (sediment load and sediment size). When driving forces outweigh resisting forces the system responds by degrading. Conversely, when resisting forces outweigh driving forces the system responds by aggrading (from www.fgmorph.com accessed 3/22/09).
Remote sensing is a valuable tool for studying DFS. Remote sensing makes it possible to analyze a large population of braided DFS, including study sites that are politically or geographically inaccessible, without the time and costs involved in extensive field-work where ground-truthing can be done. This study does not deny the importance of ground-truthing. On the contrary, DFS are so large that remote sensing allows for the careful formulation of hypotheses that can later be tested in the field, making efficient use of research time and money by selecting cases that best represent braided DFS.

Many researchers already use remote sensing to study alluvial fans. Milliaresis and Argialas (2000), for instance, designed and implemented a computer algorithm to extract and delineate alluvial fans in Death Valley, CA using Defense Mapping Agency DEMs and Landsat Thematic Mapper (TM) images. Additionally, Volker et al. (2006) used DEMs developed from Airborne Laser Swath Mapping to detect changes in local relief on alluvial fans in Death Valley, from which they were able to distinguish debris-flow vs. fluvial dominated fans. Finally, Hashimoto et al. (2008) used digital elevation models based on SRTM data to analyze depositional slope change at alluvial fan toes of humid and arid fans. Together these studies illustrate research using remote sensing; research that otherwise would not be possible with field-based methods alone.
1.5.1 Elevation data

This study uses digital elevation models based on data from the NASA Shuttle Radar Topography Mission (SRTM). SRTM spent 11 days orbiting Earth in February 2000 on the NASA Space Shuttle Endeavor, collecting data of 80% of Earth’s land surface using dual Spaceborne Imaging Radar (SIR-C) and dual X-band Synthetic Aperture Radar (X-SAR) (USGS, 2009). At the time of this study, within the United States, its territories, and possessions, SRTM data were available at 1-arc-second (30 meters) with relative horizontal accuracies of ± 15 m (circular error at 90% confidence) and relative vertical accuracies of ± 6 m (linear error at 90% confidence) (Smith and Sandwell, 2003; Farr et al., 2007). Today, SRTM data are available in these areas at 1/3-arc-second (10 meters). Global coverage outside of the United States is available between 60 degrees North and 56 degrees South latitudes at 3 arc-second (90 meters). This study used SRTM “finished” data, which were edited by the National Geospatial-Intelligence Agency (NGA) to delineate and flatten water bodies, better define coastlines, remove "spikes" and "wells" (single pixel errors), and fill small voids, although some voids are still present. Additional SRTM data from the US Geologic Survey National Map Seamless Server public website[^3] and the Global Land Cover Facility public website[^4] were used.

Because SRTM is radar derived, geometric distortions exist. Objects that are of greater heights than the surrounding local terrain tend to reflect the majority of microwave energy back to the radar (Jensen, 2007). This causes slopes inclined

towards the radar to appear compressed, an effect called foreshortening or, in extreme cases, layover (Figure 4). The opposite slopes (inclined away from the radar) appear to be in shadows, which is called backslope. This occurs when the majority of the radar signal is bounced off a topographic high with very little signal reaching the area behind it (Figure 4). In addition, void spaces are cells of no data that occur in some of the DEMs where no data is recorded for the area behind the topographic high.

![Figure 4. The effects of topographic highs using radar signals](southport.jpl.nasa.gov, accessed 3/12/09).

In addition, there are several problems that have been found specifically with SRTM data. My preliminary analysis of DFS found artifacts that appear as shallow, evenly-spaced, “trenches” in relatively flat areas with little to no change in elevation (Figure 5). The trenches affected the stream flow direction vectors, causing GIS derived water flow networks to be routed along the trenches rather than in the proper downslope direction (Figure 6). These lines are believed to be the result of a scanner calibration error when the image was acquired. The orbital path of the shuttle carrying the SRTM was such that at higher latitudes the Earth’s surface was
scanned at a high angle. This higher look-angle produced by grazing looks at higher latitudes produces an exaggerated error at higher latitudes than at lower latitudes. An assessment of SRTM accuracy by Miliareis (2008) found that the SRTM instrument (1) over-estimated elevation along E, NE and N directions while at the same time (2) under-estimated elevation in the W, SW and S directions. While this may affect the accuracy of the elevation readings, it should not affect slope calculations based on those data. SRTM data have also been found to have random noise that is particularly problematic when trying to extract basins and stream networks in low-relief settings (Bhang and Schwartz, 2008; Miliareis, 2008). Noise is a term used to describe distortions in the data that are meaningless but can occur both randomly and systematically. Furthermore, InSAR radar does not penetrate vegetation; therefore SRTM data is sensitive to the vertical structure of the vegetative canopy (Walker et al, 2006). This means that DFS with dense trees will have to be excluded from the analysis. While SRTM data have limitations, SRTM remains the best available source of digital elevation data for most locations around the world.

1.5.2 Landsat imagery

Landsat satellite imagery was also used. The Landsat satellite platforms provide ideal imagery for this study by offering (1) frequently obtained, world-wide coverage, (2) 15 m spatial resolution for panchromatic images and 30 m resolution for spectral images, (3) high spectral resolution with bands in the visible blue, visible green, visible red, near infrared, and mid-infrared, and (4) imagery that is widely available and easily accessible. Landsat images were obtained from the
United States Geologic Earth Explorer public website\textsuperscript{5} and the Global Land Cover Facility public website.\textsuperscript{6}

As with all passive remote sensing data, Landsat images are affected by the scattering and absorption of electromagnetic radiation by atmospheric particles as well as by cloud cover (Jensen, 2007). Some of these atmospheric effects can be corrected using absolute and relative radiometric techniques (Janzen et al., 2006). However, since Landsat images are collected so frequently, there are many images to choose from, which increase the chance of finding a cloud-free or low-cloud image.

\textbf{Figure 5.} (A) Satellite image of Shule He fan, China (latitude \textasciitilde 40° N). (B) Hillshade relief image of Shule He fan (area indicated by the black box in A) shows linear trenches found on SRTM data. Trenches can be seen running NE to SW at \textasciitilde 45° angle and are most prevalent on flat areas. (C) Satellite image of two fans in Chile (latitude \textasciitilde 20° S). Chile 1 is the northern most fan and Chile 2 is directly south of Chile 1. (D) Hillshade relief of Chile 1 and 2 (area indicated by black box in C) shows trenches running almost exactly north to south.

