

## TERRACES, PIRACY AND LANDSCAPE RECONSTRUCTION: A FLUVIAL GEOMORPHOLOGY LAB EXERCISE

Water is one of the primary agents driving the constant erosion of the surface of the earth. Water aids in the degradation of rocks and then transports the resulting sediment downstream to some sedimentary basin, usually the ocean. However, even though the process of erosion is constantly occurring, sediments move down a river much more slowly. Sediments, particularly gravel, can only be moved when the river is flowing with high energy, like during a flood. As a result, sediments can be temporarily stored in fluvial deposits until the next storm comes along and washes some of the sediment downstream a little further. The sediment that gets washed away will probably be replaced by more sediment from upstream. In this manner, sediments inch their way downstream, getting ever smaller in the process.

A river at equilibrium, “a graded stream”, is referred to as having a “**graded profile**” (Fig. 1). Rivers can be kicked into a state of disequilibrium because of changes in the environment such as: discharge, storm activity and intensity, sediment supply, temperature, vegetation, tectonic uplift and damming. The graded river has just the right combination of gradient and discharge a river needs to flow and carry sediment delivered by its tributaries. If a river is pushed out of equilibrium by one or more of the environmental variables listed above, the rivers respond to these changes in a variety of ways so as to attain a graded profile again. This is not to imply that a river will return to the **same** graded profile as before the disturbance occurred. Rather, the river attains a new equilibrium which is in balance with the new environmental conditions (Fig.1). The deposition of sediments, erosion, changing sinuosity (the amount of stream meandering that occurs over a length of stream channel), channel widening, channel deepening or a combination of all the above may happen as the river tries to attain equilibrium. Because the environment is always changing, the equilibrium a river seeks is, in essence, always changing too. This variability makes it hard for a river to reach equilibrium.

Another definition of a graded river is:

“A graded river is one in which, over a period of years, slope and channel characteristics are delicately adjusted to provide, with available discharge, just the velocity required for the transportation of the load supplied from the drainage basin. The graded stream is a stream in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will cause a displacement of the equilibrium in a direction that will tend to adsorb the effect of the change.” (Mackin, 1948, pp. 471, 484, modified by Leopold and Maddock, 1953, p. 51)

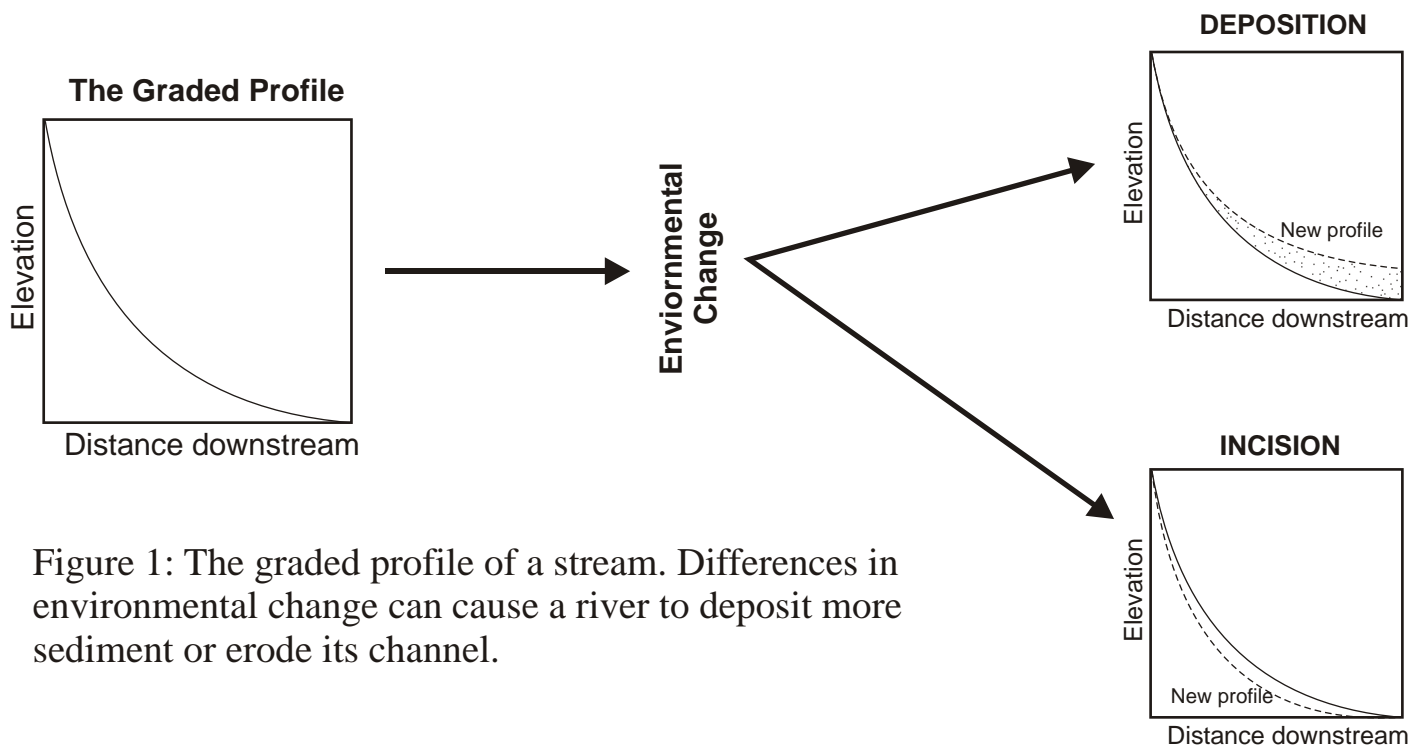


Figure 1: The graded profile of a stream. Differences in environmental change can cause a river to deposit more sediment or erode its channel.

Over the course of time however, rivers can reach a quasi-equilibrium where the river is more or less stable, neither incising nor depositing very much vertically. During these times, the river meanders back and forth, erodes its banks laterally (from side the side) and deposits sediments. In the process, the same sediments are reworked over and over again. This progression results in the formation of a wide, flat plain next to the river called the **flood plain** (Fig. 2). The flood plain is underlain by fluvial sediments (called **alluvium**) deposited over hundreds to thousands of years. The contact of the river deposits with the eroded bedrock surface below them is called the **strath**.

