WYOMING STATE GEOLOGICAL SURVEY
Gary B. Glass, State Geologist

A new look at the Laramide orogeny in the Seminoe and Shirley mountains, Freezeout Hills, and Hanna Basin, south-central Wyoming

by

Jason A. Lillegraven and Arthur W. Snoke

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Laramie, Wyoming

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Front Cover: View to east along crest of ridge dominated by main trace of The Breaks fault system. The left two vertical layers of well-indurated, fine-grained sandstones of the Hanna Formation are only a few hundred feet above the local base of the formation. These sandstones represent the top of the footwall of the fault system; stratigraphic "up" is to the left, and the vertical beds resulted from drag along the base of the hanging wall of the fault. The right-hand layer of vertical sandstone represents the base of the hanging wall of the fault system, and stratigraphic "up" is to the right. The bottom of the hanging wall is more than 3000 feet above the local base of the Hanna Formation. See the discussion on pages 27 - 28 and **Figures 14** and **20**. Photograph by J.A. Lillegraven.

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A NEW LOOK AT THE LARAMIDE OROGENY IN THE SEMINOE AND SHIRLEY MOUNTAINS, FREEZEOUT HILLS, AND HANNA BASIN, SOUTH-CENTRAL WYOMING

Prepared for a field trip on October 24-27, 1996 associated with the

1996 Annual Meeting of the Geological Society of America in Denver, Colorado

by

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Laramie, Wyoming

1996

Acknowledgments

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We are particularly appreciative of the unfailing cooperation that we have received from the following ranchers and land-managers in the Hanna Basin: Victor and Nancy Anderson, Powd and MaryAnn Boles, Bill and Mary Lou Ellis, Bob Faulkner (representing the Miller Estate Company), Frederick and Pat Hoffman, Dick Jarrard, Bob Korkow, Mark E. Miller, Burt and Kay-Lynn Palm, Casey and Nellie Palm, and Gary and Lynn Vivion.

Finally, we thank our long-suffering wives, Linda Lillegraven and Judy Snoke, for their unflagging patience as we have pursued all aspects of this research.

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Abstract

This field trip focuses on the Laramide orogeny in the heart of the Rocky Mountain foreland. We present new information on depositional and tectonic histories of the southeastern flank of the Sweetwater arch (involving parts of the Seminoe and Shirley mountains, Freezeout Hills, and Flat Top anticline) and adjacent northern margin of the Hanna Basin. The relatively minuscule Hanna Basin exhibits a fossil-rich sequence of Upper Cretaceous to lower Eocene marine and nonmarine strata that probably is the thickest syn-Laramide section in the Rockies. New paleontological and structural data allow documentation of a multi-phasic local deformational history, and provide insight to the sequence and nature of tectonic interactions between the basin and its adjacent uplifts. We provide evidence in support of prolonged, sequential, and exquisitely complex Laramide tectonism in south-central Wyoming.

The local base of the Hanna Formation in the northeastern Hanna Basin was deposited late in the early Paleocene, upon deeply eroded flanks of newly formed, enormous, basin-margin anticlines. Final deformation of the radiating, fan-like arrangement of anticlinal/synclinal axes that constitutes the southern Shirley Mountains, Freezeout Hills, and Flat Top anticline occurred early in Eocene time, following deposition of most of the Hanna Formation. At that time, the southern or western ends of the anticlinal axes existing at the structural margin of the Hanna Basin steepened their plunges nearly to vertical, or even beyond. Strata of the basin margin commonly became overturned, and a vast, complex series of out-of-the-basin thrusts developed within the extraordinarily thick Upper Cretaceous and Paleogene section of the northern basin. Although the northern Hanna Basin itself represents the hanging wall for this late deformation, the tectonically more active component of the system was the footwall (*i.e.*, the southern Shirley Mountains and Freezeout Hills).