\textsuperscript{5}http://edcns17.cr.usgs.gov/EarthExplorer/
\textsuperscript{6}http://glcfapp.umb.cs.umd.edu:8080/esdi/index.jsp
Figure 6. Blue lines represent vectorized linear stream networks on top of (A) a hillshade relief map and (B) a true color satellite image. Note how the stream networks, especially in the lower left area of the image, are heavily influenced by the trenches and not true topography.

1.6 Large Database Creation

Databases are potentially powerful tools for aiding scientific research. A good database is (1) well organized, (2) well managed, and (3) efficiently stored. In order to facilitate scientific research, careful consideration must go into how, and to what ends, the database will be used (Wertz, 1993; Jasco, 1999; Teorey et al., 2006). A database must be set up so that it will answer researchers’ questions, but must also anticipate what possible directions the project can go, which requires good research design. If a database is not well designed from the beginning “...it can result in wasting a lot of time and money by working on the wrong solution to the wrong problem” (Wertz, 1993, p.15). Communication between researchers and the database designer is key to insuring that the database will contain the information necessary to carry out the study and that it is organized in such a way that new information can be added in the future.
Good database design also requires that the database be organized so that people other than the designer can use it. This is especially important in an academic setting where researchers collaborate on a project for varying lengths of time. Therefore, the database organization needs to be self-explanatory and all steps must be well documented. Another concern with databases is in how to store, backup, and query the large amounts of data collected (Roman, 1999). Data stored in different locations that is simultaneously worked on by different people commonly results in versioning errors. One solution is to store all of the data in one location. However, this is not always practical as mass storage devices can be very expensive, not to mention the risks associated with keeping everything in one place. Finally, if data are too hard to access then the database will not be useful.

All of these issues addressed apply to the large database of >700 active continental sedimentary basins and 415 large (>30km long) DFS currently under construction by myself and the other FSRG members (Appendix 1). The larger project will result in a relational database using Microsoft Access and a spatial database in ArcGIS. Researchers will be able to query both tabular data as well as spatial data, such as satellite images, DEMs, raster calculations, and vectorized data.

II. METHODS

2.1 DFS

Initially, 107 large DFS with braided planforms throughout Asia where selected for this study as identified by Hartley et al. (2010) including a single braided channel that is maintained downstream and a single braided channel that
bifurcates into smaller braided, straight, or sinuous channels downstream that do not reconnect with the original channel. The latitude and longitude of the apex and toe points of the DFS allowed the acquisition of the appropriate SRTM and LandSat imagery that encompassed the entire DFS (Appendix 2).

While it may appear that the finest DEM resolution available would be ideal for slope measurement, small structural features on the fan can obscure the accuracy of slope measurements. A study by Hashimoto et al. (2008) of slopes on alluvial fans in Death Valley, California, and Japan using DEMs found that small-scale surficial features, including "shallow entrenched channels, levees and debris-flow lobes are often found on the alluvial fans and adjacent lowlands" and negatively impact the accuracy of slope measurements of alluvial fans. Most of these landforms on the Death Valley alluvial fans exist on a scale of < 100 m (Staley et al., 2006; Volker et al., 2006; and Wasklewicz et al., 2007) suggesting that a DEM would need to have a resolution > 100 m to mitigate the effect of these features.

Hashimoto et. al (2008) calculated slopes on DEMs with varying resolutions and found that slopes calculated on DEMs with resolutions < 150 m were directly affected by the changes in resolution, whereas slopes calculated on DEMs with resolutions between 150 m and 300 m were found to be almost independent of the DEM resolution. They concluded that coarsening the resolution of the DEM minimizes the effect of small-scale landforms on slope. In addition, they found that the two main methods used to coarsen the DEM, resampling the data over a specified interval and applying a smoothing filter over the DEM, produced similar results.
With these concepts in mind, I tested slopes along several DFS at different resolutions and found that coarsening the DEMs above 300 m resolution caused a noticeable change in the DFS topography (Figure 7). I decided to coarsen the SRTMs from their original 90 m resolution to 180 m resolution, to stay within the range of acceptable resolutions found by Hashimoto et al. (2008) and because 180 m was simply doubling the original resolution while staying within the Hashimoto range.

Additionally, because SRTM data are sensitive to the vertical structure of vegetative canopy, the SRTMs were coarsened using a neighborhood statistic tool, which smoothes the SRTM cell elevation using the minimum elevation value. This counters the effect of smaller scale vegetation (Figure 8). This neighborhood statistic tool in effect creates a three-by-three cell "neighborhood" and calculates a minimum elevation value over that area. This minimum value would likely represent ground elevation and not vegetation. Despite these steps, DFS with large amounts of high growing vegetation, in particular trees, were excluded from this study.
Figure 7. A through D show changes in topographic features along the long-profile of Mongolia 01 as the resolution of the DEM is coarsened from 90 m, 180 m, 220 m, and 400 m respectively. From 90 m to 180 some of the smaller features are smoothed over. The trough shown in the graphs (indicated by the red arrow) is almost completely lost as the resolution coarsens from 220 m to 400 m.
Figure 8. The effect of using a minimum neighborhood filter to coarsen the resolution of the DEM of China 39. A) The Landsat image of China 39 using an RGB band combination of 4, 2, 1 respectively. Band 4 represents near infrared wavelengths and is therefore an indicator of the presence of vegetation. In this image vegetation is shown as red with most highly concentrated area of vegetation (circled) occurring approximately 12,000 m down fan. B) The profile of China 39 from the apex to 20,000 m down fan at 180 m resolution coarsened using a mean filter and C) the profile of the same area at 180 m resolution coarsened using a minimum filter to help control for vegetation.

DFS were not included in this study if the DEM or Landsat images were not available or if the images were poor and it was difficult to see the DFS clearly. As a result, of the original 107 DFS, 98 were analyzed in the final study.

Next, the Landsat images of each DFS were visually reviewed to make sure that they each contained: 1) a clear apex, or the point where the river exits the confinement of mountain valleys and enters a sedimentary basin; 2) a radial pattern of channels from the apex or, if only a single active channel was present, evidence of
abandoned channels that branch out away from the apex; 3) a roughly fan-shaped lobe of sediment that decreased in slope both across the system and down the system; 4) either a single channel or bifurcating channels that decrease down system with no tributary channels below the apex; and 5) an active channel length of > 30 km from apex to toe.

After determining that the DFS listed met all of these criteria, they were once again analyzed to verify visually that were braided systems. A braided system is a central river channel that is divided into a network of interwoven branches separated by small islands stabilized by vegetation of sediment or bars of unvegetated sediment. Finally, each braided DFS was classified according to one of two braided planforms: 1) a single braided channel that is maintained downstream (Figure 9) and 2) a single braided channel that bifurcates into smaller braided, straight, or sinuous channels downstream that do not reconnect with the original channel (Figure 10).
2.2 Data Processing

A measure of slope was taken across 98 fans using SRTM data to determine if slope ratio is an accurate measure of bifurcation. SRTM images of the DFS were first cleaned by removing cells with no data. The resolution of the images was then coarsened from 90 m to 180 m using a minimum value neighborhood statistics analysis.