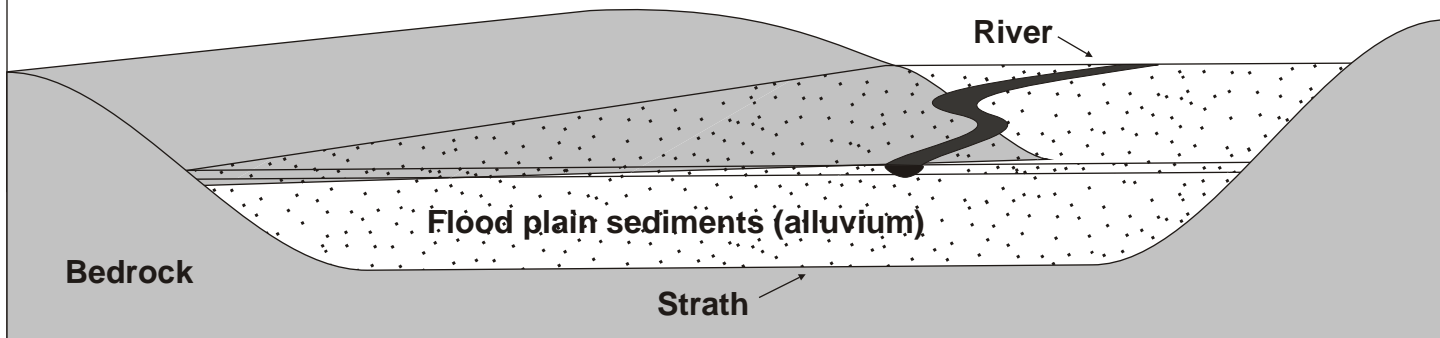


Figure 2: A schematic diagram of a flood plain.

If the river experiences a period of incision, these deposits can be left stranded above the river's new level, forming a **strath terrace**. 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. 3). **Strath terraces** have relatively flat straths while **fill terraces** have an irregular strath (Fig. 3). These terraces, and their straths, can be used to determine where the river used to flow and a little about the river's former characteristics, such as gradient, sinuosity, channel width and depth, sediment load and discharge.

The forces of nature that form these terraces also seek to destroy these deposits; thus the record is typically sporadic and incomplete. With the right conditions and climate, however, terraces can be preserved in the landscape for hundreds of thousands of years or longer. Most important to this preservation process is the composition of the terrace forming sediments. If the terrace deposits are composed mainly of fine-grained mud and silt, then they are much more susceptible to erosion by surface runoff and they are often removed. On the other hand, if the deposits are composed of highly permeable sand and gravel, erosion of the terrace tread will be greatly reduced because the rainwater soaks into the deposit rather than running off of the surface of the terrace, carrying the sediment away.

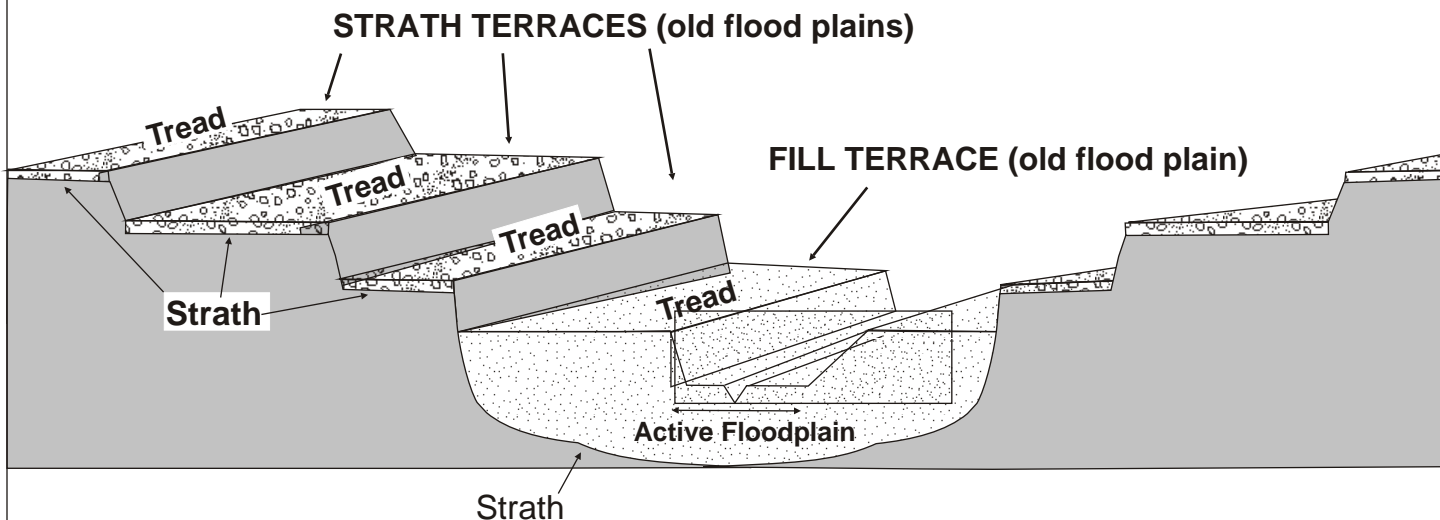


Figure 3: A cross-sectional profile through a set of fluvial terraces. This diagram shows the difference between strath and fill terraces and their respective straths and treads.

Sometimes rivers change their course significantly because of **stream piracy**. The most common type of stream piracy is by a process that occurs when one stream (River A, Fig. 4a) erodes **headward** into the channel of another stream (River B, Fig. 4a) and diverts (pirates) its water (Fig. 4b). 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. 4b). 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 the surface area of the land from which a stream or river receives water. The drainage basin of the capturing stream 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; there is 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 flood plain is generally proportional to the river's discharge. However, when piracy occurs, the flood plain of a captured river may be much larger than the new discharge of the river would normally dictate.

In this lab exercise, you will study the geomorphology of the Black Hills in general and three examples of river piracy in the Black Hills. There are four parts to this lab. Section 1 examines the Black Hills as a whole, while Section 2 focuses upon a piracy near Alzada, Montana. Section 3 examines a piracy near Spearfish, South Dakota and Section 4 inspects at an area near Sundance, WY. In all but section 2, a DEM and a geologic map are presented. Follow the directions and answer the questions. Be sure to follow the instructions carefully and **be neat**. There are clues scattered everywhere if you take the time look and think.....

