Lithologic and Structural Controls on Green River Channel Morphologies and the Magnitude of Response to the Closure of Flaming Gorge Dam, Utah and Colorado

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ABSTRACT

Variations in large-scale (~1 to 10 mi) channel planform geometries along the Green River from Flaming Gorge Dam to the Split Mountain boat ramp are strongly correlated with the longitudinal distribution of river-level bedrock exposures, reflecting first-order bedrock lithologic and structural controls over channel morphologies. Additionally, regional bedrock lithologies and deformation structures provide secondary controls on sediment delivery processes, thus influencing local scale (~0.1 to 1 mi) alluvial depositional environments. The closure of Flaming Gorge Dam (1962) and resultant hydrogeomorphic process alterations have forced in-channel morphological adjustments downstream from the dam site (Andrews 1986, Grams and Schmidt 2002, 2005). The direction and magnitude of these form adjustments varies at both the reach and segment scales, reflecting the influences of regional geologic structures and lithologies, and inherited channel planform morphologies.

INTRODUCTION

While floating down the Green River from Flaming Gorge Dam to the Split Mountain boat ramp, one cannot help but notice the dramatically different landscapes which come and go with each passing day. Any given morning might start with a nervous run of steep rapids between the towering walls of a bedrock canyon, only to give way to a lazy afternoon float through the flat and broad expanse of an open basin. Similar observations were made by the earliest explorers of the Green River, and John Wesley Powell (1875) even ventured to postulate the hardness of the surrounding rock might be responsible for the varying channel morphologies (shapes and forms) he observed (Schmidt 1999). Thus, Powell became the first of many scientists to theorize how bedrock lithologies (their physical character) and structures (their architecture) control the shape and character of canyon-bound streams like the Green River.

This chapter explores the role of bedrock lithology and geologic structures in controlling the shape and form of the Green River between Flaming Gorge Dam and the Split Mountain boat ramp (Figure 1). To facilitate this exploration, regional bedrock characteristics and the first-order structural (ductile and brittle) controls on river-level bedrock outcropping will be presented. Then, it will be shown how the erosional resistance of river-level bedrock exerts a direct control on channel form over large spatial scales (1 to 10 km), while deformation structures (faults and joints) control channel morphologies at much smaller scales (~0.1 to 1 km) by influencing tributary sediment delivery processes (Mackley 2005, Thompson 2006, this volume). Finally, the roles regional geology and inherited channel planform morphologies play in the rate and magnitude of the downstream geomorphic adjustment to the 1962 closure of Flaming Gorge Dam will be discussed.