Associated with closing phases of local Laramide deformation along the northeastern basinal margin was extensive development of faults having components of oblique-slip separations that cumulatively totaled several kilometers. Our new geologic mapping requires major revision of the standard interpretation of the "Shirley thrust." This fault, as exposed at the surface, is a basement-involved, high-angle reverse fault that terminates in a tight fold in Upper Cretaceous strata immediately east of the southeastern corner of the Shirley Mountains. More easterly parts of what has been mapped previously as the "Shirley thrust" are in reality out-of-the-basin thrust faults, directed northward rather than southward (as required under standard interpretation of the "Shirley thrust").

We are evaluating two main hypotheses in explanation of uplift of the Seminoe-Shirley mountains and Freezeout Hills. One hypothesis is based upon postulated existence of a blind, deep Shirley thrust (*i.e.*, a new sense of a Shirley thrust) that served as a controlling, master fault for the high-angle Shirley fault (in the sense of this paper, and seen to be of limited extent). Other locally important, relatively high-angle faults that reach the surface may represent additional splays off a deep, shallowly dipping, presently hypothetical, master fault.

An alternative interpretation explains much of the uplift of the Seminoe and Shirley mountains and Freezout Hills, including Flat Top anticline, through contractional strain related to development of the fan-like array of west or northwest-vergent, faulted, asymmetric anticlines that constitute the southeastern margin of the Sweetwater arch. Axial ribs of the anticlinal fan converge geometrically to roughly a common point within the northeastern corner of the Hanna Basin. This scenario requires significant left-lateral transfer of the Shirley Mountains-Freezeout Hills terrane relative to the northern margin of the Hanna Basin, possibly along traces of the out-of-the-basin thrusts.

These two main hypotheses are not mutually exclusive. Indeed, evidence exists to support the concept that both scenarios played important roles in structural development of the Seminoe-Shirley mountains, Freezeout Hills, and Flat Top anticline in relation to the northern Hanna Basin.

Road directions to the various stops

Day one of field trip

Route to Stop 1–"Tepee-ring Ridge"

From Medicine Bow, drive west 2.4 miles on U.S. Highway 287 (= U.S. 30, part of the pre-Interstate Lincoln Highway) to the intersection with Carbon County Road 121 (indicated on the topographic map of the Como East 7.5-minute Quadrangle as the Medicine Bow-Difficulty road). See map on **Back cover** and page 8 for location of field trip stops.

Turn right (north) on Road 121 (unpaved, and extraordinarily awful if soaked). Travel 8.3 miles north and northwest (ignoring smaller side-roads) until reaching the top of a steep downgrade that leads to a bridge that crosses the Medicine Bow River. A yellow road sign heralds approach to the downgrade.

Immediately before the steep downgrade, turn left (west) to join a not very obvious two-track that soon comes to a closed gate at the edge of private land. With prior permission, follow the two-track west (onto the Como West 7.5-minute Quadrangle) almost to the road's end, near the SW corner of section 3, T23N, R80W. The final few hundred yards of this road is badly eroded, and should not be driven. Park, and climb the short distance up to the viewpoint (Stop 1) at the eastern crest of the ridge (here dubbed "Tepee-ring Ridge") seen immediately to the north.

Route to Stop 2–Sledge Creek

Retrace the two-track from Stop 1 and return to Carbon County Road 121. Turn left onto the graveled road. From the top of the steep grade, follow the county road down to the old steel bridge that crosses the Medicine Bow River (1.5 miles). After crossing the bridge, continue west on the main road 1.1 miles, to the point at which the power lines cross the road. With prior permission, turn right (north) onto the two-track that crosses private land, initially close to the path of the power lines. The two-track leads toward the mouth of an obvious canyon, which on the Difficulty 7.5-minute Quadrangle map is labeled "Sledge Creek." Park south of the fence line, at the south end of the large stock dam (near the SW corner of section 26, T24N, R80W). A half-mile hike to the north from here constitutes Stop 2.