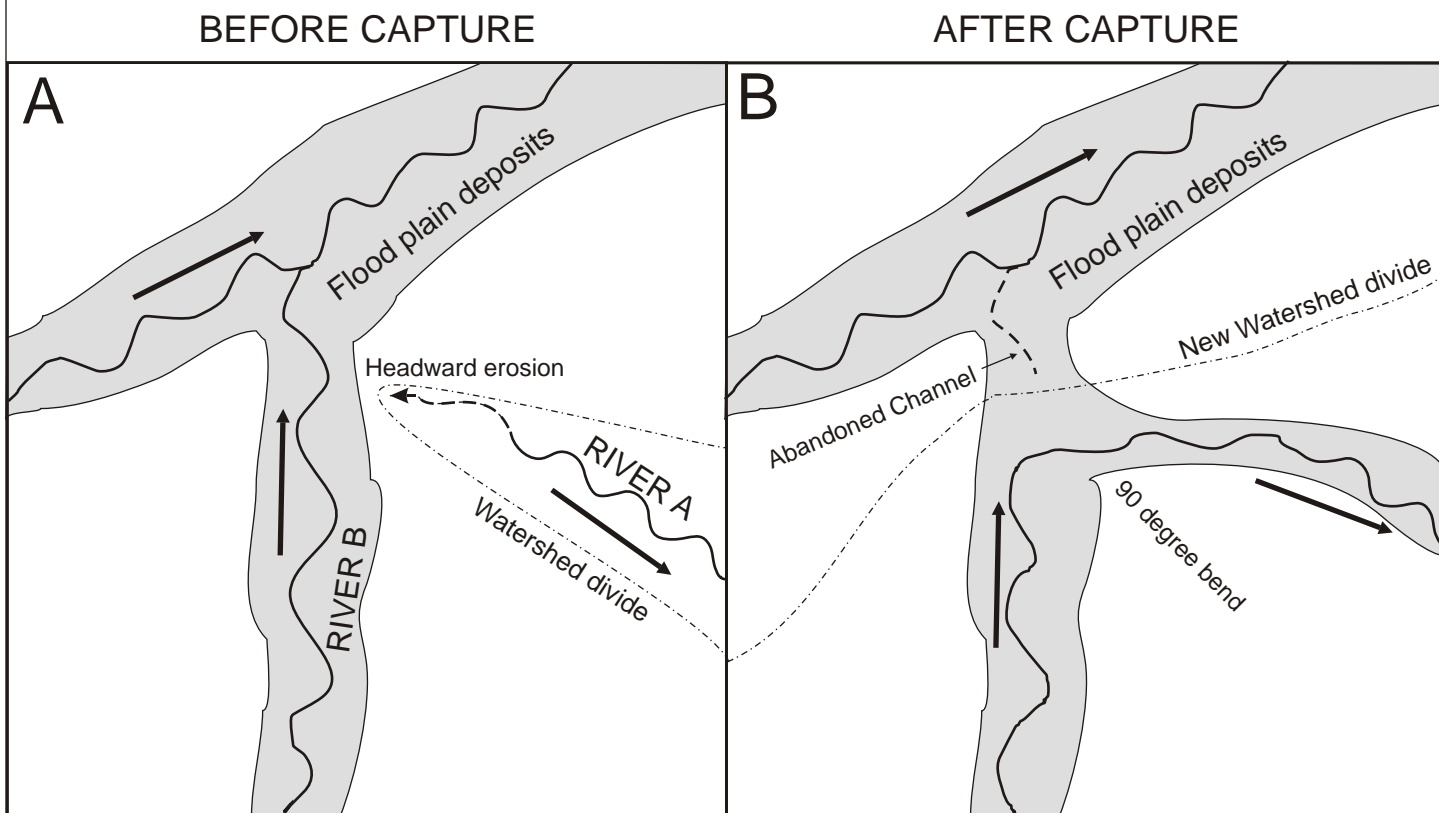


Figure 4: An example of stream piracy. Notice how the capture event caused the newly formed river channel forms a distinct 90 degree bend called an “elbow of capture”.. Also, the capturing stream has gained an basin area at the other river's expense.

## **PART I: THE BLACK HILLS**

The Black Hills is a late Cretaceous - early Tertiary asymmetrically domed uplift in South Dakota, Wyoming and Montana (Fig. 5). The Black Hills is home to many different types of bedrock and surficial deposits including some extensive fluvial gravel, sand and mud deposits. Many of these deposits, particularly the fine grained deposits, are exposed in the famous Badlands of South Dakota.

1. Look in the southeastern part of the geologic map at the Tertiary deposits. These deposits, called the “White River Group”, have a mineral assemblage which could only have come from the igneous and metamorphic rocks exposed in the core of the Black Hills. How do you think the White River Group sediments got to where they are now?

**The deposits were laid down by streams flowing from NW to SE**

Why do you think there are no streams flowing in the area between the Cheyenne River and the White River ?

**River piracy captured the streams which used to flow across the area**

What path do you think rivers in the southeastern part of the Black Hills used to follow when the Tertiary deposits were being laid down? Draw arrows on your map to show this.

**See Figure 5**

Look at the way the small streams flow out of the Black Hills. How would you describe this pattern? Is the pattern the same in the north as it is in the south? Explain.

**The drainage pattern is basically radial. However, the pattern is different in the north, compared to the south. In the north, some of the streams don't flow in a radial pattern. More specifically, some streams flow back *into* the hills.**



## PART II: ALZADA, MONTANA

Near the town of Alzada, Montana is a wide, flat plain called Stoneville Flats (Figure 6). This plain is underlain by fairly thick fluvial deposits. The Belle Fourche River flows past the southern end of this plain, while the Little Missouri River flows past the northern end of the plain. There is one very small intermittent stream (only has water in it part of the time) which runs down the center of the plain (Arkansas Creek). This plain is believed to be the site of a major stream piracy, causing the 90 degree bend in the Belle Fourche River.

The Belle Fourche River on the southern edge of Stoneville Flats is one of the main rivers in the Black Hills and carries most of the discharge from the northern part of the region. Near Stoneville Flats, the river flows through a narrow canyon with steep walls of shale and sandstone. The Belle Fourche River carries a bedload of coarse gravels composed of a wide variety of rock types, with some sand and silt

The Little Missouri River flowing past the northern edge of Stoneville Flats is a small stream which begins in the Powder River Basin. Near the town of Alzada, this river has a bedload of sand and clay along with some gravel, but this gravel is generally finer grained than the gravel in the Belle Fourche River. Upstream of Alzada, the Little Missouri River carries very little gravel and its flood plain deposits are fine-grained sands.

1. Table 1 is a spreadsheet with data describing the composition of gravels (in %) from the sites numbered 1-7 on figure 3. The composition of the gravels were determined by randomly selecting at least 100 pebbles at each study site and determining the lithology of each one. Calculate the relative percentages of each lithology by dividing the number of each rock type by the total number of pebbles at each site. Group the data into three categories: Igneous, Carbonate and Clastic and fill in the pie diagram at each sample locale. Use red for igneous rocks, blue for carbonates and yellow for clastics.

A. Is the composition of the gravel at each site similar? Which sites are alike?

**The composition is very similar at sites #4-7. Site #1 is completely composed of sandstone and siltstone. Sites #2 & #3 have minor amounts of igneous and limestone lithologies in their gravels.**

B. What do you think the gravel composition at site #1 implies?

**The Little Missouri River doesn't "see" igneous and carbonate rocks during its journey from the Powder River Basin. Therefore, the gravel on the flood plains at sites #2 and #3 must have come from some other source, i.e. the Black Hills**

2. Compare the width of the Little Missouri River flood plain at Sites 1 and 2. If flood plain width is proportional to discharge, what does the difference in flood plain width between Sites 1 and 2 imply about the Little Missouri River (downstream of Stoneville Flats) before the stream piracy occurred?