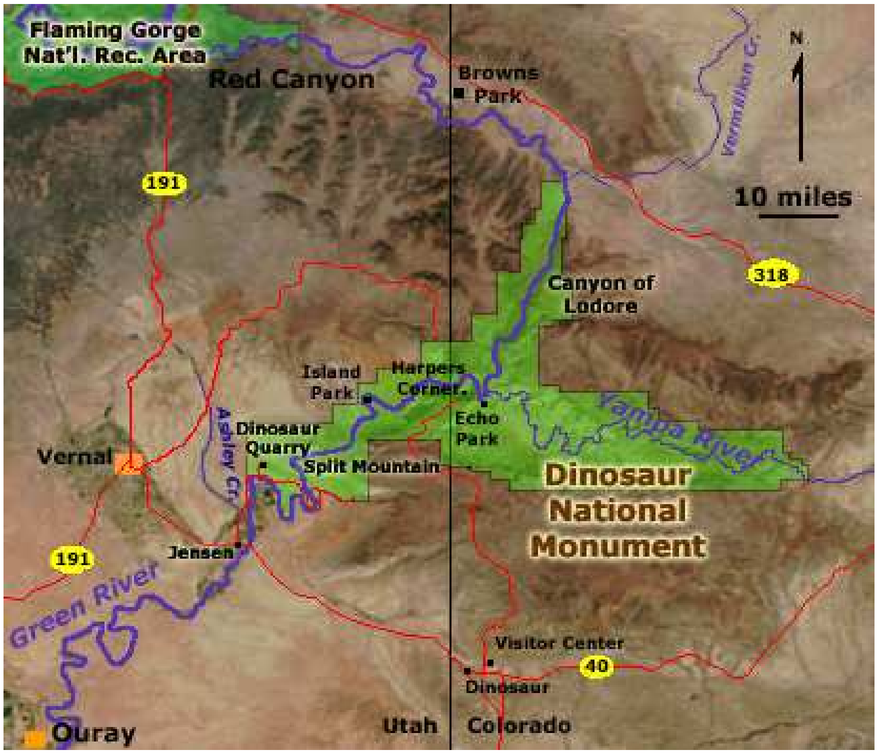

Figure 1. The Green River from Flaming Gorge Dam to the Split Mountain boat ramp (from USGS 2004)

GREEN RIVER: LITHOLOGY AND STRUCTURE

Bedrock Lithologies

Vastly different bedrock lithologies are observed along the Green River, with river-level exposures ranging from the flaming-red Precambrian (~1 billion years old) quartzites of the Uinta Mountain Group to the white Tertiary (~25 million years old) conglomerates of the Brown's Park Formation (Hansen 1986, 1996). At large scales (~1 to 10 mi), the resistance of these varying bedrock lithologies to erosive forces such as wind, water and biological organisms directly influences the shape and geometry of canyon-bound channels (Harden 1990, Grams and Schmidt 1999). This erosional resistance is primarily controlled by a rock's density, level of cementation and fracture spacing (Mackley 2005), with dense, well-cemented and massive bedrock units exhibiting the greatest ability to inhibit erosion (Harden 1990, Grams and Schmidt 1999, Sklar and Dietrich 2001, Mackley 2005). If river-level bedrock lithology exerts a primary control on channel form, then understanding the geologic mechanisms controlling how these rocks are distributed along the course of the Green River becomes important in explaining the longitudinal variations in channel planform morphologies observed between Flaming Gorge Dam and the Split Mountain boat ramp. Regional and local geologic structures provide the keys to explaining these mechanisms.

Regional Structures

The Green River flows through the Eastern Uinta Mountains, located along the eastern end of a regional geologic structure termed the Uinta Anticline (Figure 1). The regional distribution of bedrock is primarily controlled by the three-dimensional geometry of this east-west trending, 160 mile long and 25 mile wide (Hansen 1986) geologic structure formed during a 40 to 70 million year old continental-scale mountain building event known as the Laramide Orogeny. Intense compressional stresses associated with this period of mountain building are responsible not only for the formation of the Eastern Uinta Mountains, but also the formation of the Rocky Mountains and the Continental Divide (Hansen 1986).

Structurally, anticlines are folds of rock that are convex in the direction of the youngest strata (Figure 2). A simple way to envision the creation of a fold is to lay a piece of paper on a table and slowly push the ends together. A convex-up fold will slowly begin to grow away from the table, roughly mimicking the processes responsible for the creation of the Uinta Anticline. A unique feature of an anticlinal fold is that bedrock strata dip (or slope) away from a central fold axis, creating two “limbs” comprised of similar bedrock strata sequences “dipping” in opposite directions. This folding and associated uplift results in the oldest bedrock strata being exposed at the center, or “core”, of the anticline, with progressively younger rocks exposed along each outer limb.

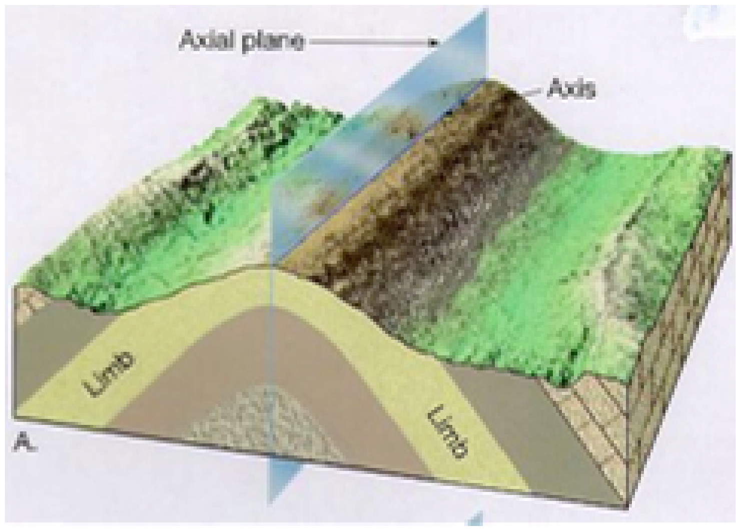

Figure 2. A conceptual model of anticlinal folding (from Seton Hall University, 2004)

