Stream piracy in the Black Hills: A geomorphology lab exercise

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ABSTRACT

The Black Hills of South Dakota exhibits many fine examples of stream piracy that are very suitable for teaching geomorphology lab exercises. This lab goes beyond standard topographic map interpretation by using geologic maps, well logs, gravel provenance and other types of data to teach students about stream piracy. Using a step-by-step method in which the lab exercises ramp up in difficulty, students hone their skills in deductive reasoning and data assimilation. The first exercises deal with the identification of stream piracy at a variety of spatial scales and the lab culminates with an exercise on landscape evolution and drainage rearrangement.

KEYWORDS: geomorphology, stream piracy, fluvial, terraces, Black Hills

INTRODUCTION

The Black Hills of South Dakota and Wyoming has long been a popular area for geology field camps, tourists and sportsmen. This relatively small, Laramide uplift has many excellent exposures of a variety of rock types, which range from pegmatite and schist and in the crystalline core of the uplift to karstic limestone, sandstone, gypsum, and brick red mudstone in the overlying sedimentary sequence. The Black Hills is also home to a magnificent suite of fluvial terraces and other surficial deposits which document several examples of stream piracy (Darton, 1909; Wanless, 1923; Zaprowski et al, 2001). We combine maps and sedimentological data from the Black Hills to design a laboratory exercise that not only helps students learn about fluvial terraces and stream piracy, but also helps students develop their deductive reasoning skills. This exercise is geared towards geomorphology students who have completed some type of introductory geology class.

The goal of this lab exercise is to show students how to recognize the evidence for stream piracy using a variety of maps and other data such as well logs and gravel counts. In addition, the lab ultimately shows students how to synthesize data to reconstruct the evolution of a landscape over time. This approach differs from other map exercises (Wood, 1963; Fonseca, 1992; Vitek et al., 1996; Miller et al., 2000), which focus only on topographic maps and how to interpret them. Few labs develop geomorphic concepts such as landscape evolution (Locke, 1996; Orndoff and Stamm, 1997; Field and Pearthree, 1997). We believe that teaching students to reason through a data set to reach a logical conclusion (in this case, stream piracy) requires a step-by-step approach. This strategy is similar to the approach of Locke (1996), who taught geomorphology through a series of spreadsheet exercises in which students, while learning topical material in a traditional sequence, progressed from a simple "cookbook" exercise to more realistic, process-based exercises.

The lab exercise is divided into four sections, starting with the Black Hills in general and then focusing on three specific field sites. In the lab exercise, each section begins with an introduction highlighting the geologically important areas of the site and the character of the major streams and rivers. These introductions are written so as to give the students some important clues concerning how to complete the exercise. Each section then has a series of questions about different parts of the map. The questions are designed to lead the students to each of the places on the map that contains some supporting evidence for a stream capture event. At the end of each section, the students are asked to summarize their thoughts into a sequence of geologic events in chronological order. This sequence is similar to the exercises commonly seen in introductory geology lab books for teaching stratigraphic principles (Strahler and Strahler, 1984; Busch, 1990; Brice et al., 1993).

The step-by-step method gives the student a functional checklist of how to approach and solve geologic problems. The step-by-step process also provides additional mental reinforcement by asking the student to reorganize their lab answers into a readable summary, thus exposing them to the same concepts twice. The four sections of the lab build in difficulty, both in the concepts covered and in the quality of the answers expected from the student. The four sections of the lab also look at stream piracy in the Black Hills using a variety of map scales.

The specific geomorphic concepts covered in this lab exercise require some background discussion of terraces and rivers, either in the lab or classroom. It is also helpful for the students to have some knowledge of how to produce a topographic profile and manipulate map scales. Our on-line version of this lab includes a brief introduction to the concepts covered and the Black Hills in general, including the full-color maps used in the lab (http://henson1.ssu.edu/~bjzaprowski/piracy_web_page.htm). This introduction serves as a reference for the students throughout the exercise.

FLUVIAL TERRACES AND STREAM PIRACY

Over the course of time, rivers can reach a quasi-equilibrium state where the river is more or less stable, neither incising nor depositing in the vertical direction. During these times, the river meanders back and forth, erodes its banks laterally (from valley side the valley side) and deposits sediments. This progression results in the formation of a wide, flat plain next to the river called the floodplain (Fig. 1a). The floodplain is underlain by fluvial sediments (called alluvium) deposited over years to thousands of years. The contact of the river deposits with the eroded bedrock surface below them is called the strath.

If the river experiences a period of incision, these deposits can be left stranded above the river’s new elevation, forming a strath terrace (Fig. 1b). The top of the terrace is now called a tread. Conversely, if the river undergoes a period of deposition and then incision, a fill terrace will form (Fig. 1c). Strath terraces have relatively flat straths while fill terraces have an irregular strath. Long valley strath terrace profiles can be used to determine in what direction the river was flowing when the terrace deposits were still part of the active floodplain.