**This would imply that the Little Missouri River, downstream of Stoneville Flats, must have once had a greater discharge than at present because the flood plain at site #2 is much wider than would be expected to form from the present discharge at that site.**

3. On the following page is a cross-section A-A' (see Figure 6) across Stoneville Flats. What is the elevation of the Belle Fourche River? Of the Little Missouri River? Why do you think they are so different?

**They are different because the Belle Fourche River incised into bedrock after capture, probably due to increased discharge, while the Little Missouri River did not, probably due to decreased discharge.**



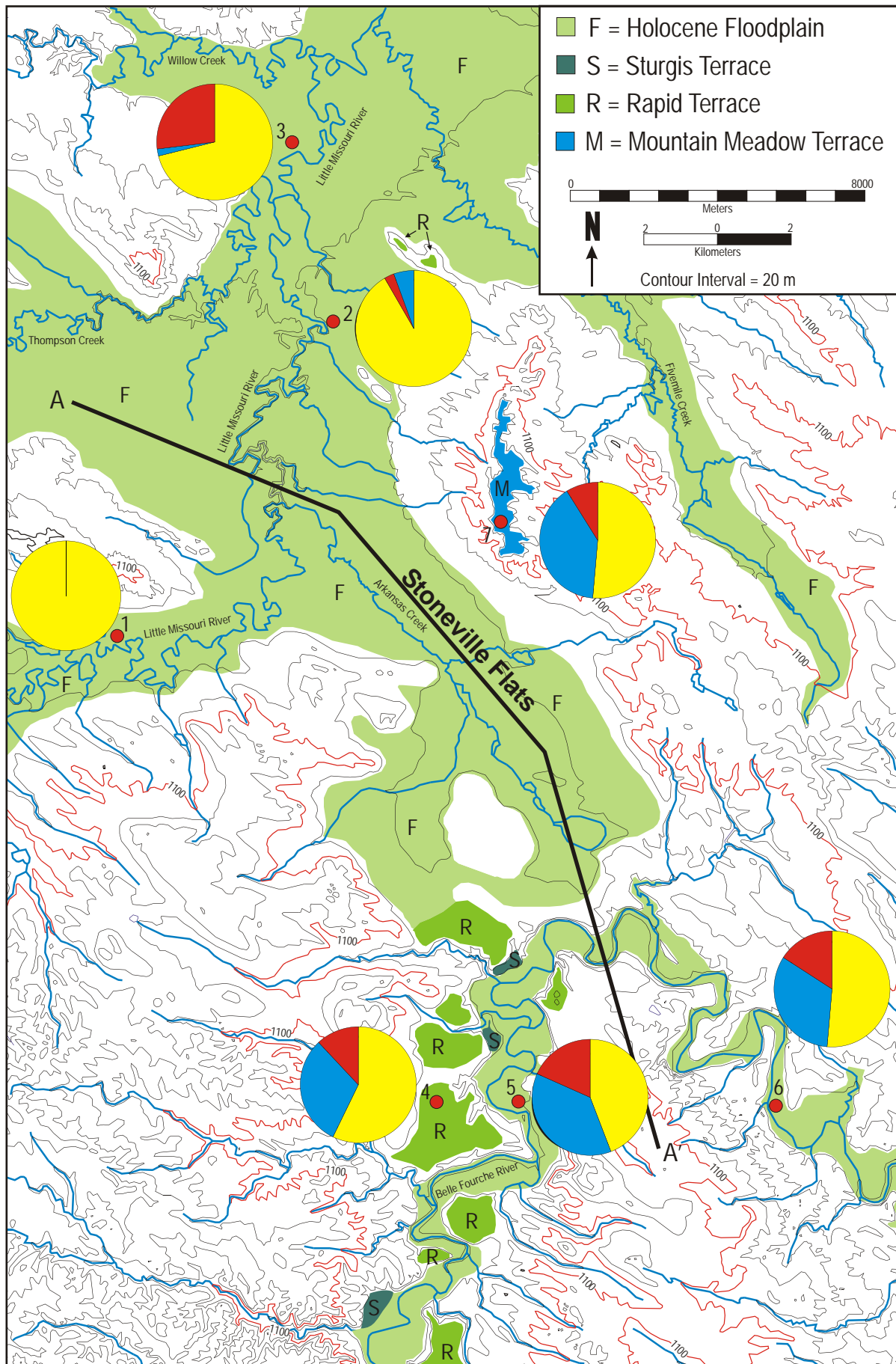


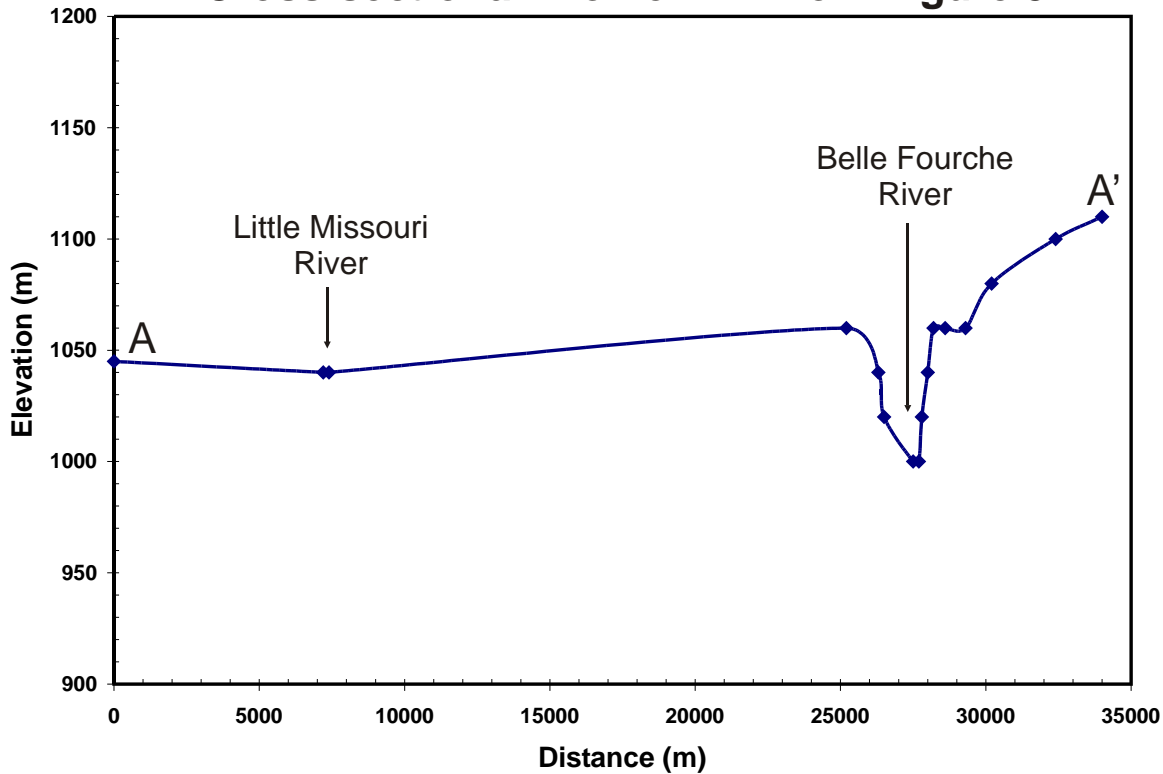
Figure 6: Terrace deposits near the town of Alzada, Montana. The white circles are for pie diagrams of pebble counts.