The east-west trending Uinta Anticline is characterized by a core of Precambrian Quartzite (the Uinta Mountain Group) flanked by limbs of Paleozoic and Mesozoic sedimentary rocks (Figure 3) formed from materials deposited in ancient seas and deserts. Millions of years of erosion have stripped off the crestal (upper) rock formations, exposing both the older rocks at the core of the anticline, and progressively younger rocks along the limbs (Figure 2). The present day Green River initially flows eastward through Brown’s Park (Figure 1) along the eroded core of the Uinta Anticline, which has since been filled with Tertiary (~25 million years old) sediments of the Brown’s Park Formation (Hansen 1986). At the Gates of Lodore (Figure 1), the river turns southward and flows across the southern limb of the Uinta Anticline. Consequently, traveling downriver from the Gates of Lodore to the Split Mountain boat ramp generally exposes progressively younger rock formations. Thus, at a regional scale (10 to 100 mi), the Uinta Anticline exerts a strong structural control on river-level bedrock exposures.

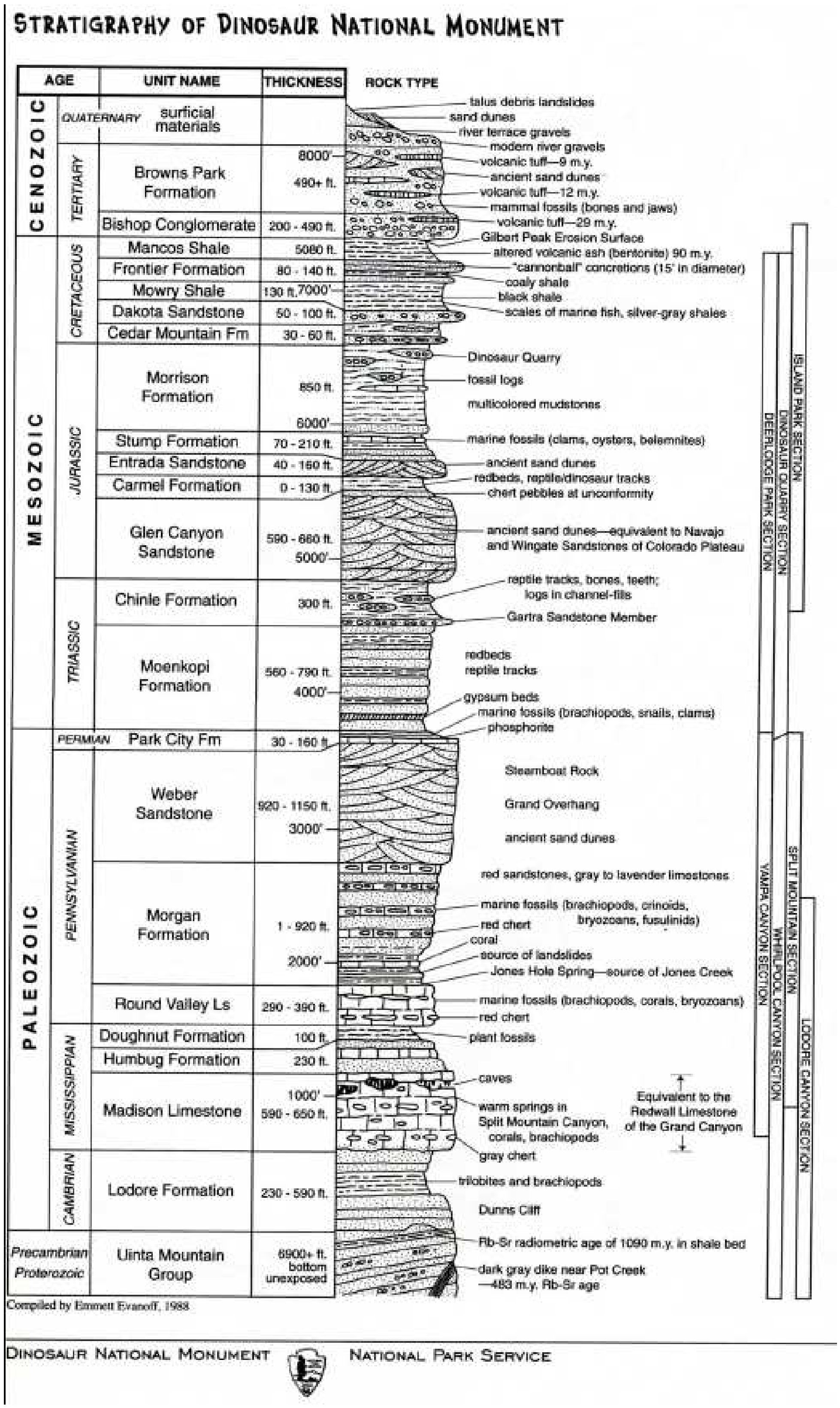

Figure 3. Generalized bedrock stratigraphy in Dinosaur National Monument (from NPS 2006)

Local Structures

While the Uinta Anticline provides a large-scale structural control over river-level bedrock exposure, smaller scale structures (1 to 10 mi), namely faults, also help control the distribution of river-level lithologies. Faults are discrete surfaces along which rocks rupture, and movements parallel to the fault