To find the long-profile slope, a line was drawn using the ArcGIS profile tool from the apex to the toe of each DFS, while trying to keep the long-profile line along the active river channel as much as possible, as shown in Figure 11. The long-profile line was divided into ten equidistant points down the DFS. Again, using the profile tool, two cross-profile lines were drawn at each point starting at the long-profile line and extending out 1 km in either direction perpendicular to the long-profile line for each of the ten points down the DFS. Each of the 21 slope lines on each DFS was graphed using the 180 m resolution elevation data and the data were exported.
Next, a qualitative assessment was made of each 1 km$^2$ long- and cross-profile analysis area to determine if the area contained an active channel or channels and if so, whether they were non-bifurcating or bifurcating in that area. Using Landsat images of the DFS, long- and cross-profile analysis areas were assessed to determine if the area was outside of the basin and assigned an area number (Table 3 and Figure 12).

**Figure 11.** A) The long-profile line drawn on the Landsat image of China 49 starting from the apex and extending to the toe. B) The long-profile line is then divided into ten equidistant points. C) At each point two cross-profile lines 1 km in length are drawn perpendicular to the long-profile line and extend from the long-profile line out in either direction. D) The long- and cross-profile analysis area is made up of the 1 km$^2$ area composed of the 1 km cross-profile line and the long-profile area taken 500 m above and below the analysis point (1 km total). The red square represents the left long- and cross-profile area and the orange square represents the right long- and cross-profile area at that point.
Table 3. Description of long- and cross-profile analysis area.

<table>
<thead>
<tr>
<th>Area Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>area is on slopes marginal to the DFS (i.e. on the drainage basin)</td>
</tr>
<tr>
<td>1</td>
<td>river flows through area while maintaining a non-bifurcating channel or channels (no points of bifurcation)</td>
</tr>
<tr>
<td>2</td>
<td>river flows through areas and contains at least one point of bifurcation</td>
</tr>
<tr>
<td>3</td>
<td>area is away from the active river channel but still on the DFS</td>
</tr>
<tr>
<td>4</td>
<td>area is off the DFS</td>
</tr>
</tbody>
</table>
Figure 12. Landsat images of five different profile-long- and cross-profile analysis area classifications shown in the red boxes: A) China 10, area type 0-area is out of basin, B) China 10, 1- single channel, C) China 11, 2- channel with at least one point of bifurcation, D) China 10, 3- off the active river channel, E) China 49, 4- off of the DFS but still within the basin.
Long-profile, or channel, elevation values were measured and entered into the database over a 1 km distance centered at the point where the cross-profile intersects the long-profile for every point except the last value on the fan (point #10) where the elevation was measured 1 km above the analysis point. Cross-profile elevation values were also measured and recorded for every point along the left side of the DFS (looking down the DFS from apex to toe) and the right side of the DFS.

The long-profile slope at each of the ten points down the DFS was calculated as a regression line of each of the elevation values using the following equation:

\[ b = \frac{\sum (x-x')(y-y')}{\sum (x-x')^2} \]

where \( x = \) known horizontal distance or run; \( y = \) known vertical distance or rise; and \( b = \) slope. Left and right cross-profile slopes were calculated at each of the ten points down the DFS using the elevation values at each point. Slope for both left and right areas where calculated using the same equation as long-profile.

The raw slope ratio was calculated for both the left and right sides of the DFS using the following equation:

\[ S_{ratio} = \frac{S_{cross-profile}}{S_{long-profile}} \]

The area number, slope ratio values, long-profile slope values, and cross-profile slope values were imported into Microsoft Access and sorted so that only points with an area number of 1 (non-bifurcating channel(s)) and 2 (bifurcation channel(s)) were reported. Finally, the means of all area values of 1 and 2 were
compared statistically using a two-sample t-test assuming unequal variance with a significance level of 5%.

III. RESULTS

3.1 SLOPE RATIOS, LONG-PROFILE SLOPES, AND CROSS-PROFILE SLOPES

This section describes the statistical distribution of slope ratio, long-cross slope, and cross-profile slope of non-bifurcating channel and bifurcating areas of large braided DFS. Non-bifurcating channel slope ratio data (n = 822) reveal normally distributed measurements centered around 0, with a large range from -2692.41 to 470 (Figure 13 and Table 4), while the mean is -3.62 and the mode and median are both 0. The standard deviation and the variance are also extremely large, 99.43 and 9885.63, respectively.

That the mode and the median are both 0, and the variance is extremely large, is accounted for by a small number (n=16) of extreme outliers that result from extremely low profile slope values. The average long-profile slope value for these outliers is $3.65 \times 10^{-6}$ while the average long-profile slope value used to calculate slope ratios excluding these outliers is $5.21 \times 10^{-3}$, making the outlying long-profile slope values smaller by three orders of magnitude. When these 16 outliers are removed the mean for non-bifurcating channel areas shifts from -3.62 to -0.30, the standard deviation from 99.43 to 3.24, and the variance from 9885.63 to 10.74 (Table 5).

Bifurcating channel area slope ratios have a sample size of 290 and also show a normal distribution centered around 0 (Figure 14). The data have a range of -3.48
to 6.91 with a mean of 0.07, a mode of 0, and a median of 0.01 (Table 5). The standard deviation is 0.94 and the variance is 0.88. The average long-profile slope ratio used to calculate bifurcating slope ratio is $9.65 \times 10^{-3}$. Figure 15 shows overlapping histograms of non-bifurcating and bifurcating slope ratios. Figures 16 and 17 show the distribution of slope ratios at each analysis point along the DFS for both non-bifurcating and bifurcating channel areas, respectively. Again, across these three figures we see that non-bifurcating channel areas have a wider range of slope ratio values than bifurcating channel areas.
Figure 13. A. Histogram of all values of non-bifurcating channel slope ratios showing a normal distribution centered around 0. B. A truncated histogram of the same data focused in on the lower part of the graph in order to show detail of smaller values.

Table 4. Description of all non-bifurcating channel slope ratio data.