| <b>Site 1</b>   | Clast count | %             |  | <b>Site 5</b>   | Clast count | %             |
|-----------------|-------------|---------------|--|-----------------|-------------|---------------|
| Sandstone       | 75          | 74.3%         |  | Sandstone       | 21          | 19.3%         |
| Limestone       | 0           | 0.0%          |  | Limestone       | 41          | 37.6%         |
| Igneous         | 0           | 0.0%          |  | Igneous         | 20          | 18.3%         |
| Iron Concretion | 0           | 0.0%          |  | Iron Concretion | 25          | 22.9%         |
| Siltstone       | 26          | 25.7%         |  | Siltstone       | 0           | 0.0%          |
| Quartz          | 0           | 0.0%          |  | Quartz          | 0           | 0.0%          |
| Chert           | 0           | 0.0%          |  | Chert           | 2           | 1.8%          |
| <b>Total</b>    | <b>101</b>  | <b>100.0%</b> |  | <b>Total</b>    | <b>109</b>  | <b>100.0%</b> |
|                 |             |               |  |                 |             |               |
| <b>Site 2</b>   | Clast count | %             |  | <b>Site 6</b>   | Clast count | %             |
| Sandstone       | 43          | 40.2%         |  | Sandstone       | 37          | 31.1%         |
| Limestone       | 3           | 2.8%          |  | Limestone       | 39          | 32.8%         |
| Igneous         | 3           | 2.8%          |  | Igneous         | 19          | 16.0%         |
| Iron Concretion | 9           | 8.4%          |  | Iron Concretion | 23          | 19.3%         |
| Siltstone       | 34          | 31.8%         |  | Siltstone       | 0           | 0.0%          |
| Quartz          | 3           | 2.8%          |  | Quartz          | 0           | 0.0%          |
| Chert           | 12          | 11.2%         |  | Chert           | 1           | 0.8%          |
| <b>Total</b>    | <b>107</b>  | <b>100.0%</b> |  | <b>Total</b>    | <b>119</b>  | <b>100.0%</b> |
|                 |             |               |  |                 |             |               |
| <b>Site 3</b>   | Clast count | %             |  | <b>Site 7</b>   | Clast count | %             |
| Sandstone       | 28          | 18.8%         |  | Sandstone       | 38          | 34.2%         |
| Limestone       | 3           | 2.0%          |  | Limestone       | 44          | 39.6%         |
| Igneous         | 40          | 26.8%         |  | Igneous         | 9           | 8.1%          |
| Iron Concretion | 28          | 18.8%         |  | Iron Concretion | 16          | 14.4%         |
| Siltstone       | 40          | 26.8%         |  | Siltstone       | 0           | 0.0%          |
| Quartz          | 0           | 0.0%          |  | Quartz          | 1           | 0.9%          |
| Chert           | 10          | 6.7%          |  | Chert           | 3           | 2.7%          |
| <b>Total</b>    | <b>149</b>  | <b>100.0%</b> |  | <b>Total</b>    | <b>111</b>  | <b>100.0%</b> |
|                 |             |               |  |                 |             |               |
| <b>Site 4</b>   | Clast count | %             |  |                 |             |               |
| Sandstone       | 44          | 40.0%         |  |                 |             |               |
| Limestone       | 34          | 30.9%         |  |                 |             |               |
| Igneous         | 13          | 11.8%         |  |                 |             |               |
| Iron Concretion | 12          | 10.9%         |  |                 |             |               |
| Siltstone       | 5           | 4.5%          |  |                 |             |               |
| Quartz          | 0           | 0.0%          |  |                 |             |               |
| Chert           | 2           | 1.8%          |  |                 |             |               |
| <b>Total</b>    | <b>110</b>  | <b>100.0%</b> |  |                 |             |               |

Table 1: Pebble counts from 7 different sample locales along the Belle Fourche and Little Missouri River. To calculate the percentage for each rock type, divide the number of pebbles by the total number of pebbles counted. To calculate the angle of each “wedge” of the pie, multiply 360 by the % of the rock type.



## Cross-sectional Profile A-A' from Figure 3



4. Using your map and the data you generated above, complete the following statements below:

I believe that the northward flowing portion of the Belle Fourche River used to flow

**North to the Little Missouri River**

My evidence for this is:

1. **The gravel composition along the Belle Fourche and Little Missouri River**
2. **The presence of gravel under Stoneville Flats**
3. **The changing widths of the Little Missouri River**

Then, the **Belle Fourche River** was captured by

**A tributary of the Cheyenne River**

My evidence for this is:

1. **The distinct bend in the Belle Fourche River**
2. **The difference in elevations between the Belle Fourche and Little Missouri Rivers**
3. **The composition of the gravels**

As a result, the drainage basin for the Little Missouri River became **smaller**

While the drainage basin of the Belle Fourche River became **larger**

### **PART III: SPEARFISH, SOUTH DAKOTA**

The city of Spearfish, South Dakota sits at the mouth of Spearfish Canyon on the flood plain of Spearfish Creek (Figure 7). There are many strath terraces in this area along with a large, flat plain called Centennial Prairie. Centennial Prairie is underlain by more than of 80 feet of sand and gravel. The southern part of figure 4 is underlain by limestone bedrock incised by streams flowing in narrow, steep-sided canyons. The fluvial deposits across the middle of figure 4 are predominantly underlain by red-beds, while Lookout Peak is capped by a resistant sandstone. The location of many wells can also be found on figure 4.

1. Using the data provided in Table 2, calculate the elevation of the bedrock beneath each of the wells by subtracting the depth to bedrock from the wellhead elevation. Write this elevation next to each corresponding well on the map (Fig. 7).
2. Contour the elevation of the bedrock under Centennial Prairie using 50 foot contour intervals. What do you think the contours indicate?

#### **A buried paleovalley**

3. Use the elevation of the bedrock at wells #16, #17, & #18 to determine the dip direction of the strath underlying the Rapid terrace. Indicate the dip direction on your map using an arrow. Outline this terrace on your DEM as well.
4. Repeat the procedure for the string of Mountain Meadow terraces southeast of Lookout Mountain using the data from wells #10 and #11. Outline these terraces on your DEM.
5. Study the cross-section B-B' on the following page. What is the elevation of Spearfish Creek on the profile? What is the elevation of False Bottom Creek on the profile? Why do you think they are different? (Hint: think about your answer to #3, Part II, Alzada)

**Given the similarities between this site and Alzada, perhaps the capture of Spearfish Creek caused it to incise bedrock, while False Bottom Creek did not due to a loss of discharge.**

6. Write a short summary of the list of events, in chronological order starting with the oldest, which must have conspired to produce the deposits we see today. Be sure that your list can explain the formation of the Mountain Meadow, Rapid and Sturgis terraces, as well as the bedrock trough under Centennial Prairie and the formation of the thick fill terraces under the modern flood plain. Feel free to use neatly drawn labeled arrows on your map or DEM to indicate how you think streams flowed in the past. Be sure to explain the evidence you used to determine the events in your list with a sentence or two.