surface force strata to become offset (Burbank and Anderson 2001). Compressional and tensional stresses associated with regional mountain building have induced localized (feet to mile scale) faulting within the Uinta Anticline. Evidence of tensional (normal) and compressional (reverse) faulting can be observed along the Green River (Hansen 1983), with pronounced examples in Lodore Canyon and Echo Park. Movement associated with faulting juxtaposes rocks of varying ages on either side of a fault plane (or zone), and thus river-level bedrock lithologies can change dramatically in locations where the river crosses a fault. This phenomena can be spectacularly observed while crossing the Mitten Park Fault, a compressional (reverse) fault located in the northeast corner of Echo Park (Figure 4). Regardless of the fault mechanism or character, localized faulting provides a primary control on the distribution of river-level bedrock exposures.

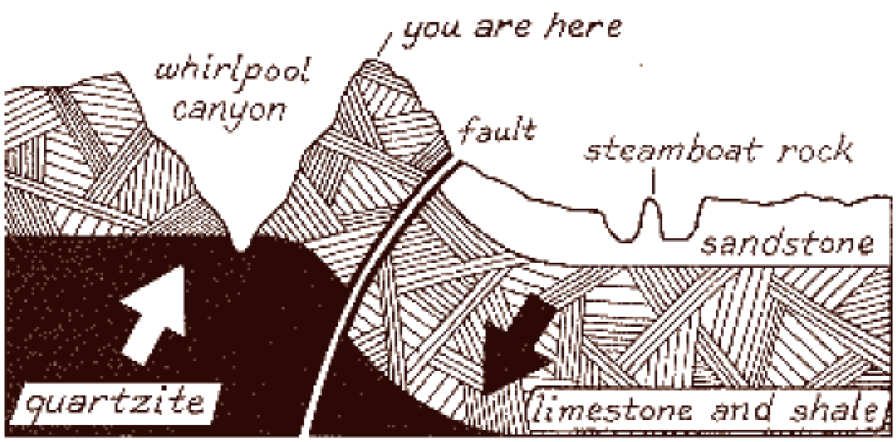

Figure 4. The compressional (reverse) Mitten Park Fault at Echo Park. Arrows indicate direction of relative motion (from West 1997)

LITHOLOGIC AND STRUCTURAL CONTROLS ON CHANNEL FORM

The Green River from Flaming Gorge Dam to the Split Mountain boat ramp can be classified into three distinct channel types based on observed changes in planform morphologies and alluvial depositional settings (Grams and Schmidt 1999, 2002 and 2005). These channel types include: 1) Debris-fan dominated canyons (Schmidt and Rubin 1995); 2) fixed meanders; and 3) restricted meanders (Figure 5).