Sometimes rivers change their direction of flow significantly because of stream piracy. The most common type of stream piracy occurs when one stream (River A, Fig. 2a) erodes headward into the channel of another stream (River B, Fig. 2a) and diverts (pirates) its water (Fig. 2b). Usually, the capturing stream has the advantage of a steeper gradient than the captured stream. When this happens, the captured stream will abandon the downstream portion of its old channel and flow into the channel of the capturing stream (Fig. 2b). This greatly reduces the discharge of the captured stream below the point of capture and fundamentally changes the characteristics of the drainage basin of both streams. A drainage basin is defined as all of the surface area from which a stream or river receives water. The drainage basin of the capturing stream instantly grows at the expense of the captured stream's drainage basin. In addition, the fluvial deposits of the captured stream, downstream of the capture point, are left high and dry ("x", fig. 2b); there may be little, if any, discharge left in the downstream channel of the captured stream to move sediment. This evolution can present the geologist with an interesting paradox in the field: fluvial deposits whose characteristics do not reflect the size of the stream adjacent to them. The width of a river's floodplain is generally proportional to the river's discharge. However, when piracy occurs, the floodplain of a captured river may be much larger than the new discharge of the river would dictate.

Our lab exercises address the wide variety of geologic data that can be used to indicate that stream piracy has occurred. For instance, many stream piracies produce an "elbow of capture" (Fig. 2b), where a river has a distinct 90 degree bend in it. However, an elbow of capture need not be present in all cases of piracy. Surficial geologic maps also provide important clues. In some cases, fluvial deposits (including terraces) may exist in areas where there are small to non-existent streams. Terraces also provide excellent clues for recognizing changes in stream flow. The dip direction of a terrace strath reflects the direction the stream flowed when the terrace sediments were being deposited. If the terrace strath dip direction is distinctly different than the flow direction of the modern stream channel, this could indicate stream piracy. Gravel provenance can also provide important clues for stream piracy. If a fluvial deposit contains rock types not accessible by the present stream, this could indicate than piracy has occurred because prior to capture, different rock types may have been deposited into the alluvium.

THE BLACK HILLS

There are many books, maps and field guides that describe the bedrock geology and other features of the Black Hills (Harksen and MacDonald, 1969; Rich, 1986; DeWitt et al., 1989; Agenbroad, 1994; Dodge, 1998; Gries, 1996). The inner core of the Black Hills, a doubly plunging anticline, is composed of Achaean and Proterozoic igneous and metamorphic rocks (Fig. 3). These crystalline rocks are overlain by several hundred meters of Paleozoic carbonates with thinner, interbedded layers of sandstone and shale. The spectacular Triassic red beds of the Spearfish Formation form a distinct erosional valley nicknamed the "Red Racetrack", while a hogback ridge, held up by Cretaceous sandstone, flanks the Red Racetrack. Fissile, easily erodible Cretaceous shales underlie the plains that surround the Black Hills. Masses of Tertiary phonolite intrude all of these rocks in and around the Black Hills, some forming volcanic necks. The fluvial terraces are well preserved on the red-beds of the Spearfish Formation and the shales of the High Plains, while terraces are scarce and very small in the mountainous regions of the Black Hills.

There are four distinct strath terraces in the Black Hills, although this lab exercise focuses on sites in which the youngest (Farmingdale) terrace is missing (Fig. 4). These terraces can be identified readily on both a topographic map and in the field. The younger ones are more obvious than older ones because they have not been as deeply incised. Younger terraces have broad, flat treads, while the older terraces tend to be smaller isolated "islands" of bedrock with coarse gravel on them. On the High Plains, there are laterally extensive terrace deposits, but in the Red Racetrack, the deposits tend to be relatively small in area. Because the terraces in the Red Racetrack have straths of red mudstone, the contact between the terrace gravels and the bedrock is easy to see.

THE LAB EXERCISES

The first section of this lab presents an example of stream piracy on a very large scale (Fig. 3). The Tertiary deposits in the southeastern portion of Fig. 3 are fluvial sand, gravel and clay, many of which are exposed in the famous Badlands of South Dakota. These sedimentary deposits have minerals in them that could only have been derived from the Black Hills. In addition, the contact (strath) between the Tertiary fluvial deposits and the underlying Cretaceous shale dips towards the east-southeast. At the present time, streams draining the southeastern portion of the Black Hills flow to the southeast and into the Cheyenne River. The Cheyenne River then flows northeastward and eventually eastward to the Missouri River. By studying the stream patterns in this area carefully, students should note two things. First, the Cheyenne River, in this portion of the Black Hills, only has tributaries flowing into it from the west, while the White River only has tributaries flowing into it from the east. Second, in between the rivers is an area of land that lacks any significant tributaries. Given the provenance of the Tertiary deposits, the dip of the strath under those deposits, and the distinctive drainage patterns, students should come to the conclusion that the southeastern Black Hills once drained into the White River and at some point, the Cheyenne River came along and captured each of the streams, one by one. The captured sections of the tributaries that previously flowed into the White River are now abandoned.