Route to Stop 3–Beer Mug anticline

Backtrack from Stop 2 to Carbon County Road 121 and turn right (west) onto it. About two miles down the road drive past the small airfield seen to the south. Disregard the right-hand branch of the road (just before the cattle guard) that goes north toward the headwaters of Difficulty Creek. A short distance west of the airfield the county road dips sharply downward into the valley of Difficulty Creek. Buildings of the Beer Mug Ranch are situated immediately east of the creek. From Difficulty Creek, continue 0.5 mile west on the graveled road. With prior permission, turn right (north) onto the two-track that crosses private land northward toward the southwest corner of the (strikingly obvious) Beer Mug anticline. Park just west of the center of section 20, T24N, R80W. (Difficulty 7.5-minute Quadrangle). A short hike to the east leads to the focus of Stop 3 (south flank of Beer Mug anticline).

Route to Stop 4–"The Breaks fault system" in The Breaks

Backtrack from Stop 3 to Carbon County Road 121 and turn right (west) onto it. Drive 4.7 miles west on the main graveled road, ignoring the multiplicity of side-road alternatives, until a complex intersection of roads is encountered, immediately beyond a cattle-handling facility that abuts the north edge of the road. At this point, Road 121 joins County Road 291, known locally as the Hanna-Leo road. Directions for Day 2 of our trip begin from this intersection (in the SE extreme of section 21, T24N, R81W, TE Ranch 7.5-minute Quadrangle).

At intersection of Roads 121 and 291, turn left (south) on Road 291, leading toward the town of Hanna, and continue 1.9 miles to the cement bridge at the Medicine Bow River. The first part of the road parallels cultivated farmland (west of the road) in the floodplain of Troublesome Creek. Continue past the cattle guard (adjacent to coaly strata of the Hanna Formation at the crest of a hill, in a narrow pass) and follow the main road southeastward along the north bank of the Medicine Bow River.

Cross the Medicine Bow River. Starting up the hill, roughly 0.3 mile south of the bridge, turn left (east) off the Hanna road onto a narrower road (the so-called MetFuels road).

Follow the steep, winding, main course of the MetFuels road (generally southeastward) up the hill, for 2.0 miles. At that point, the road is headed due south. Turn diagonally left off the MetFuels road onto a relatively indistinct two-track. Just beyond this point, private land is encountered once again.

With prior permission, negotiate the plexus of two-track ranch roads to the west-central edge of section 4, T23N, R80W (Como West 7.5-minute Quadrangle). The last two miles of this journey should not be attempted in the absence of a four-wheel drive vehicle, or during wet conditions. A short hike to the northwest leads to Stop 4.

Day two of field trip

Route to Stop 1–Eastern termination of Shirley fault, and Smith Creek anticline

Directions begin at the complex intersection of Carbon County Roads 121 and 291, as described above in the section for Day 1 entitled "Route to Stop 4 . . . ."

From the intersection, drive west on Carbon County Road 291 for 0.6 mile, to the side-road that leads northward. A sign announces the distance (4 miles) to the 9V ("Nine-Vee") Ranch. The present 9V Ranch is the former "TE Ranch" indicated on the 7.5-minute topographic quadrangle of that name. The main road soon enters privately owned land. With prior permission, follow the road, which wanders northward and westward, for 4.2 miles to the two-story, main house of the 9V Ranch (in SE of section 6, T24N, R81W). Immediately north of that building, turn west and follow the two-track, through the gate, for 0.4 mile, toward the south-eastern extreme of the Shirley Mountains. A short hike to the south, crossing Smith Creek, leads to Stop 1.

Route to Stop 2–Out-of-the-basin thrusts between Schneider and Horseshoe ridges

From Stop 1, backtrack on the 9V Ranch road to Carbon County Road 291 (Hanna-Leo road). Turn right, and drive 11.2 miles westward, then northward to cross Austin Creek, just beyond the now-defunct Austin Creek School. This entire leg traverses steeply dipping strata of the undifferentiated Ferris/Hanna Formation. Continue north 1.0 mile from the bridge at Austin Creek, and park on the wide shoulder on the southeast side of the road (north-central part of section 12, T24N, R83W, Schneider Ridge 7.5-minute Quadrangle). Short hikes to the west and northeast lead to various subjects related to Stop 2.