Debris-fan dominated canyons of the Green River (Red, Lodore, Whirlpool and Split Mountain Canyons) are characterized by steep and narrow alluvial valleys whose widths are often restricted by tributary debris fans which have aggraded into the river channel (Grams and Schmidt 1999, 2005). Debris fans strongly influence in-channel morphologies by altering local hydraulics and creating fan-eddy complexes (Grams and Schmidt 1999, 2005, Thompson 2006, this volume). Low-gradient meandering reaches are described as either fixed or restricted meanders. Fixed meanders are typically confined within narrow bedrock canyons (Echo Park) and exhibit few channel constrictions (i.e. debris fans), while restricted meanders (Brown's Park and Island Park) laterally migrate in wide alluvial valleys. The magnitude of lateral channel migration is "restricted" by the presence of erosionally resistant bedrock (Grams and Schmidt 2005).

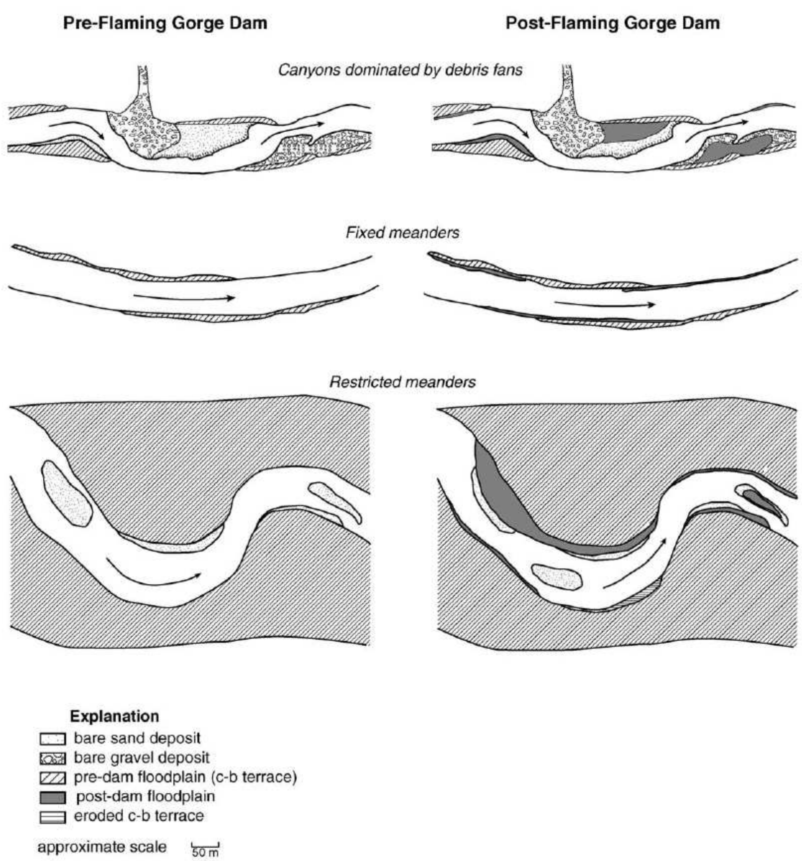

Figure 5. Green River channel planform morphologies (from Grams and Schmidt 2005)

The occurrence of each of these unique channel planforms is directly correlated with bedrock lithologies. In the case of debris-fan dominated canyons, channel morphologies are also indirectly controlled by the presence of structurally-controlled drainages (Hansen 1996, Grams and Schmidt 1999, 2002, 2005, Mackley 2005).

Direct Lithologic Controls

As discussed above, numerous studies have shown that lithologic resistance exerts a primary control on large-scale channel planform geometry (Harden 1990, Mackley 2005). In a comprehensive study of the Green, Colorado and San Juan Rivers, Harden (1990) showed that channel gradient is the most important variable in determining whether an incised channel is straight or meandering, and that channel gradients are in large part controlled by bedrock lithologic resistance to erosion. Reaches characterized by steep gradients and straight planform geometries are typically underlain by highly resistant bedrock, while reaches exhibiting moderate gradients and meandering planforms are underlain by bedrock lithologies which are moderately to weakly erosionally-resistant (Harden, 1990).