<table>
<thead>
<tr>
<th>Sample Size</th>
<th>822</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>-2692.41</td>
</tr>
<tr>
<td>Maximum</td>
<td>470.93</td>
</tr>
<tr>
<td>Mean</td>
<td>-3.62</td>
</tr>
<tr>
<td>Mode</td>
<td>0.00</td>
</tr>
<tr>
<td>Median</td>
<td>0.00</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>99.43</td>
</tr>
<tr>
<td>Variance</td>
<td>9885.63</td>
</tr>
</tbody>
</table>
Table 5. Description of non-bifurcating channel area (excluding 16 extreme outliers) and bifurcating channel area slope ratio data.

<table>
<thead>
<tr>
<th></th>
<th>Non-Bifurcating Channels</th>
<th>Bifurcating Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>sample size</td>
<td>806</td>
<td>290</td>
</tr>
<tr>
<td>minimum</td>
<td>-27.37</td>
<td>-3.84</td>
</tr>
<tr>
<td>maximum</td>
<td>24.01</td>
<td>6.91</td>
</tr>
<tr>
<td>mean</td>
<td>-0.30</td>
<td>0.07</td>
</tr>
<tr>
<td>mode</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>median</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>standard deviation</td>
<td>3.28</td>
<td>0.94</td>
</tr>
<tr>
<td>variance</td>
<td>10.74</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Figure 14. Histogram of all values of bifurcating channel slope ratios showing a normal distribution centered on 0.
In addition to the 16 outliers, 115 non-bifurcating channel area and 21 bifurcating channel area data points were not included in this analysis because the long-profile slope ratio was 0, creating a division error in the calculation. Non-bifurcating channel area long-profile slope values have a range from -0.036 to 0.016 while bifurcating channel area long-profile slope values range from -0.036 to 0.004. Histograms of long-profile slopes for both areas show a left-skewed distribution, indicating that the majority of long-profile slope values are negative, or grade in a downhill direction (Figure 18 and Figure 19). Figures 20 and 21 show the distributions of non-bifurcating channel area long-profile slope values between the range of -0.01 and 0.004 and bifurcating area long-profile slope values between the range of -0.035 and 0.005 at each of the ten points along the DFS. Slope values are
predominately negative along each analysis point for both areas. Table 6 shows that average long-profile slope values at each point along the DFS for both non-bifurcating and bifurcating channel areas. Bifurcating slope areas have steeper gradients at every point along the DFS.

Figure 16. Plot of non-bifurcating channel area slope ratio values between -30 and 30 at each of the ten analysis points down the DFS. The left shaded area (points 1-3) represents the proximal regions of DFS, the middle (points 4-6) represents medial, and the right shaded area (points 7-10) represents distal areas.

Figure 16. Plot of bifurcating channel area slope ratio values between -30 and 30 at each of the ten analysis points down the DFS. The left shaded area (points 1-3) represents the proximal regions of DFS, the middle (points 4-6) represents medial, and the right shaded area (points 7-10) represents distal areas.
**Figure 17.** Plot of bifurcating channel area slope ratio values between -6 and 8 at each of the ten analysis points down the DFS. The left shaded area (points 1-3) represents the proximal regions of DFS, the middle (points 4-6) represents medial, and the right shaded area (points 7-10) represents distal areas.

![Histogram of Non-Bifurcating Channel Area Long-Profile Slopes](image1)

**Figure 18.** Histogram of all values of non-bifurcating channel area long-profile slopes showing a left skewed distribution showing that the majority of long-profile slope values are negative, or in the downhill direction.

![Histogram of Bifurcating Area Long-Profile Slopes](image2)

**Figure 19.** Histogram of all values of bifurcating channel area long-profile slopes showing a left skewed distribution showing that the majority of long-profile slope values are negative, or in a downhill direction.
**Figure 20.** Plot of non-bifurcating channel area long-profile slope values between -0.01 and 0.004 at each of the ten analysis points down the DFS. The left shaded area (points 1-3) represents the proximal regions of DFS, the middle (points 4-6) represents medial, and the right shaded area (points 7-10) represents distal areas.

**Figure 21.** Plot of bifurcating channel area long-profile slope values between -0.035 and 0.005 at each of the ten analysis points down the DFS. The left shaded area (points 1-3) represents the proximal regions of DFS, the middle (points 4-6) represents medial, and the right shaded area (points 7-10) represents distal areas.
Non-bifurcating channel area cross-profile slope measurements range from -0.111 to 0.025, while bifurcating areas range from -0.009 to 0.011. Both areas show a normal distribution centered on zero (Figure 22 and Figure 23). For non-bifurcating channel area cross-profile slopes, approximately 43% have a positive slope value, grading in the direction of the long-profile line; approximately 12% have a slope measurement of 0 and are therefore flat; and approximately 45% of the measured cross-profile slope values are negative and thus grade away from the long-profile line. Bifurcating channel area cross-profile slopes are approximately 37% positive values; approximately 14% equal 0; and approximately 50% are negative values. Table 9 shows the average cross-profile slope values for non-bifurcating and bifurcating channel areas at each analysis point along DFS. Again the data show that non-bifurcating channel areas have more positive slope values, particularly in the proximal areas of DFS. In addition, Table 10 shows the average negative cross-profile slope values for non-bifurcating and bifurcating channel areas at each analysis point along DFS. Non-bifurcating channel areas have much higher (almost double) average cross-profile slope values than bifurcating channel areas in analysis points 1 through 3 of DFS while bifurcating channel areas have higher average cross-profile slope values at analysis points 4 through 7.

<table>
<thead>
<tr>
<th>Table 6. Average long-profile slope values at each point along the DFS for non-bifurcating and bifurcating channel areas.</th>
</tr>
</thead>
<tbody>
<tr>
<td>point 1</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>non-bifurcating</td>
</tr>
<tr>
<td>bifurcating</td>
</tr>
</tbody>
</table>
Figure 22. Histogram of all values of non-bifurcating channel cross-profile slope showing a normal distribution around 0.

Figure 23. Histogram of all values of bifurcating channel cross-profile slopes showing a normal distribution around 0.

Figure 24 and Table 7 and Figure 25 and Table 8 show how cross-profile slopes vary along each of the ten analysis points down the DFS for non-bifurcating channel areas and bifurcating channel areas respectively. In non-bifurcating channel areas, the highest concentrations of positive slopes occur at analysis point 1, which could be the result of incision or confinement and is most likely to occur in the
proximal most portions of the DFS. Areas with no cross-profile grade (cross-profile slope values of 0) increase toward the toe of the DFS. In bifurcating channel areas the highest concentration of positive slopes occur in more of the medial portion of the fans. Areas with no cross-profile grade (cross-profile slope values of 0) are higher overall than on non-bifurcating channel portion of DFS. For example, Figure 26 shows cross sectional views of cross-profile slope profiles at each analysis point down a DFS, where analysis points 1, 2, 3, 5, 6, 9, and 10 are characterized by non-bifurcating channel areas and points 4, 7, and 9 represent bifurcating channel areas along this DFS.