- 1. Proto-Spearfish Creek flowed to the northeast, forming the Mountain Meadow terraces under wells #10 and #11.**
- 2. At some point in time, stream piracy occurred, forming the Rapid terrace and diverting Spearfish Creek to the northwest.**
- 3. Sturgis terraces formed along Spearfish Creek and on Centennial Prairie.**
- 4. Incision continued, forming the now buried paleovalley under Centennial Prairie.**
- 5. Deposition of fluvial sediments filled up the paleovalley, forming the flat Centennial Prairie.**

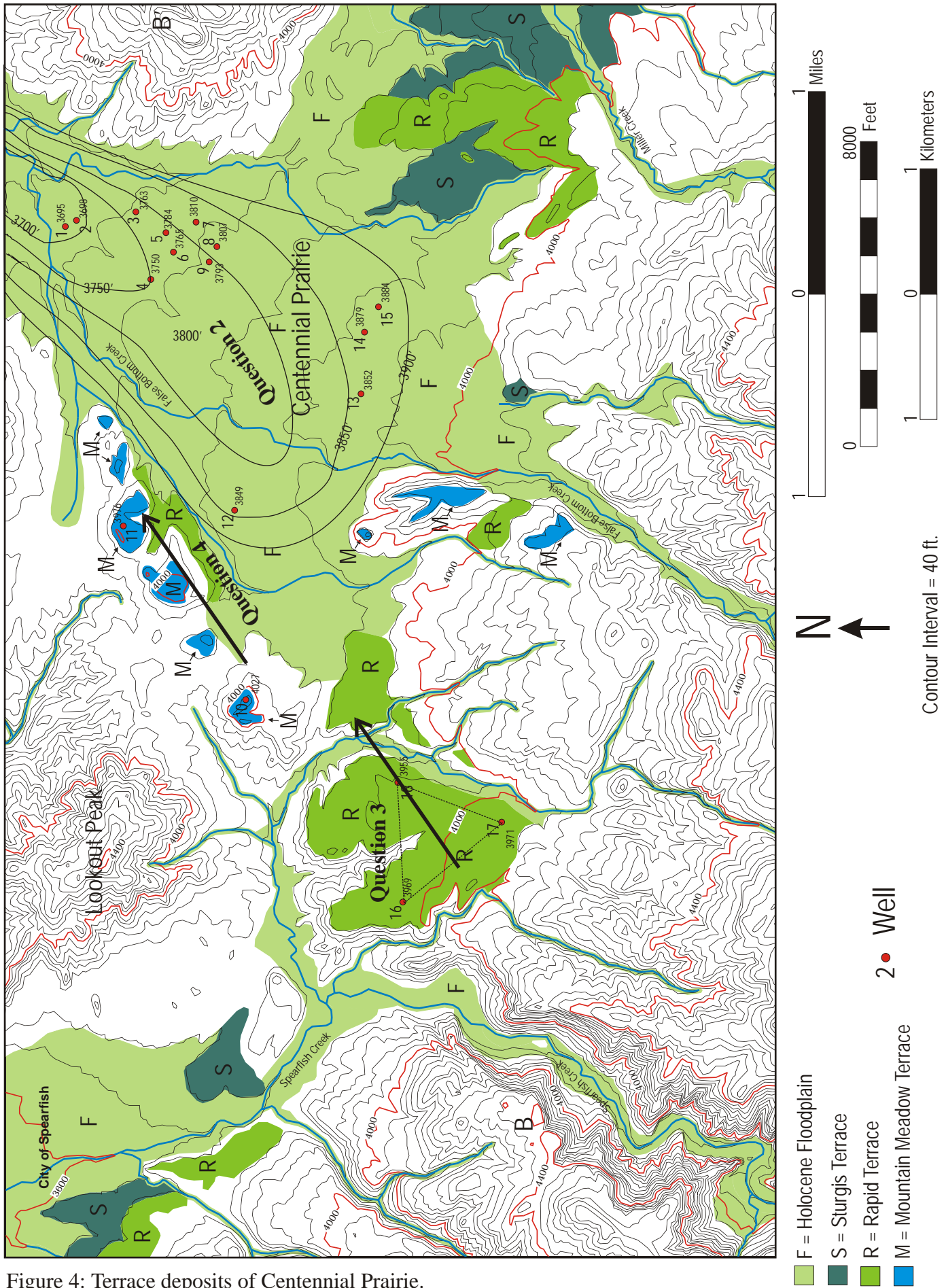
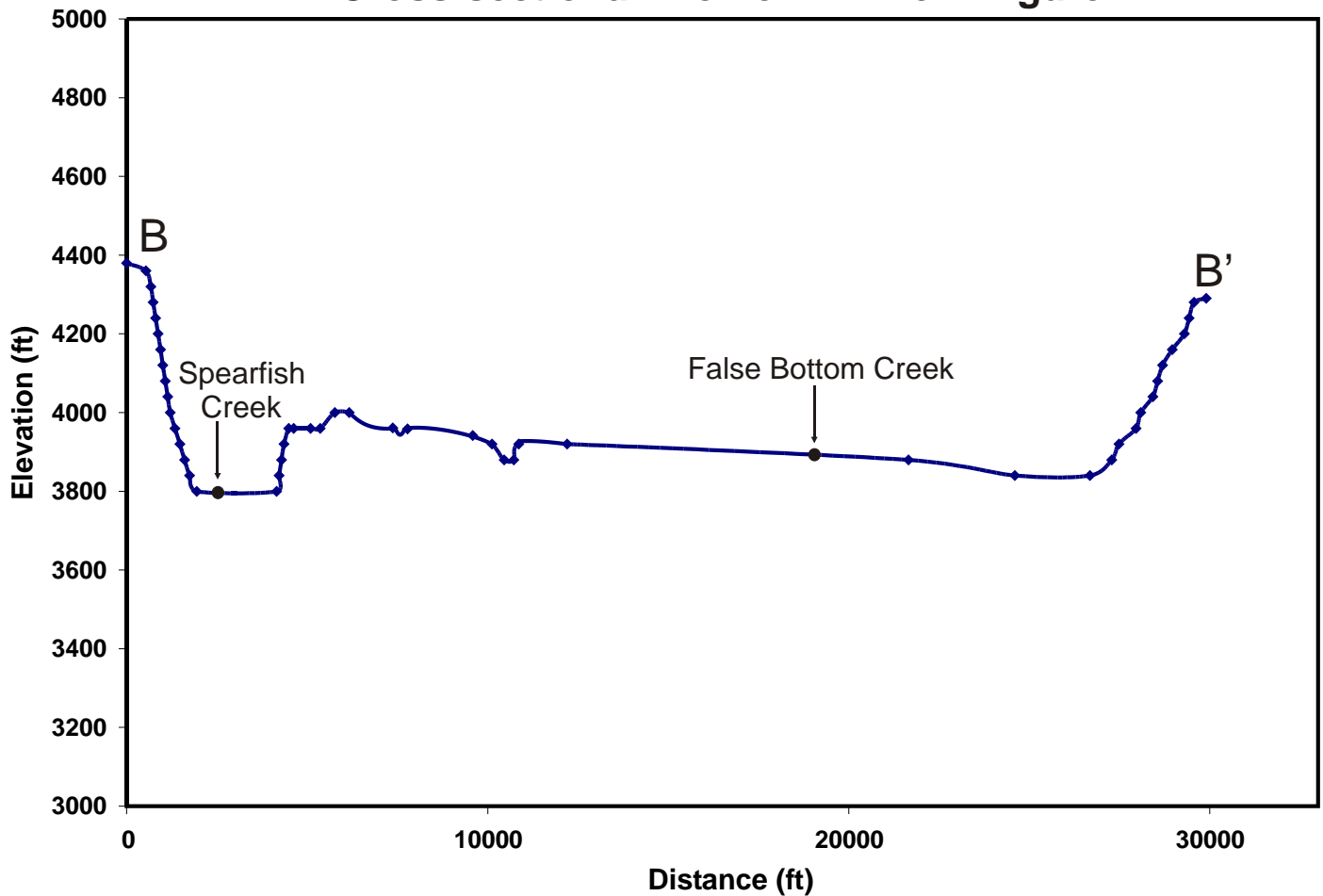