Applying Harden's (1990) bedrock resistance classification to channel reaches along the Green River, Grams and Schmidt (1999, 2005) were able to correlate varying channel gradients with bedrock resistance (Figure 6). In their more detailed 2005 study, Grams and Schmidt showed that river-level bedrock resistance was significantly correlated with the three aforementioned channel morphologies, with canyon reaches exhibiting highly resistant rock, fixed meanders characterized by moderately resistant bedrock, and restricted meanders dominated by moderately to minimally-resistant bedrock lithologies. While channel gradients correlate well with meandering vs. straight channel morphologies, this correlation breaks down when comparing fixed meander to restricted meander channel morphologies (Grams and Schmidt 2005).

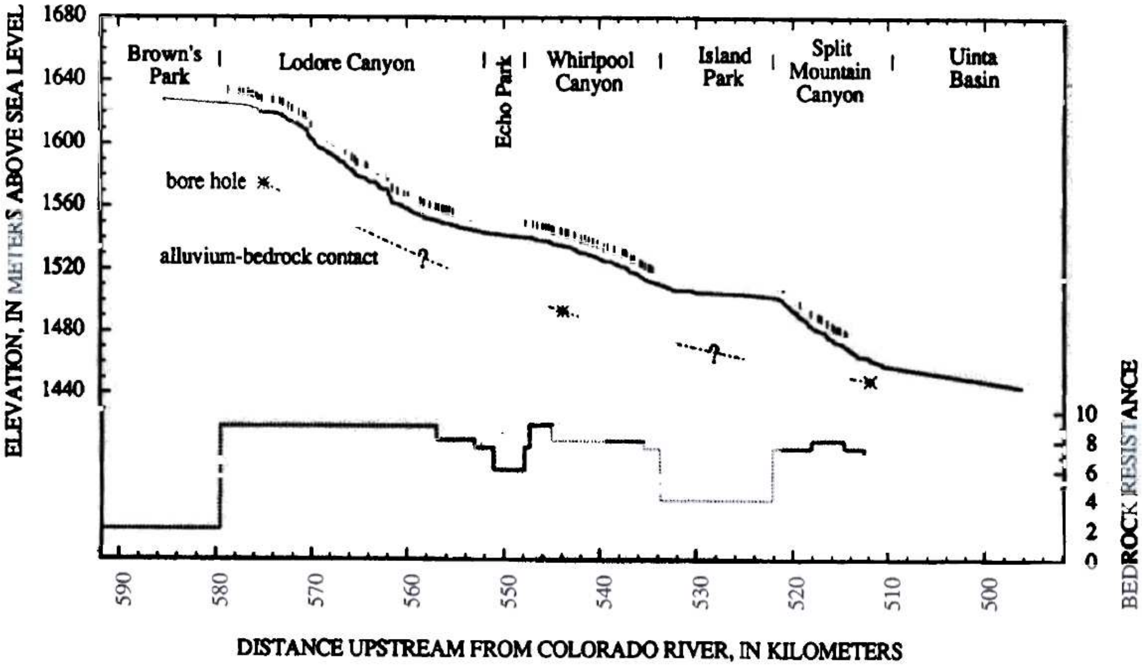

Figure 6. Green River longitudinal profile showing the correlation between channel gradient and bedrock resistance (from Grams and Schmidt 1999)

Indirect Structural Controls

While regional and local-scale geologic structures help control the longitudinal distribution of river-level bedrock and, consequently, planform channel geometries (Harden 1990, Grams and Schmidt 1999, 2005), local scale brittle deformation structures such as faults and joints indirectly control small scale (~0.1 to 1 mi), in-channel morphologies by influencing tributary sediment delivery process (Mackley 2005, Thompson 2006, this volume).

Faults

Geomorphic studies performed along the Colorado (Howard and Dolan 1981, Mackley 2005) and Green Rivers (Hansen 1996, Grams and Schmidt, 1999) indicate local fault zones are often occupied by side-canyon tributaries and gullies. This correlation is largely due to the preferential weathering of bedrock along fault zones, which accelerates erosional and sediment transport processes, facilitating the creation of side-canyon tributaries and gullies.