**Figure 24.** Plot of non-bifurcating channel cross-profile slope values between -0.01 and 0.01 at each of the ten analysis points down the DFS. The left shaded area (points 1-3) represents the proximal regions of DFS, the middle (points 4-6) represents medial, and the right shaded area (points 7-10) represents distal areas.
Table 7. Number and percentage of non-bifurcating channel area cross-profile slopes that are positive (grading toward the profile line), zero (no grade), and negative (graded away from the profile line) for each analysis point down the DFS.

<table>
<thead>
<tr>
<th>point</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>positive slopes</td>
<td>61 (62%)</td>
<td>36 (47%)</td>
<td>42 (47%)</td>
<td>39 (40%)</td>
<td>52 (48%)</td>
<td>46 (46%)</td>
<td>46 (41%)</td>
<td>36 (33%)</td>
<td>28 (30%)</td>
<td>18 (37%)</td>
</tr>
<tr>
<td>zero slopes</td>
<td>2 (2%)</td>
<td>2 (3%)</td>
<td>4 (5%)</td>
<td>7 (7%)</td>
<td>1 (1%)</td>
<td>8 (8%)</td>
<td>17 (15%)</td>
<td>28 (26%)</td>
<td>28 (30%)</td>
<td>11 (22%)</td>
</tr>
<tr>
<td>negative slopes</td>
<td>36 (36%)</td>
<td>38 (50%)</td>
<td>43 (48%)</td>
<td>52 (53%)</td>
<td>56 (51%)</td>
<td>47 (47%)</td>
<td>49 (44%)</td>
<td>45 (41%)</td>
<td>36 (39%)</td>
<td>20 (41%)</td>
</tr>
<tr>
<td>total</td>
<td>99</td>
<td>76</td>
<td>89</td>
<td>98</td>
<td>109</td>
<td>101</td>
<td>112</td>
<td>109</td>
<td>92</td>
<td>49</td>
</tr>
</tbody>
</table>

Figure 25. Plot of bifurcating channel area cross-profile slope values between -0.005 and 0.005 at each of the ten analysis points down the DFS. The left shaded area (points 1-3) represents the proximal regions of DFS, the middle (points 4-6) represents medial, and the right shaded area (points 7-10) represents distal areas.
Table 8. Number and percentage of bifurcating channel area cross-profile slopes that are positive (grading toward the long-profile line), zero (no grade), and negative (graded away from the long-profile line) for each analysis point down the DFS.

<table>
<thead>
<tr>
<th></th>
<th>point 1</th>
<th>point 2</th>
<th>point 3</th>
<th>point 4</th>
<th>point 5</th>
<th>point 6</th>
<th>point 7</th>
<th>point 8</th>
<th>point 9</th>
<th>point 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>positive</td>
<td>16 (36%)</td>
<td>25 (44%)</td>
<td>16 (32%)</td>
<td>15 (39%)</td>
<td>9 (32%)</td>
<td>7 (21%)</td>
<td>11 (48%)</td>
<td>10 (59%)</td>
<td>6 (30%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>zero</td>
<td>0 (0%)</td>
<td>4 (7%)</td>
<td>5 (10%)</td>
<td>8 (21%)</td>
<td>6 (21%)</td>
<td>10 (30%)</td>
<td>3 (13%)</td>
<td>1 (6%)</td>
<td>4 (20%)</td>
<td>1 (100%)</td>
</tr>
<tr>
<td>negative</td>
<td>28 (64%)</td>
<td>28 (49%)</td>
<td>29 (58%)</td>
<td>15 (39%)</td>
<td>13 (46%)</td>
<td>16 (48%)</td>
<td>9 (35%)</td>
<td>6 (50%)</td>
<td>0 (0%)</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>44</td>
<td>57</td>
<td>50</td>
<td>38</td>
<td>28</td>
<td>33</td>
<td>23</td>
<td>17</td>
<td>20</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 9. Average cross-profile slope values at each point along the DFS for non-bifurcating and bifurcating channel areas.

<table>
<thead>
<tr>
<th></th>
<th>point 1</th>
<th>point 2</th>
<th>point 3</th>
<th>point 4</th>
<th>point 5</th>
<th>point 6</th>
<th>point 7</th>
<th>point 8</th>
<th>point 9</th>
<th>point 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-bifurcating</td>
<td>0.0019</td>
<td>-0.0006</td>
<td>-0.0001</td>
<td>-0.0003</td>
<td>-0.0005</td>
<td>0.0003</td>
<td>-0.0001</td>
<td>-0.0003</td>
<td>-0.0003</td>
<td>0.0002</td>
</tr>
<tr>
<td>bifurcating</td>
<td>-0.0003</td>
<td>-0.0002</td>
<td>-0.0005</td>
<td>-0.0002</td>
<td>-0.0010</td>
<td>-0.0006</td>
<td>0.0002</td>
<td>0.0001</td>
<td>-0.0001</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Table 10. Average negative cross-profile slope values at each point along the DFS for non-bifurcating and bifurcating channel areas.

<table>
<thead>
<tr>
<th></th>
<th>point 1</th>
<th>point 2</th>
<th>point 3</th>
<th>point 4</th>
<th>point 5</th>
<th>point 6</th>
<th>point 7</th>
<th>point 8</th>
<th>point 9</th>
<th>point 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-bifurcating</td>
<td>-0.0051</td>
<td>-0.0037</td>
<td>-0.0033</td>
<td>-0.0022</td>
<td>-0.0022</td>
<td>-0.0015</td>
<td>-0.0015</td>
<td>-0.0019</td>
<td>-0.0020</td>
<td>-0.0014</td>
</tr>
<tr>
<td>bifurcating</td>
<td>-0.0023</td>
<td>-0.0018</td>
<td>-0.0021</td>
<td>-0.0030</td>
<td>-0.0031</td>
<td>-0.0019</td>
<td>-0.0019</td>
<td>-0.0014</td>
<td>-0.0014</td>
<td>N/A</td>
</tr>
</tbody>
</table>

A. China 26: Point 1

B. China 26: Point 2
China 26: Point 3

\[ y = 0.0003x + 2792.3 \]

China 26: Point 4

\[ y = 0.0002x + 2778.2 \]

China 26: Point 5

\[ y = 9 \times 10^{-5}x + 2765.2 \]

China 26: Point 6

\[ y = -0.0003x + 2753.6 \]