The second section of the lab focuses on a large river capture event near the town of Alzada, Montana (Fig. 5). There is a large, flat plain underlain by fluvial gravels (Stoneville Flats) situated between the Little Missouri and Belle Fourche Rivers. The students' first step is to make pie diagrams of gravel composition from seven different sample sites along each river (only three of the sites are shown Fig. 5). This provides the students with the gravel provenance data needed to recognize than the gravel in the floodplain deposits along the Little Missouri River, north of the point of capture and under Stoneville Flats, must have come from the Black Hills. Thus, there must have been a fluvial connection between the Belle Fourche and Little Missouri Rivers at some time in the past. The students also compare the widths of their floodplains. The students should realize that the Little Missouri River has an unusually large floodplain for a very small river, while the Belle Fourche River has a relatively narrow floodplain. In addition, the students should recognize the significance of the gravel deposits under Stoneville Flats, the lack of any modern stream in Stoneville Flats capable of carrying gravel, and the distinctive elbow of capture on the Belle Fourche River. Given this data, the students should easily reach the conclusion that the Belle Fourche River, prior to stream capture, used to flow across Stoneville Flats and into the Little Missouri River.

The third section of the lab focuses on the fluvial terraces near the city of Spearfish, South Dakota (Fig. 6). This site has a collection of both hypothetical and actual well logs associated with it; the hypothetical well logs help fill in gaps to assist the students. The students first use the well logs to contour the bedrock beneath Centennial Prairie, a large, flat plain underlain by up to 80 feet of fluvial sand and gravel. This portion of the exercise shows the students that a large buried river valley, trending to the northeast, runs under the plain parallel to the Mountain Meadow and Rapid Terraces. Next, the students use the well logs to determine the dip direction of select terrace straths. The dip direction of the Mountain Meadow and Rapid Terrace straths that fringe Centennial Prairie indicate that the former stream flowed towards the northeast. The students should also notice that there are no modern streams that could have transported the gravel found in the terraces. In addition, the backfilling of the buried valley is related to the drastic decrease in discharge available to transport sediment after piracy occurred. Once, again, the inevitable conclusion the students should reach is that stream piracy diverted Spearfish Creek.

The fourth section of the lab focuses on terraces near the town of Sundance, Wyoming (Fig. 7). The study map for this section is composed of nine 7.5' quads joined together, and many examples of stream piracy can quickly be discerned from the map patterns and the strath dip directions. The students "tour" this area as directed by the questions. For example, site "A" has terraces that dip towards the south while the adjacent stream, with a distinctive elbow of capture, flows north, clearly indicating stream piracy. At site "B", there are distinct sets of Rapid and Sturgis terraces which flank a very small stream that is headed near the terraces. In this instance, the stream that originally formed these terrace deposits was beheaded, leaving behind deposits that are mismatched in size with the adjacent stream. Site "C" is even more complex, as the Rapid terraces dip towards the north-northwest, the nearby Sturgis terraces dip towards the southeast and the modern stream flows towards the northeast. Site "D" has Rapid terraces which dip to the southeast, while the modern stream that drains that area takes a sharp turn and flows towards the west, again indicating stream piracy. By carefully studying the various sites, the overall stream pattern and applying the lessons learned in the previous sections of the lab, students should come to the conclusion that the drainage network in this area has fundamentally been altered over time. The difficult part of this final exercise is determining exactly how the drainage network used to look and several different scenarios can be supported by the data, so there is no single correct answer.

CONCLUSIONS

We feel that our lab exercise is an excellent tool for training geology students about stream piracy, specifically, and deductive reasoning, in general. We have posted our lab in its digital format for public viewing and download at: henson1.ssu.edu/~bjzaprowski/piracy_web_page.htm. In addition, we anticipate that instructors who regularly visit the Black Hills region would be interested in developing this lab exercise into a field exercise in the near future. All of the locations we discussed in this paper have good vantage points that are easily accessible from Interstate 90. Directions to these areas will be given at the end of this paper.

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DIRECTIONS TO THE STUDY SITES

Alzada, Montana

From Spearfish S.D.: Travel north on Rt. 85 from exit 10 of Interstate 90 to the town of Belle Fourche. Once you have passed through town, you will come to Rt. 212 West. Follow this route to Alzada. The trip to Alzada from Spearfish takes about 45 minutes. From Devil's Tower: Take Rt. 24 North to Huelett, WY. From Huelett, take Rt. 112 North to Alzada. Trip from Devil's Tower takes about ½ hour. Alzada is a very small rural town which does have one small store and gas station, but little else. The land in this area is private, and permission must be obtained for off-road travel.

Spearfish, South Dakota

Locations described in this part of the lab exercise are accessible from exit 14 of Interstate 90. Good views of the terraces can seen from the parking lot of K-Mart right off the exit or from Lookout Peak. Many fine camping facilities and hotels can be found in Spearfish near exit 14.

Sundance, Wyoming

Sundance is located at several exits of Interstate 90. The terraces in Government Valley are best seen by getting off exit 199 of Interstate 90 and driving south on the service road that parallels the interstate. Alternatively, Government Valley Rd. is the first right hand turn you pass on the service road and it takes you along a dirt road right through the terraces. The road arrives on the outskirts of Sundance. There is also trailhead parking area for the Black Hills National Forest on this road. This parking area offers an excellent view of the terraces in the southern part of Government Valley. More terraces can be observed along Rt. 14 north (west of Sundance, exit 185) as you head towards Devil's Tower. The terraces south of Sundance can be viewed along Rt. 585 south (exit 187). Sundance Wyoming is about a ½ hour drive from Spearfish and about a 15-minute drive from Devil's Tower.