Joints

When the tensile strength of a stressed rock is exceeded, the rock typically pulls apart creating fracture surfaces (joints) oriented perpendicular to the direction of movement. Unlike faults, joints are small-scale (feet) fractures unaccompanied by displacement. Joints are often created during the tectonic uplift of rocks (Davis and Reynolds 1996), and thus many of the rocks exposed throughout the Uinta Anticline (particularly the Precambrian quartzites) exhibit significant jointing (Hansen 1996), often occurring systematically in parallel orientations. Similar to faults, joints present zones of preferential weathering, favoring the formation of side-canyon tributaries and gullies (Hansen 1996, Grams and Schmidt 1999).

Sediment Delivery and Channel Morphology

Side-canyon tributaries or gullies aligned with known fault zones (e.g. Jack Springs Draw and Pot Creek in Lodore Canyon) or joint sets directly control smaller-scale, in-channel morphologies by supplying large volumes of sediment to the main-stem of the Green River (Hansen 1996, Grams and Schmidt 1999). These side-canyon tributaries are often associated with the formation of debris fans resulting in the repeated occurrence of alluvial depositional sequences known as fan-eddy complexes (Thompson 2006, this volume).

GEOLOGIC INFLUENCES ON THE DOWNSTREAM GEOMORPHIC RESPONSE TO THE CLOSURE OF FLAMING GORGE DAM

Geomorphic theory suggests that prior to the closure of Flaming Gorge Dam (1962), the morphologic and sedimentologic character of the Green River dynamically adjusted to accommodate changes in water discharge and sediment load (Grams and Schmidt 2002, 2005). By fundamentally altering the downstream hydrogeomorphic (water and sediment) regime through reductions in sediment supply and the suppression of peak flood flows, dam closure has forced in-channel morphological adjustments (i.e. changes in channel widths, bed elevations and/or bed textures) downstream from the dam site (Andrews 1986, Grams and Schmidt 2002, 2005). However, the direction and magnitude of these form adjustments varies at both the reach and segment scales, reflecting the influences of both regional geology and inherited channel planforms (Grant et al. 2003).

Most studies of downstream geomorphic responses to the placement of large dams assess channel form alterations solely in relation to the degree of dam-induced changes to the hydrologic and sediment transport regimes (Grant et al. 2003). In this context, the magnitude of adjustment should: 1) scale to the degree of hydrogeomorphic process alteration (Williams and Wolman 1984); and 2) decrease downstream as water and sediment inputs from tributaries gradually “reset” the river’s hydrogeomorphic regime to pre-dam conditions, a conceptual model known as the “serial discontinuity concept” (Stanford and Ward 2001).

This theoretical framework for channel response suggests that the magnitude of channel adjustments downstream from Flaming Gorge Dam should gradually decrease until channel morphologies are fully “recovered” to pre-dam conditions. However, empirical studies (Andrews 1986, Grams and Schmidt 2002, 2005) indicate the magnitude of channel form adjustments (particularly adjustments to channel width and bed elevation) along the Green River between Flaming Gorge Dam and the Split Mountain boat ramp often change abruptly, suggesting that non-hydrogeomorphic variables contribute to the style and magnitude of geomorphic response to dam closure. Grant et al. (2003) maintain that both the regional geologic setting and pre-dam channel planform morphologies (i.e. debris-fan dominated canyons, fixed meanders, and restricted meanders) have played a significant role in controlling the direction and magnitude of the downstream geomorphic response to the closure of Flaming Gorge Dam.

Regional Geology

Regional geologic characteristics combine with climatic influences to provide first-order controls on basin-scale hydrologic regimes and sediment supply (Grant et al. 2003). Bedrock lithologies and structures directly control regional topography and drainage network patterns, thus strongly influencing the duration, magnitude, timing and frequency of water discharges (Grant et al. 2003). Similarly, regional bedrock lithologies help determine the volume and character of sediment supplied to a drainage network. For example, basins characterized by soft, easily weathered and eroded rocks will supply more sediment to a channel network than basins characterized by erosionally-resistant materials.