China 26: Point 7

\[ y = -7 \times 10^{-5}x + 2743.1 \]
3.2 Statistical Analysis

The focus of this study was to determine if there is a correlation between the ratio of channel slope and floodplain slope and channel bifurcation on large braided DFS. 1,112 slope ratios were measured and analyzed for both non-bifurcating channels and bifurcating channels across the 98 braided DFS (Table 11). 822 slope ratio values were measured for non-bifurcating channel areas and had a mean of -

Figure 26. 10 cross-sectional profiles (A-J) at each analysis point along the China 26 DFS including trend lines and equations for each profile. Analysis points 1, 2, 3, 5, 6, 9, and 10 are classified as single channel areas while points 4, 7, and 8 are bifurcating areas. Note that the vertical exaggeration is 100X for the profile areas.
3.36 while bifurcating channel areas contained 290 slope ratio values and had a mean of 0.07 (Table 11). The means of all slope ratios of non-bifurcating and bifurcating channels were compared statistically using a two-sample t-test assuming unequal variance with a significance level of .05. No statistical difference was found between the two groups.

**Table 11.** Results of T-Test: Two-Sample Assuming Unequal Variances between non-bifurcating channel and bifurcating channel slope ratios.

<table>
<thead>
<tr>
<th></th>
<th>Non-Bifurcating Channel</th>
<th>Bifurcating Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-3.62</td>
<td>0.07</td>
</tr>
<tr>
<td>Variance</td>
<td>9885.63</td>
<td>0.88</td>
</tr>
<tr>
<td>Observations</td>
<td>822</td>
<td>290</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>821</td>
<td></td>
</tr>
<tr>
<td>t Stat</td>
<td>-1.07</td>
<td></td>
</tr>
<tr>
<td>P(T&lt;=t) two-tail</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>t Critical two-tail</td>
<td>1.96</td>
<td></td>
</tr>
</tbody>
</table>

However, when the 16 points of outlying data were removed and the statistical analysis was reran the results showed statistical significance (Table 12). The variance of non-bifurcating channel slope ratios drops to 10.74. In addition, the t-value (-2.94) is well beyond the t-critical value (-1.96) with a probability value of 0.00336. This strongly supports the relationship between slope ratio and bifurcation.
IV. Discussion

4.1 Slope and Bifurcation on DFS

While there are many factors that affect bifurcation of distributive rivers, this study focused solely on slope ratio. A strong theoretical correlation exists in the literature between slope ratio and bifurcation (Mackey and Bridge, 1995; Jones and Schumm, 1999; and Karssenberg and Bridge, 2008), and the high availability and accessibility of digital elevation data around the world easily lends itself to an empirical test of this theoretical correlation on large braided DFS.

The observed relationship between slope ratios of non-bifurcating channel areas of DFS and bifurcating areas of DFS found in this study does indeed reflect the theoretical relationship described by Mackey and Bridge (1995), Jones and Schumm (1999), and Karssenberg and Bridge (2008). According to these works, a channel can bifurcate when the ratio between the down channel slope and gradient

<table>
<thead>
<tr>
<th></th>
<th>Non-Bifurcating Channel</th>
<th>Bifurcating Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>-0.30</td>
<td>0.07</td>
</tr>
<tr>
<td>Variance</td>
<td>10.74</td>
<td>0.88</td>
</tr>
<tr>
<td>Observations</td>
<td>806</td>
<td>290</td>
</tr>
<tr>
<td>Degrees of Freedom</td>
<td>1060</td>
<td></td>
</tr>
<tr>
<td>t Stat</td>
<td>-2.94</td>
<td></td>
</tr>
<tr>
<td>P(T&lt;=t) two-tail</td>
<td>0.00336</td>
<td></td>
</tr>
</tbody>
</table>

Table 12. Results of T-Test: Two-Sample Assuming Unequal Variances between non-bifurcating channel and bifurcating channel slope ratios excluding extreme outliers.
perpendicular to the channel surpass a critical threshold, causing instability in the original channel. This study found that there was a strong statistical difference between slope ratios of the two types of channels (though there is overlap in the populations). In particular, this study found that slope ratios of non-bifurcating channel areas have a mean slope ratio of -0.30 while bifurcating channel areas have a mean slope ratio of 0.07. When comparing the absolute value of these slope ratio averages we see that non-bifurcating channel areas have a higher slope ratio than bifurcating channel areas. It is not surprising that non-bifurcating channel areas have a negative average slope ratio as these areas are more likely to have positive cross-profile slope values and negative long-profile slope values. Conversely, bifurcating channel areas are more likely to have both negative cross- and long-profile values.

Long-profile slopes are closely connected to channel behavior. Jones and Schumm (1999) posit that as the gradient of a channel decreases a river is more likely to shift, or avulse, after a high flood event. Additionally, Karresenberg and Bridge (2008) found through computer modeling that there is a period of time after a bifurcation takes place that the new channel belts will have higher slopes. To summarize, these researchers argue that as long-profile slopes increase, channel stability decreases. This study found long-profile slopes for non-bifurcating channel areas to be smaller than those of bifurcating channel areas (Table 6), making them less stable, agreeing with the theoretical results.

Cross-profile gradient becomes somewhat more complicated to interpret because there is the complexity of looking at not just slope, but whether slope is
facing toward or away from the long-profile line. A point flanked by two cross-profile slopes with positive values indicates that that portion of the DFS is confined, for example, by incision. It would therefore be expected that channels along these areas with positive slope values would be less likely to bifurcate. Indeed, the analysis in this study found that non-bifurcating channels, in particular proximal portions of DFS, have a higher percentage of positive slope values (Table 7) making them more likely to be confined.

Jones and Schumm (1999) argue that, as gradients perpendicular to a channel decrease a channel will more likely change course. When non-bifurcating and bifurcating channel areas with negative cross-profile slope are examined across DFS an interesting pattern emerges. Non-bifurcating channel areas have much higher (almost double) average cross-profile slope values than bifurcating channel areas in the proximal areas of DFS. Bifurcating channel areas, by contrast, have higher average cross-profile slope values in the medial areas. Non-bifurcating channel areas have higher cross-profile slopes in the distal areas and is likely to be influenced by the fact that there are no representative negative cross-profile slope values of bifurcating channel areas at analysis point 10 (Table 8). This suggests that channel movement in the proximal areas of DFS is dominated by avulsions whereas medial areas of DFS are dominated by bifurcations.