Route to Stop 3–Plunging anticline at eastern extreme of Seminoe Mountains

From Stop 2, follow the winding Hanna-Leo road northward and westward for 6.0 miles, and park within sight of the east-plunging, basement-involved, anticlinal nose of the eastern Seminoe Mountains. A short hike leads to an overview site situated on Mississippian Madison Limestone at the eastern extreme of the Seminoe Mountains. We will begin our discussion at this locality.

Day three of field trip

Route to Stop 1–Oil Springs/Flat Top anticlines

From the intersection of U.S. Highway 287/30 and State Highway 487 in Medicine Bow, drive 7.7 miles northward on Highway 487. Turn left (west) onto the Oil Springs graveled road. Continue west for 3.3 miles until the main road makes an almost 90° bend to the south. At that point, follow the diverging, less traveled road westward. Drive about 0.6 mile and park. We are situated along the northern flank of the Oil Springs anticline, near its eastern terminus.

Route to Stop 2–Relatively undeformed Upper Cretaceous section at Pine Draw

From Stop 1, return to the town of Medicine Bow, backtracking on the Oil Springs road and Highway 487.

From Medicine Bow, once again drive 2.4 miles westward on U.S. Highway 287 to Carbon County Road 121 (as though repeating the drive toward Stop 1 of Day 1).

Again, turn right (north) on Road 121. But this time proceed northward only 5.5 miles, to the two-track road heading west just beyond the giant road-culvert for Pine Draw (south-central part of section 17, T23N, R79W; Como East 7.5-minute Quadrangle). The two-track crosses private land. With prior permission, drive west past the first set of outcrops (sandstone slabs in upper parts of the Steele Shale), then southwest to park at the outcrops of massive white sands (base of Haystack Mountains Formation). A half-mile hike to the west, along spectacular outcrops of the entire Mesaverde Group, constitutes Stop 2.

Where are we?

Welcome to the southeastern flank of central Wyoming's Sweetwater arch (= Sweetwater uplift, Blackstone, 1993a; = Granite Mountains, Love, 1970) and adjacent northern rim of the Hanna Basin. We are in the heart of the Rocky Mountain foreland (**Figure 1**), a region characterized by broad, asymmetric basement arches (Blackstone, 1993b; Erslev, 1993) that, along thrust and/or reverse faults, commonly overrode adjacent rims of rapidly subsiding, syntectonic depositional basins ("Laramide-style" deformation; Hamilton, 1981; Brown, 1988, 1993).