FIGURE CAPTIONS:

Figure 1: a) The primary components of the river system. b) Cross-section showing a strath terrace. c) Cross-section showing a fill terrace.

Figure 2: An example of stream piracy. Notice how the capture event caused a distinct 90-degree bend, called an "elbow of capture", to form in the capturing stream. Also, the capturing stream has gained basin area at the other drainage basin's expense.

Figure 3: Geologic Map of the Black Hills of South Dakota and Wyoming. Locations of stream piracy exercises are also shown: Fig. 5, Alzada, Montana; Fig. 6, Spearfish, South Dakota; Fig. 7, Sundance, Wyoming.

Figure 4: A schematic diagram showing the major terrace units in the Black Hills used in this exercise.

Figure 5: A map of fluvial deposits near the town of Alzada, Montana. The pie diagrams show gravel composition at select sites. C = carbonate, S = Siliclastic, I = Igneous.

Figure 6: Map of fluvial terraces in the northern half of the Chicken Creek Quadrangle. The dashed contour lines represent the elevation of the bedrock beneath Centennial Prairie.

Figure 7: Map of the Sundance, WY area showing terrace deposits.

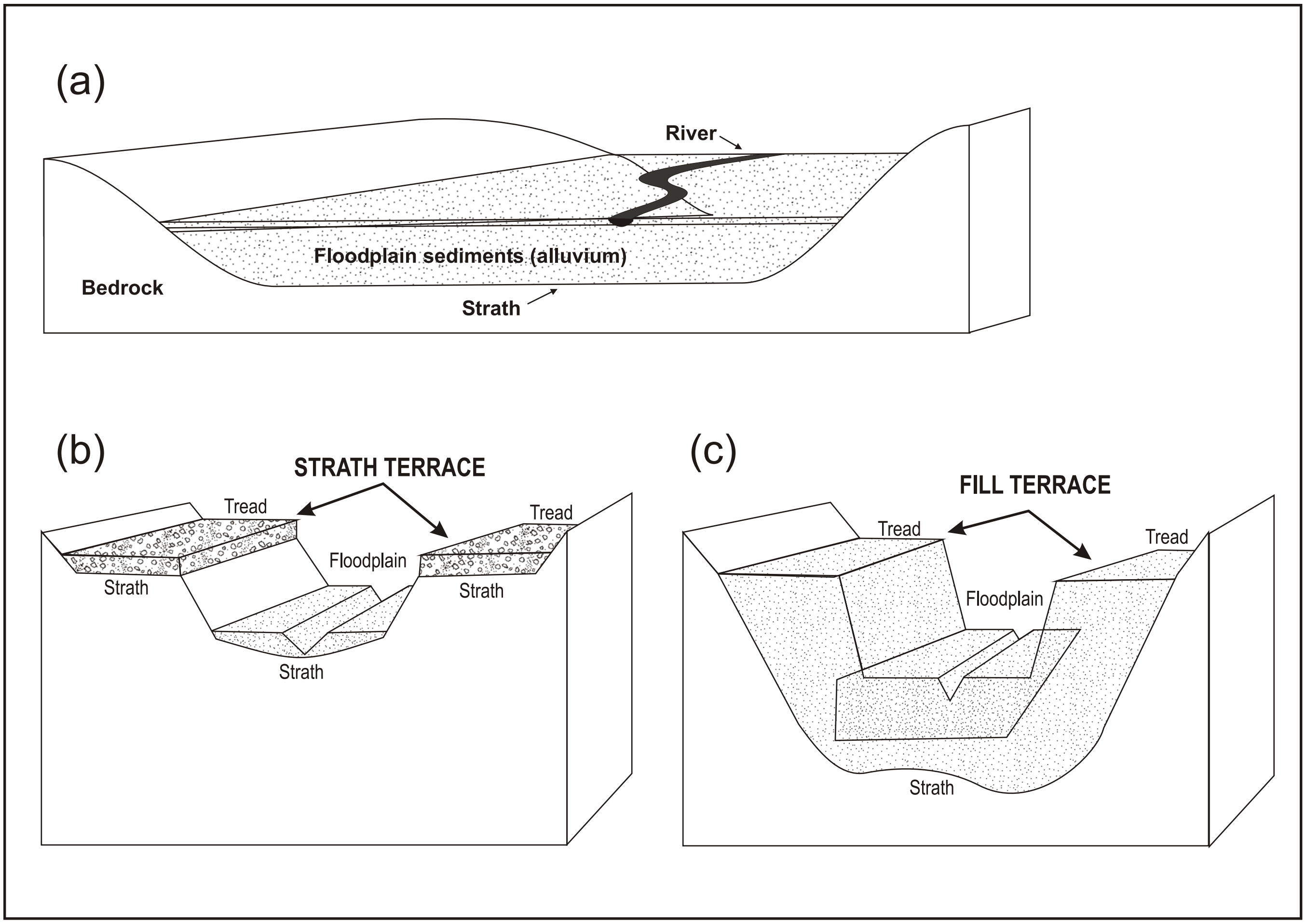


FIGURE 1: ZAPROWSKI, EVENSON & EPSTEIN

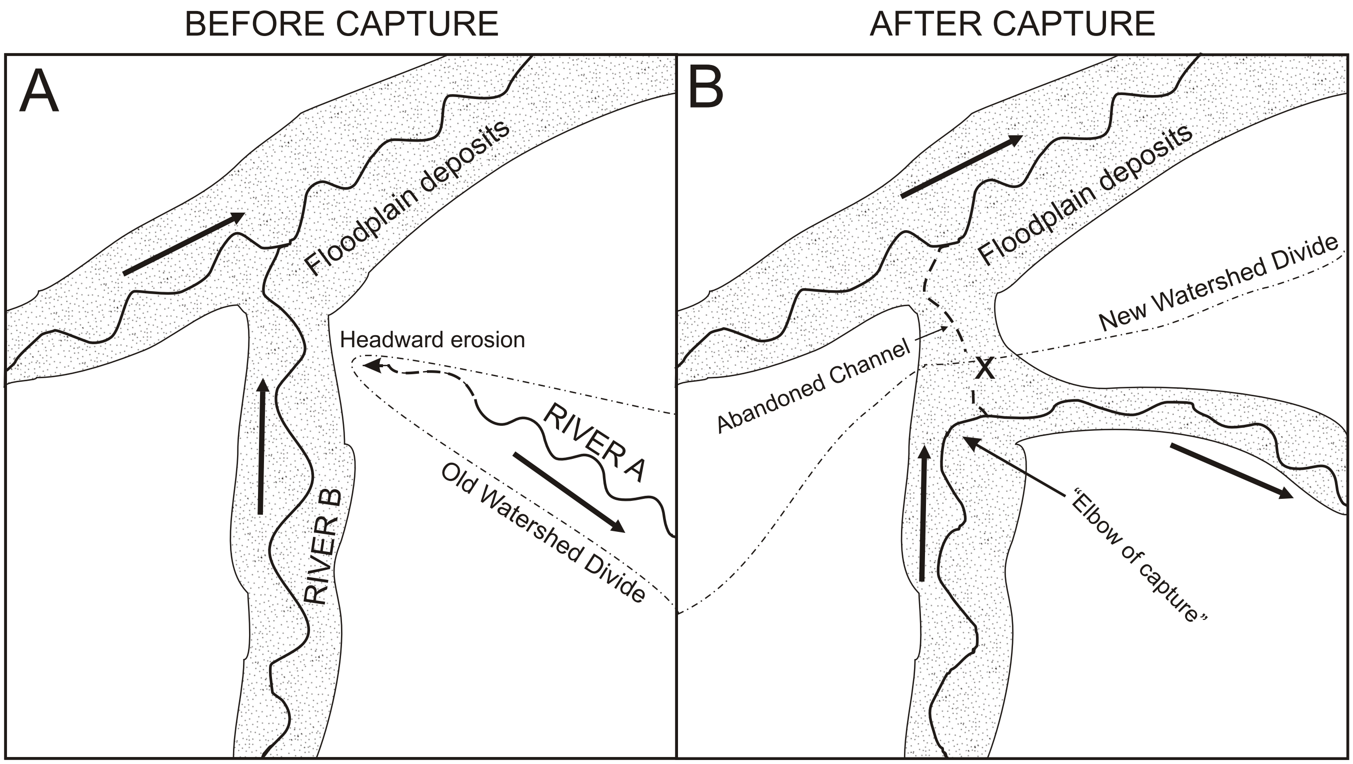


FIGURE 2: ZAPROWSKI, EVENSON & EPSTEIN

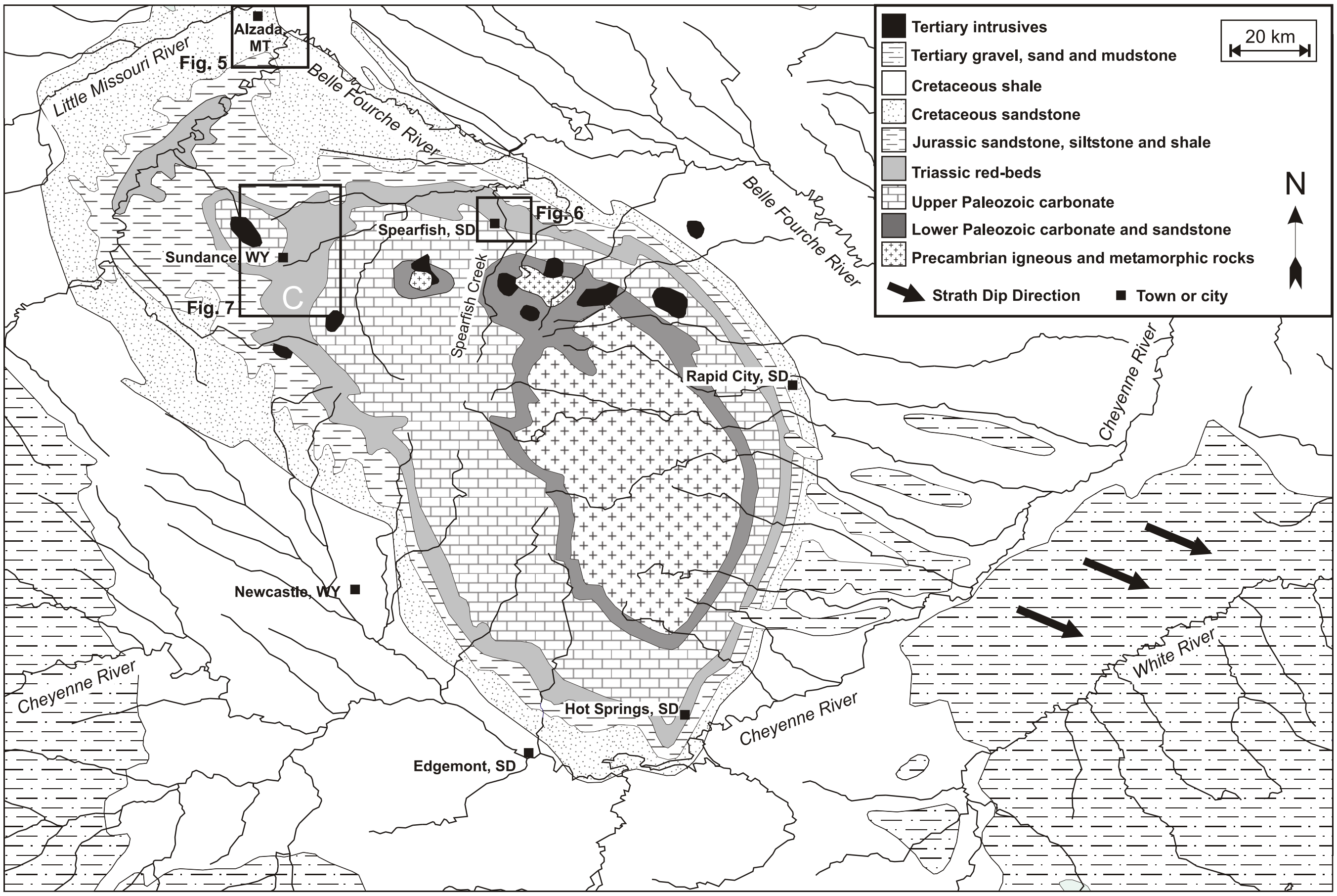


FIGURE 3: ZAPROWSKI, EVENSON & EPSTEIN

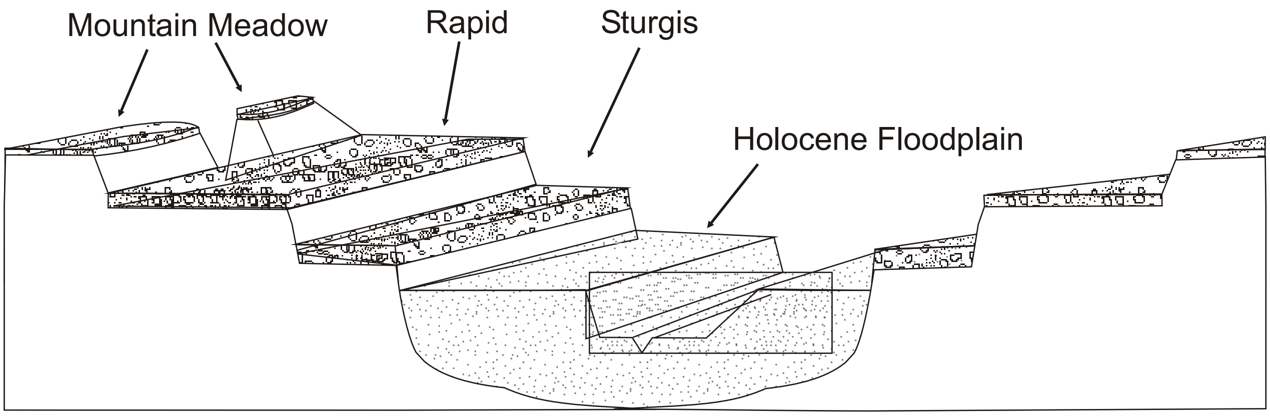
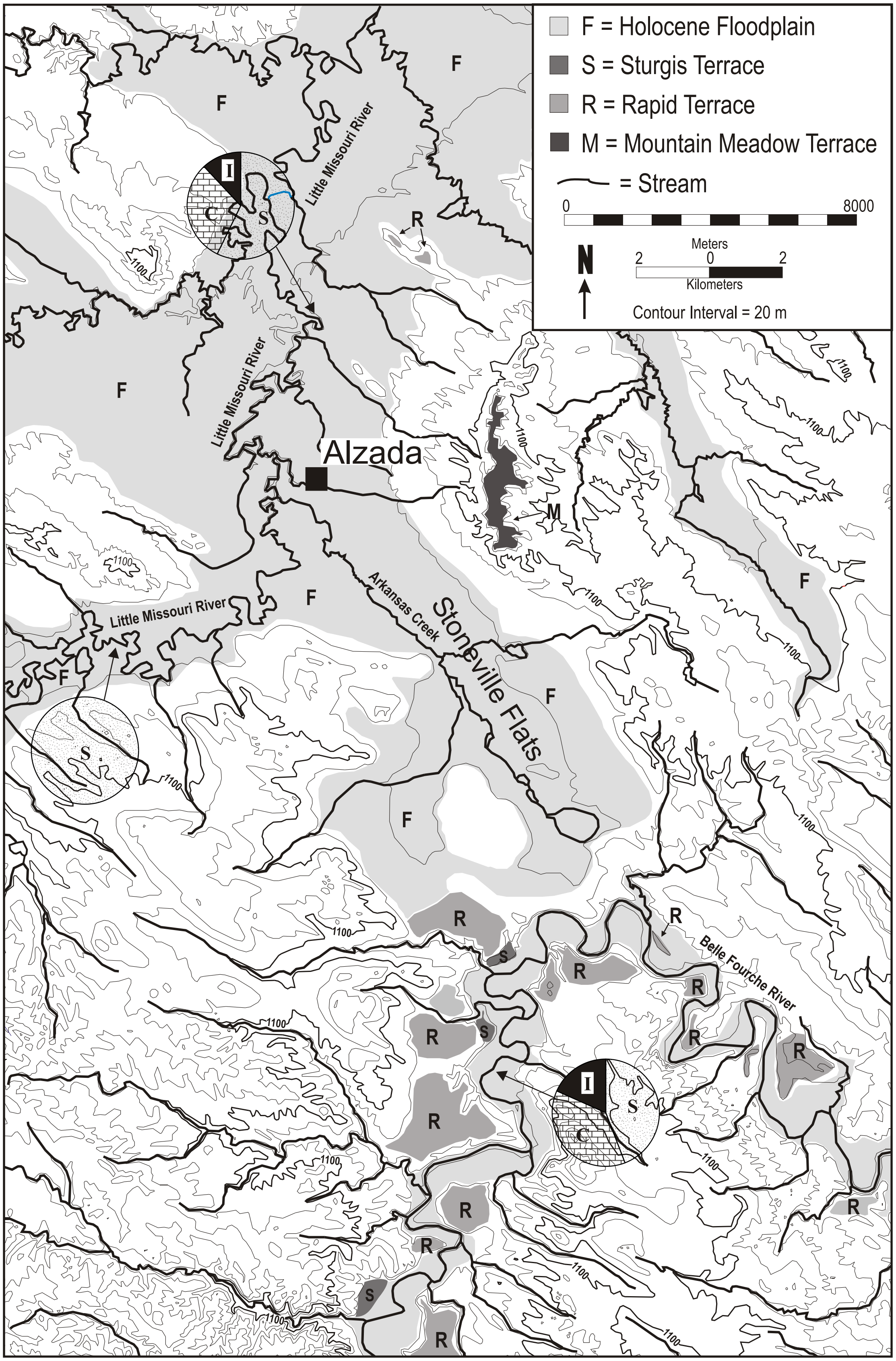