Studies in channel morphology are complicated by several other factors. Jones and Schumm (1999) discuss that while a favorable slope ratio must be present for a river channel to change course, either through bifurcation or avulsion, there must also be a trigger, such as a flood, that causes overbank flow. It is possible that
some of the rivers in this study had a favorable slope ratio for a bifurcation to occur but had not yet experienced the right trigger. In the case of an avulsion there may also be (1) a reduction in the original channel's capacity to carry water and sediment, including, but not limited to, blockages from in-channel sediment deposition, vegetation encroachment, and log and ice jams; (2) a redirection of the channel due to animal trails or roads; or (3) a loss of the original stream due to stream capture or groundwater sapping (Jones and Schumm, 1999). The method used in this study precludes testing these exogenous factors.

Discharge and sediment load are also important factors in determining bifurcation. Slingerland and Smith (1998) discuss the complex relationship between the slope of an offshoot channel, and its sediment load and size to determine whether that channel would avulse, heal, or reach an equilibrium and thus bifurcate. In their models they determined that in order for a stream to abandon its original channel (avulse) it must reach an upper slope threshold, which is primarily determined by (1) the height on the new channel floor relative to the main channel floor, (2) the water depth in the original channel, and (3) the ratio of the new channel slope to the main channel slope. If this threshold has not been met, offshoots of a stream will either heal or both channels will maintain capacity (bifurcate). However, they found that sediment load and size also played an important role. If the new channel exceeds its sediment-transport capacity then sedimentation may occur at its mouth, blocking the channel and causing healing. A new channel that has not reached its sediment-transport capacity will start to incise and likely to avulse. These conditions can occur because of the sediment capacity of
the main channel and the size of the sediment being transported. If the sediment being transported by the main channel is relatively large bedload, then the sediment will be less likely to make it into the new channel due to the higher elevation or lip of the new channel bed and, consequently, cause a more sediment starved channel and result in degradation. Conversely, if there is finer sediment in suspension then the new channel will exceed its capacity and begin to aggrade causing the new channel to close off. As of yet, there is not a method that can extract information about sediment size and load from remote sensing data.

Finally, as previously mentioned, glacial and interglacial cycles influence the ratio of stream discharge and sediment supply and thus, whether portions of the DFS will aggrade or incise. As Weissmann et al. (2002) discuss, glacial periods and times of maximum glacial recession are characterized by shift in the intersection point toward the apex, increasing the potential for bifurcations and avulsions to occur in the proximal portions of DFS. Conversely, periods that follow glacial episodes and interglacial episodes are associated with an increase in stream discharge relative to sediment supply, causing a basinward shift in the intersection point. This results in varying degrees of confinement of the active channel belt in the proximal portions of DFS, which, as previously discussed, negatively affects the potential for bifurcations or avulsions to occur in these areas. Therefore, incision seen near the fanhead on modern DFS may be a result of this cyclicity.

4.2 Discussion of Study Methods

One way to improve the results of future studies would be to change the method with which the slope ratios were attained. Slopes were measured at ten
consistent intervals down fan, 1 km down channel and 1 km across the channel at each of the ten points. If a channel bifurcation occurred in that area, then the slope ratio was counted as a bifurcating slope ratio. If, instead, slope ratios were measured at points of bifurcation there might be a more precise correlation. This method, however, was not employed in this study due to the large number of fans in the database under investigation. It was originally hoped that a method could be automated that would take slope measurements at consistent interval along each DFS, but, in the end, it proved to be too difficult given the limitations of the software to create a script that could accommodate the variability in the long-profile trends of the DFS. The goal then became to analyze these samples by hand, using a method that could be performed in the future using a script so that further work in this area could be automated once the software limitation were overcome. Therefore, slopes were measured at consistent intervals down fan to simulate a script, instead of picking points that visually looked justifiably interesting to measure the slope. This meant that we were measuring general slopes along fans instead of channel floor slope. Another disadvantage to using this method of measuring points along a profile line was that in the majority of DFS, this profile line did not follow the channel the entire length down the DFS. This resulted in many slope ratio values, approximately 43% of those measured, that were unusable in this study. Future studies might obtain better results if measurement were taken at variable points along a channel instead of fixed points down the fan.

The decision to identify only bifurcating and non-bifurcating channels had its own limitations and strengths. By creating only two categories we made the
decision to lump non-bifurcating channels that are the result of a recent avulsion and non-bifurcating channels that have maintained their course for a greater period of time. This decision was made for several reasons. 1) We decided to group non-bifurcating channels in this study because remote sensing data are a snapshot of a moment in time on these DFS. This makes it difficult to determine if a channel was the result of a recent avulsion or had been on its current course for a while. 2) Channel network evolution is a characteristic of distributive systems. Because of the high levels of lateral movement associated with DFS channels in basins all non-bifurcating channels that are unconfined (particularly channels on the medial and distal portions of the DFS) are in their current location as the result of an avulsion and have maintained their position because slope conditions favor this course. While this may apply to many situations it is, of course, not true for every channel. There are certainly many factors that influence network evolution of DFS. According to Jones and Schumm (1999), slope sometimes favors another path but the river has not experienced an appropriate trigger, such as a significant enough flood event, to push it off course. It is also important to keep in mind that there could be a high variation in slope between recently avulsed channel slopes and more established non-bifurcating channel slopes. As discussed previously, sediment size can affect whether a channel is building up or incising at it adjusts to reach equilibrium. Ultimately, determining whether or not a river has recently experienced flood trigger events was beyond the scope of this study.

As previously mentioned, braided DFS planforms make up 73% of the large DFS identified and described by Hartley et al. (2010) making them a significant
planform to study. Using only the braided DFS found in Asia as the sample had many great benefits. Asia contains 107 of the 301 large braided DFS identified and described by Hartley et al. (2010), more than any other continent by far. Asia contains large braided DFS that are located in all four of the different basin settings identified by Hartley et al. (2010), allowing the gathering of data for DFS in all of these settings. In addition, the DFS are located at longitudes ranging from ~10°N to ~68°N, spanning dryland, continental, subtropical, tropical, and polar climates. However, because Asia is in the northern hemisphere, any variation, particularly in wind and weather patterns, that might occur in the southern hemisphere is not reflected in this study. The braided DFS in Asia also had the greatest number unaffected by thick vegetation, which, again, was problematic because the DEMs from SRTM data do not penetrate thick vegetative canopies. With that said, it is important to recognize that environments that produce heavy vegetation, such as high precipitation levels and soil conditions, undoubtedly also have an effect on bifurcation.