Figure 4: Terrace deposits of Centennial Prairie.

| Well Number | Depth to Bedrock | Wellhead Elevation | Bedrock Elevation |
|-------------|------------------|--------------------|-------------------|
| 1           | 80               | 3775               | 3695              |
| 2           | 80               | 3778               | 3698              |
| 3           | 58               | 3821               | 3763              |
| 4           | 80               | 3830               | 3750              |
| 5           | 45               | 3829               | 3784              |
| 6           | 65               | 3830               | 3765              |
| 7           | 25               | 3835               | 3810              |
| 8           | 38               | 3845               | 3807              |
| 9           | 51               | 3844               | 3793              |
| 10          | 14               | 4041               | 4027              |
| 11          | 12               | 3988               | 3976              |
| 12          | 51               | 3900               | 3849              |
| 13          | 80               | 3932               | 3852              |
| 14          | 45               | 3924               | 3879              |
| 15          | 40               | 3924               | 3884              |
| 16          | 13               | 3982               | 3969              |
| 17          | 41               | 4012               | 3971              |
| 18          | 6                | 3961               | 3955              |

Table 2: Well logs for the Spearfish area. Subtract the Depth to Bedrock from the Wellhead Elevation to calculate the Bedrock Elevation.

### Cross-sectional Profile B-B' from Figure 4



## **PART IV: SUNDANCE, WYO MING**

Sundance, Wyoming sits in a particularly wide area of the Triassic Red Beds (See Figure 5) that has abundant amounts of gypsum present. This area also has many strath terrace deposits with beautifully exposed straths. Because this map is at a much lower resolution than the previous two sections, we have provided the dips of the straths for the larger terraces (Figure 8). The flood plain deposits only occupy narrow zones along the stream channels and have been omitted.

1. Look at the terraces at site A on figure 8. What direction do they dip towards? Which way does the stream with the 90 degree bend flow? What do you think happened here (and why do you suggest it?)

**Since the terraces dip to the southwest, it appears that the stream which formed these terraces was captured, and now flows north.**

2. Observe the Strugis terraces at site B. Do you think it is peculiar that the stream flowing between them ends so abruptly? What does the stream just north of these terraces do?

**Yes. How could large terraces form at the headwaters of a small stream? The stream just to the north of this terrace flows to the northeast, while the terraces dip to the southeast. Piracy probably captured the stream which used to be the source of gravel for those terraces.**

3. Now study the stream directly west of site B. What do you think happen here?

**The distinct 90 degree bend suggests that capture occurred here as well. The stream used to flow in the (now) abandoned valley.**

4. Note the Rapid terraces at site C. What direction do they dip towards? What direction does the stream to the east of the terraces flow? Do you think the stream was there when the terraces were deposited?

**They dip to the north. The stream flows west to east, goes *behind the terraces*, then flows north. When the terraces were deposited, the streams flowed to the northwest out of the Black Hills.**

5. Look at the terrace remnants at site D. What direction do they dip towards? Where does the stream to the northwest of the terraces flow? What happen here (and why do you suggest it?)

**The terraces dip to the west. The stream flows west to east. It is likely that the stream which formed the terraces was reversed during a capture event.**

6. Observe the pattern of the streams at site E. Compare this with the DEM in figure 9. Does something look odd about the stream channel geometry? Explain.

**Yes - the stream flows out of the carbonate bedrock and then turns north, cutting off a "spur" of carbonate bedrock before flowing out into the Red Racetrack. (And then eventually back into the carbonates a second time)**



7. Look at Cold Spring Creek and its tributaries, especially on figure 8. Compare the eastern tributaries with the western tributaries. What do you think caused the difference between each side? Do you think that this event may have impacted the ability of the streams to form large terraces like the older Rapid Terraces in Government Valley?

**The western tributaries are very short, while the eastern ones are long. This suggests that Cold Spring Creek captured and truncated streams which used to flow west into the Red Racetrack. This would cause a cessation in gravel deposition in the Red Racetrack.**