FIGURE 4: ZAPROWSKI, EVENSON & EPSTEIN



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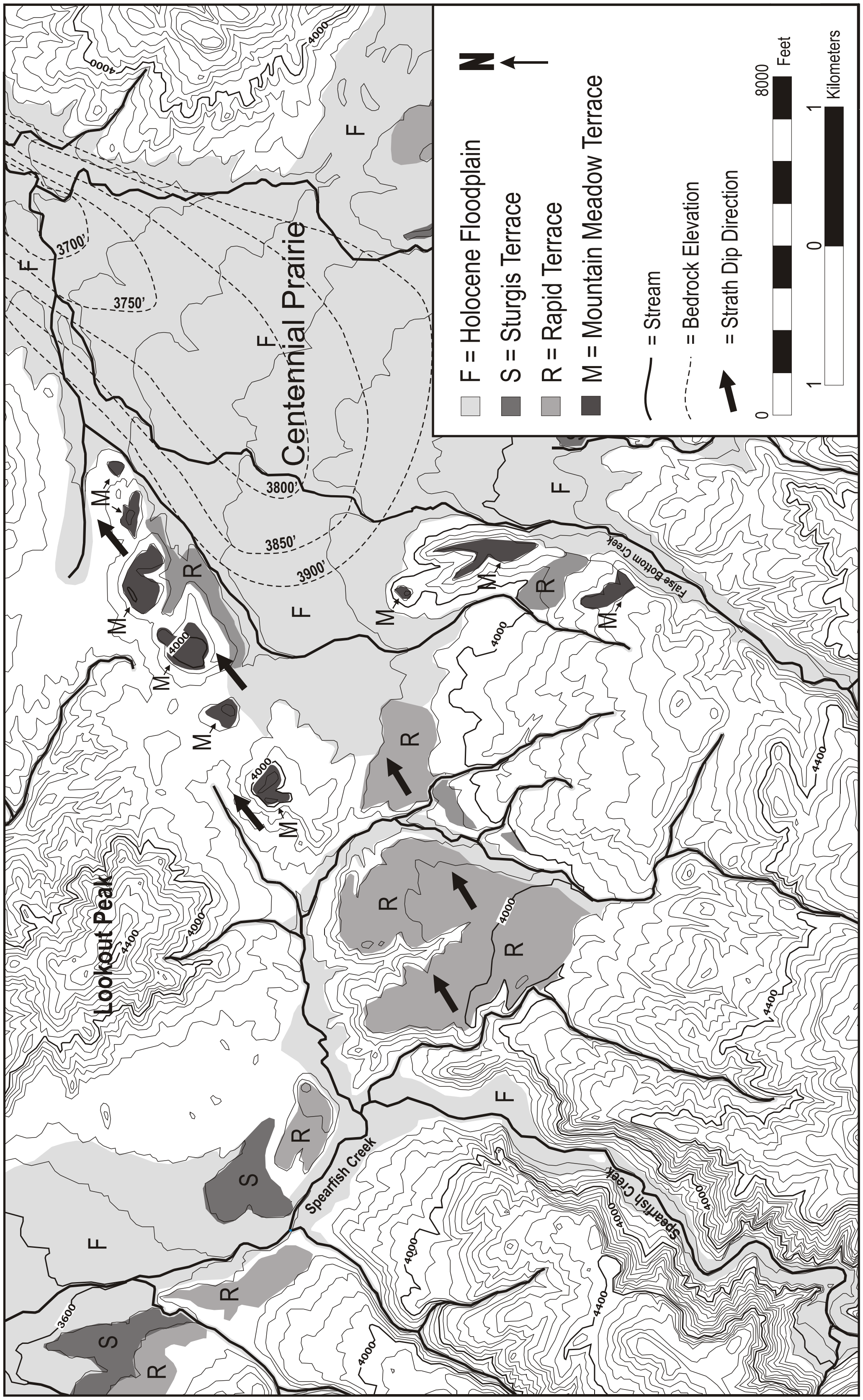