V. Conclusion

Slope ratio, discharge, sediment load, and sediment size are major forces that control channel evolution in fluvial systems. Bifurcation and avulsion are the physical manifestations of these forces as they struggle to reach an energetic equilibrium. Understanding how these forces interact with each other not only helps us make sense of the patterns of river and floodplain deposits we see in today's
sedimentary basins around the world, but helps researchers make links between these interactions and the deposits seen in the sedimentary record. These forces, however, have a complex relationship. As science gains a better understanding of how these forces interact and their effect on fluvial deposits along a DFS, the better scientists are equipped for making predictions about sedimentary deposits in the rock record, in particular, about large scale alluvial architecture.

This study sought to find a correlation between slope ratio and bifurcation at a 180 m resolution on large braided DFS and found a high statistically significant difference between slope ratios of non-bifurcating and bifurcating areas. Non-bifurcating channel areas have larger slope ratios (further from a value of 0) while bifurcating channel areas have shallower slope ratios (closer to a value of 0). Non-bifurcating areas were also found to have shallower gradients than bifurcating areas. Cross-profile slope is greater for non-bifurcating areas in proximal regions of the DFS and greater for bifurcating areas in the medial regions indicating a change from avulsion-dominated channel migration to bifurcation dominated migrate across these regions.

Further work needs to be carried out to look at the role incision plays on slope ratios on DFS, particularly in proximal regions. Deep incision of a river channel between two positive cross-profile slopes would cause the channel to stay a non-bifurcating area. If these areas were removed from the study then we would be able to understand how slope ratio varies on open areas of DFS. Additionally, a small number of long-profile slopes had positive values. More research needs to be carried out to determine what is causing these positive slope values (for example, is the
profile elevation line off of the main river channel at that point and instead recording the elevation of a terrace), and to what extent they interfere with our study of the relationship between slope and bifurcation.
REFERENCES


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Smith, N.D., and Smith, D.G., 1984, William River - an outstanding example of channel widening and braiding caused by bed-load addition: Geology, v. 12, p. 78-82.


APPENDIX 1

**Fluvial Systems Research Group Database Version 0.1: Structure and Organization**

**Summary**

A carefully planned database superstructure will increase the efficiency, accuracy, and reliability of the research goals set out by the Fluvial Systems Research Group (FSRG). The current superstructure of the FSRG database was developed at UNM with these issues in mind. The first issue we addressed in creating the current database superstructure was identifying the entities in our data. An entity is defined as some aspect of the real world, such as an object, event, or concept, with an independent existence that can be uniquely identified. These entities were then organized into a nesting hierarchy. Because of the size and complexity of this project and resulting data, it is important for all FSRG members to think about the organization of the database and come to a consensus as seemingly small mistakes now can result in a database that does not function efficiently and/or may preclude some types of analysis we may want to perform in the future.

**Background**

A well-designed, effectively managed database is a key component for the current and future research performed by the FSRG. Because of the sheer quantity of data being acquired and analyzed, great consideration must be placed into the structure and organization of the database. A good database structure will help eliminate haphazard approaches to maintaining data, reduce time spent on upkeep and database maintenance, optimize data retrieval, ensure data accuracy and reliability, and support the current and future research goals set out by the group. Therefore, it is essential that we scrutinize the current superstructure of the database. We must consider it from all imaginable angles to make sure it is appropriately organized for the types analyzes we currently envision.
performing on the data, while at the same time to allow for the flexibility of future growth in directions we can not yet anticipate. Our goal in producing this document is to develop a conversation about data structures and ideas on future needs for data access.

**DATABASE SUPERSTRUCTURE: IDENTIFYING ENTITIES AND CREATING A HIERARCHY**

Seven entities were identified in the database: 1) continent/region, 2) basin, 3) sub-basin, 4) axial system, 5) DFS apex, 6) drainage basin, and 7) DFS. The structure is represented below in Figure 1. The entity identified as highest in the hierarchy of the data was continent (i.e. South America)/region (i.e. Arabia). We first asked ourselves *What are the benefits of organizing the data according to continent/region? and Is this the most appropriate way to organize the data or should we consider another entity such a geology or tectonic setting?* We determined that this was appropriate because the ability to search for basins and DFS would be most productive by looking at continents/regions. In addition, we felt that continents/regions are the largest feature of the data and that basin and DFS occur within continents/regions.

One problem that has arisen thus far from this type of organization is the definition of a continent/region. Most continents are separate entities with definite geographic boundaries (i.e. North America or Australia), however, some have “gray areas” (i.e. Where is the distinction between Arabia and Asia and why?). Therefore we need to define concrete boundaries between continents/region to avoid problems with gray areas.

We then determined that it was rather straight forward that basins and sub-basins (if they exist) would be the next entities/level in the database structure because depositional systems occur within basins. Tectonic setting is a feature associated with basins. There are then two objects associated with basins (or sub-basins): axial systems, and DFS apices. Because drainage basins by definition do not fall within the sedimentary
basin boundary, we determined that DFS apices not only provide the link between drainage basin and DFS, the final two entities, but also represent the basin boundary and are therefore a critical entity in the data structure.

Associated with each of these entities are raw imagery files (e.g. Landsat band data, MODIS band data, and SRTM data) and derived results from analysis of these data (indices, statistical derivatives, and metadata). We envision links between imagery and each entity (based on Landsat path/row or MODIS path/row designations) so imagery can readily be retrieved for each entity of interest. We also envision production of ArcMAP files for each basin and for each large DFS using SRTM elevations and Landsat decadal images.

**CONCLUSION**

We feel that this initial organization captures the framework of depositional systems. When creating a database structure it is important that it makes sense for current and future research goals, but also has the flexibility to incorporate unforeseen of research. It is critical to think creatively and expansively with consideration of both large and small questions that might want to be answered using the database.
Figure 1. Preliminary database structure.

Figure 2. LANDSAT and SRTM database file organization.

* read only files will only be accessible to Gary Weissmann, Louis Scuderi, Proma Bhattacharyya, and Michelle Olson.
† read/write files will only be accessible to members of the FSRG.
Figure 3. LANDSAT and SRTM database file naming scheme.

1 actual file names will not contain spaces: LPPPRRR#YYDDD
APPENDIX 2

Figure 1. Landsat image path/row 001/074 (Chile 01 and Chile 02).

Figure 2. SRTM image path/row 001/074 (Chile 01 and Chile 02).

Figure 3. Landsat image path/row 131/034 (China 10 and China 11).

Figure 4 SRTM image path/row 131/034 (China 10 and China 11).

Figure 5. Landsat image path/row 136/032 (China 49).

Figure 6. SRTM image path/row 136/032 (China 49).
Figure 7. Landsat image path/row 138/028 (Mongolia 01).

Figure 8. SRTM image path/row 138/028 (Mongolia 01).

Figure 9. Landsat image path/row 146/029 (China 39).

Figure 10. SRTM image path/row 146/029 (China 39).