8. Are there any other locations where stream piracy may occur in the future? Show this on the DEM.

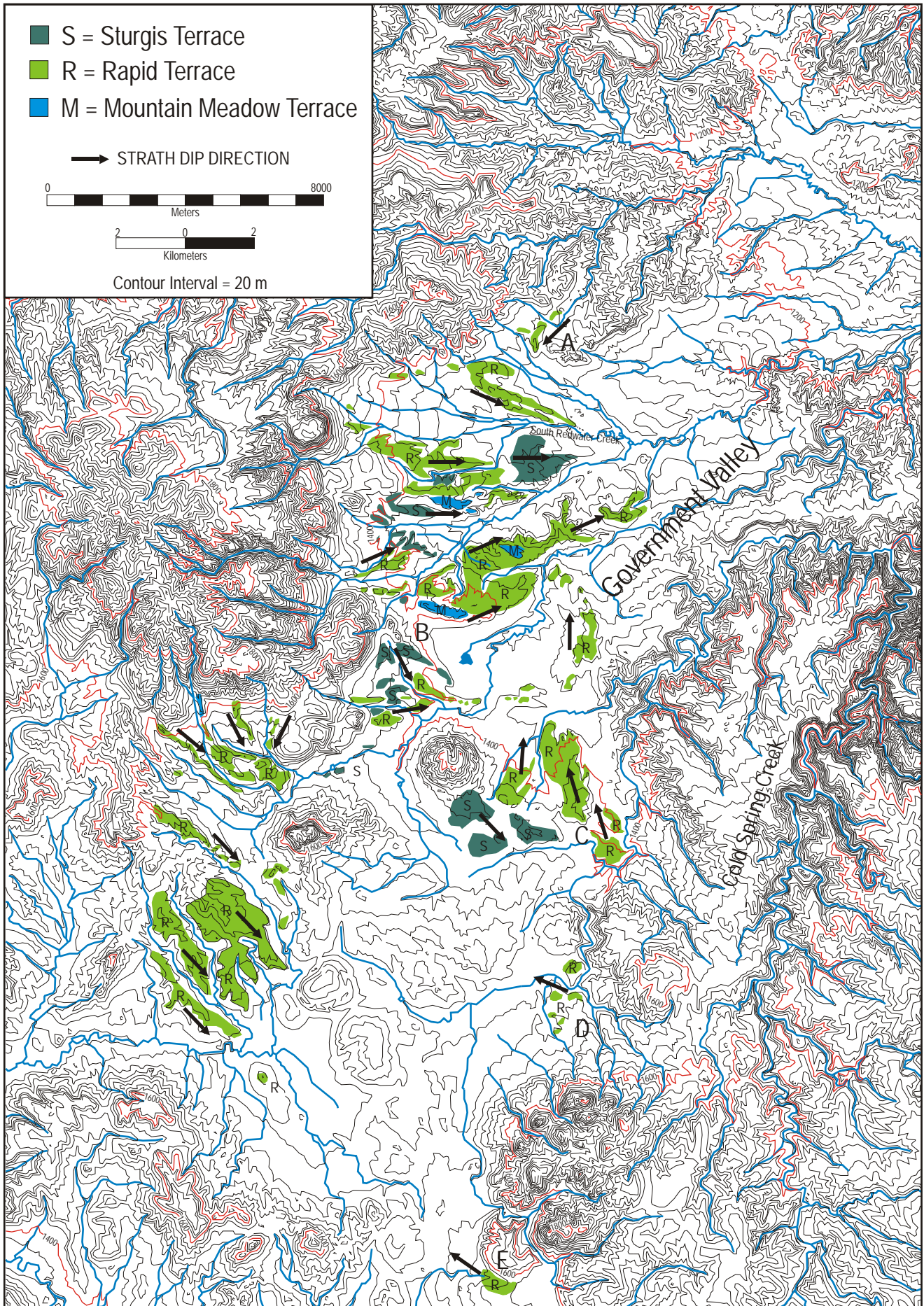


Figure 8: Terrace deposits in the Sundance, Wyoming area.



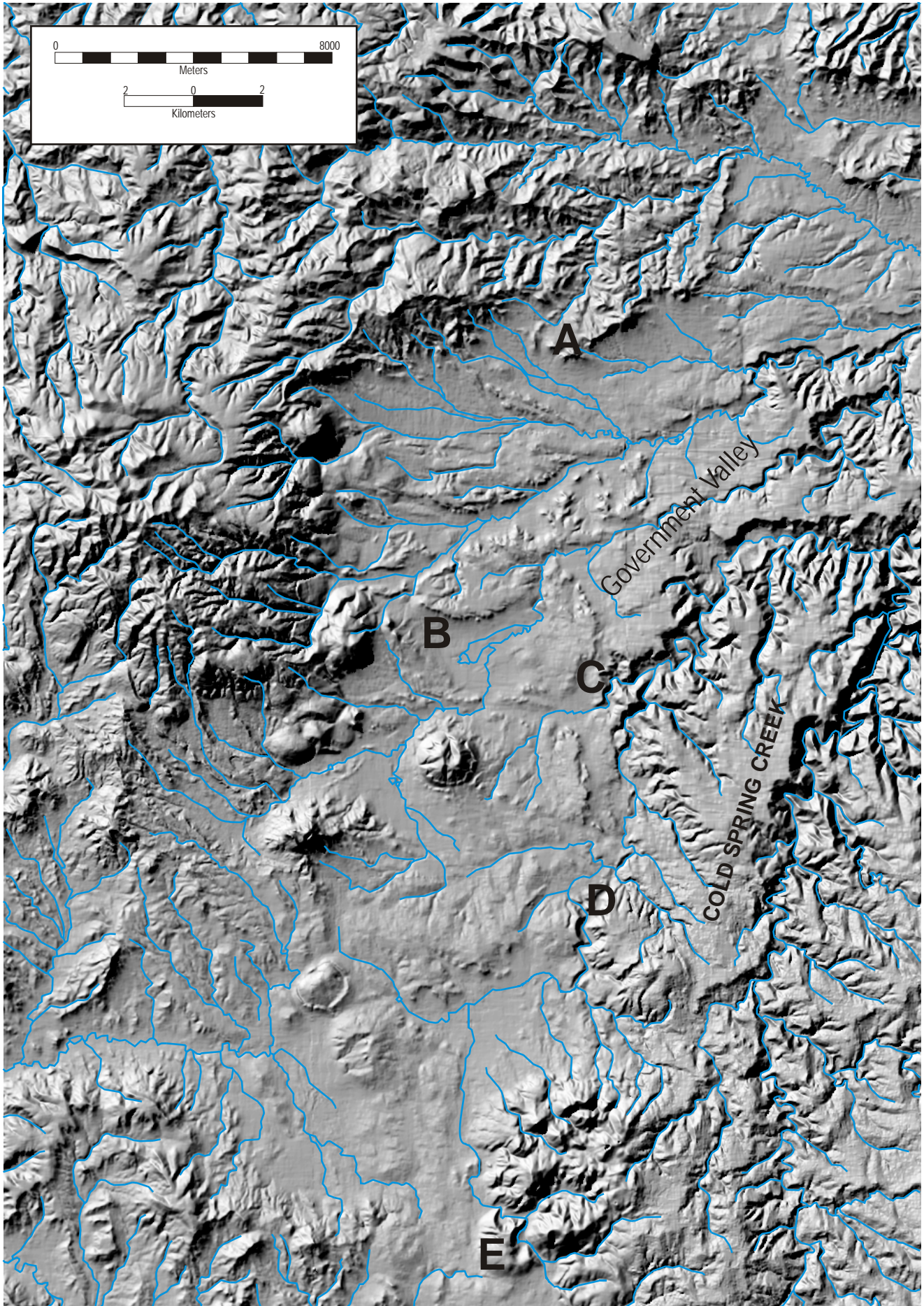


Figure 9: Digital elevation model of the Sundance, Wyoming area.