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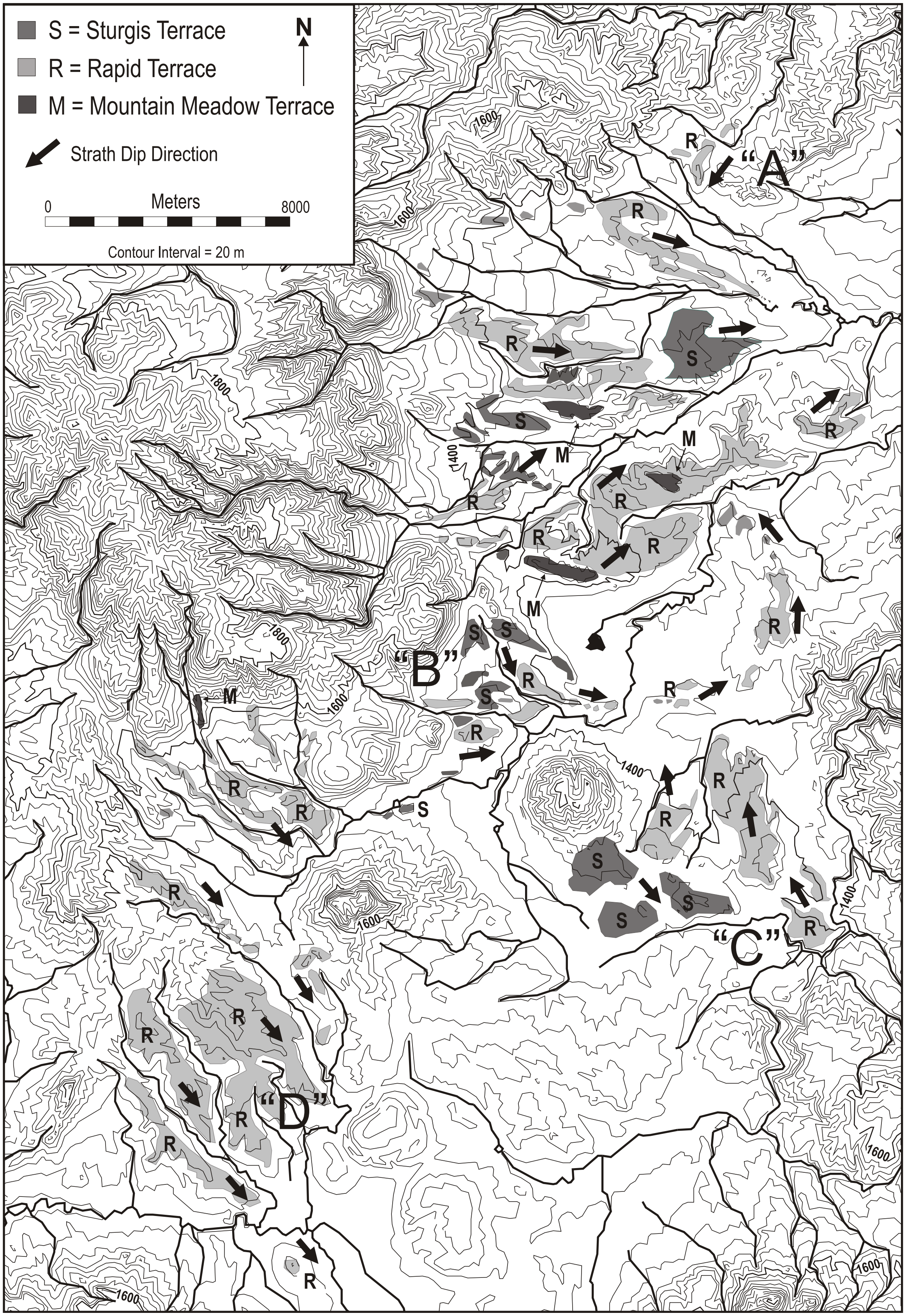

FIGURE 7: ZAPROWSKI, EVENSON & EPSTEIN