Because dams alter both the sediment transport and hydrologic regimes of fluvial systems, the location of a dam with respect to regional bedrock structures and lithologies plays a large role in determining how channel morphologies adjust to a dam-induced change in the hydrogeomorphic regime. In the case of the Green River, the majority of the water in the basin is supplied from the Wind River Range upstream of Flaming Gorge Dam, while most of the sediment (by volume) is transported to the mainstem Green River by tributaries (e.g. the Yampa River) located below the dam (Andrews 1986). Given that so much sediment is available downstream from Flaming Gorge Dam and reservoir releases have only moderately reduced the frequency of sediment-transporting discharges (Grant et al. 2003), the longitudinal extent of bed degradation is relatively moderate. Andrews (1986) has shown that channel-bed incision (degradation) only extends approximately 70 miles to the confluence with the Yampa River, downstream of which no net sediment accumulation or depletion is observed (Grant et al. 2003).

The aforementioned situation contrasts sharply with that of the Colorado River downstream of Glen Canyon Dam where most of the available sediment supply is derived from basins upstream from the dam, and thus becomes trapped behind the dam instead of transported downstream. Minimal sediment input from tributaries below the dam has led to extensive downstream channel degradation (incision) along the Colorado River (Schmidt and Graf 1990, Grant et al. 2003).

In summary, the downstream geomorphic response (particularly bed elevation changes) to dam closure is adjusted based on the degree to which the pre-dam hydrogeomorphic regime is altered, and the extent of this alteration is ultimately dependent upon the location of the dam with respect to basin bedrock lithologies and geologic structures.

Pre-dam Channel Planform Morphologies

As discussed above, the closure of Flaming Gorge Dam in 1962 represents a basin-scale disturbance to the Green River’s discharge and sediment transport regimes. The downstream geomorphic response to this regime change is predominantly characterized by channel narrowing along reaches extending from the dam’s tailwater to more than 460 km downstream (Grams and Schmidt 2002, 2005). Graf (1978) and Grams and Schmidt (2002, 2005) attribute this observed channel narrowing to multiple factors, including the spread of the non-native tamarisk, climate change and the closure of Flaming Gorge Dam.

In the context of the aforementioned serial discontinuity concept, the magnitude of channel narrowing resulting from the closure of Flaming Gorge Dam should steadily decrease downstream from the dam. However, large longitudinal variations in the magnitude of channel narrowing are observed throughout the study reach, with decreases in post-dam channel bankfull widths ranging between 0.4% and 45% (Grams and Schmidt 2002, 2005). Downstream from Flaming Gorge Dam, fixed meander reach morphologies exhibit the lowest magnitudes of channel narrowing (0.4% to 10%), while restricted meanders exhibit the greatest magnitude of narrowing (22% to 45%). Grams and Schmidt (2005) and Grant et al. (2003) suggest that these reach-scale differences in the magnitude of channel narrowing reflect the channel's ability to adjust to the post-dam hydrogeomorphic regime. This "ability to adjust" is a function of the channel's transport capacity, the erodibility of bed and bank materials, and lateral mobility (Grant et al. 2003), variables controlled by not only the inherited channel planform morphology, but also by regional and local bedrock lithologies and structures.

CONCLUSIONS

Variations in both large-scale channel planform geometries and small-scale in-channel alluvial depositional environments along the Green River from Flaming Gorge Dam to the Split Mountain boat ramp are primarily controlled by regional and local bedrock lithologies and structures. Previous investigations (Grams and Schmidt 1999, 2002, 2005) indicate that planform channel morphologies are largely determined by the longitudinal distribution of river-level bedrock exposures, while in-channel alluvial depositional environments are primarily controlled by local sediment delivery processes which are strongly influenced by local deformation structures.

Prior to 1962, in-channel morphologies along the Green River likely existed in a quasi-equilibrium state able to dynamically adjust to natural fluctuations in the discharge and sediment transport regimes. The closure of Flaming Gorge Dam (1962) and resultant hydrogeomorphic process alterations have forced in-channel morphological adjustments downstream from the dam site (Andrews 1986, Grams and Schmidt 2002, 2005). The direction and magnitude of these form adjustments varies at both the reach and segment scales, reflecting the influences of regional geologic structures and lithologies, and inherited channel planform morphologies.

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