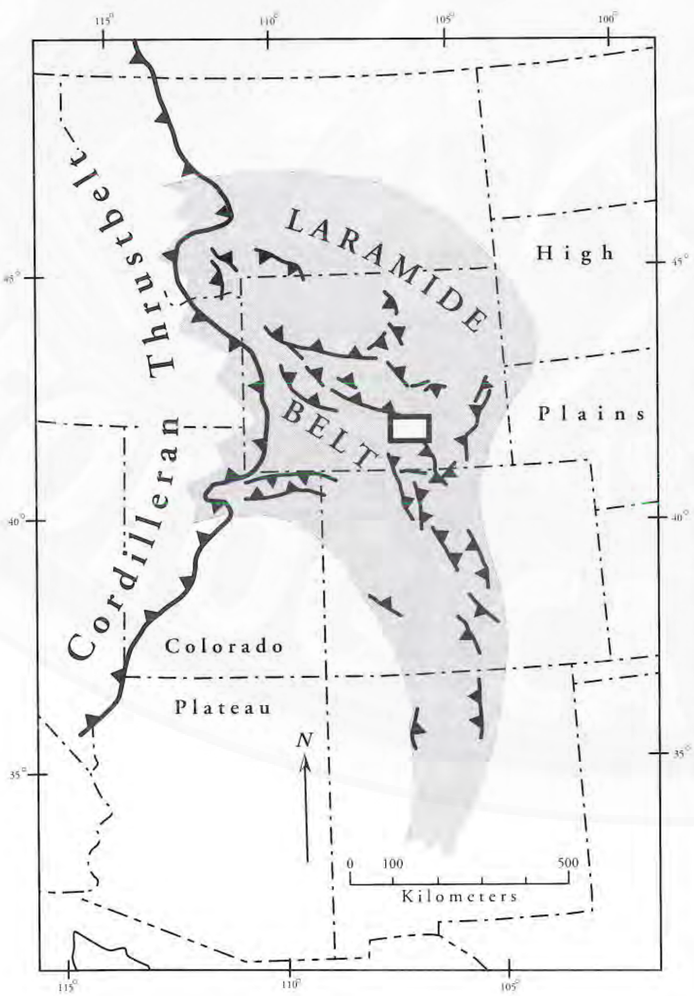


Figure 1. Reference map of the North American Western Interior, showing distribution of Laramide-style deformation during the Laramide orogeny. Rectangle indicates vicinity of Hanna Basin, the focus of this excursion, in the heartland of Laramide tectonics. Modified from Hamilton (1981).

Our field trip will focus upon available knowledge of the complex depositional/tectonic histories, during the Laramide orogeny (for usage and plate-tectonic setting, see Snoke, 1993), of: (1) eastern extensions of the southeast-plunging Sweetwater arch; and (2) northern Hanna Basin. All stops are in Carbon County.

Prime goals of the trip

The Hanna Basin is areally minuscule relative to other foreland basins of Wyoming (see Love and Christiansen, 1985). Within the basin is exposed an enormously thick, locally fossil-rich sequence of Upper Cretaceous to lower Eocene marine and nonmarine strata (Cardinal and Parsons, 1982); probably, this is the thickest syn-Laramide section in the Rockies. Parts of the sedimentary sequence of the northern Hanna Basin were affected by the same basement-involved faulting and folding that is seen more obviously in adjacent mountain blocks. Data from both areas document a multi-phasic deformational history during the Laramide orogeny, and provide excellent examples of tectonic interactions between basin and adjacent uplifts. One prime goal of the field trip is to illustrate the nature of evidence in support of prolonged and sequential Laramide tectonism in south-central Wyoming. Relatedly, the extraordinarily thick, complete, and locally well-exposed Cretaceous sedimentary sequence along the northern Hanna Basin provides an excellent platform for discussion of criteria that might be used to recognize the beginning of the Laramide orogeny.

Another prime goal of this trip is to emphasize the importance of interdisciplinary research to interpret the local Laramide story. This specific geographic area has yielded exciting new discoveries that illuminate the relevance of integrated research in vertebrate paleontology, physical stratigraphy, and structural geology. Central questions on the paleogeography of the Rocky Mountain Laramide foreland will be a unifying theme, with emphasis upon new data relevant to interpretation of the local nature and timing of physical evolution of the ancient landscape. Stops on the trip will allow examination of specific examples, derived from recent field work, of the integration of new paleontological and geological data, directly linked between the northern Hanna Basin and its marginal uplifts.

Yet another goal is to provide a coherent update of geologic knowledge of the local area beyond what is portrayed in existing literature and published maps. We have discovered much that is new, and our tectonic interpretations differ markedly from those found in existing publications. The local tectonic picture is exquisitely more complex than previously appreciated. The concept of a single vector of regional shortening during the Laramide orogeny, for example, is questioned and challenged through the structural chronology that we have deciphered in the areas of the field trip. On the outcrop, we will attempt to contrast newly discovered local relationships of deformed elements of the basement and strata with general tectonic models of the Rocky Mountain foreland (*e.g.*, Gries, 1983a, b; Brown, 1988, 1993; Erslev, 1993).

A final goal of this trip is for the principal investigators themselves to benefit from questions, geologic criticisms, and insights that surely will issue from fresh observations made by other participants.

Miscellaneous practical items concerning the itinerary

Despite the small, relatively human scale of the Hanna Basin, satisfactory appreciation of the stops described below requires at least two-and-a-half days in the field. Part of the travel is on unpaved public roads built upon bentonite-rich Upper Cretaceous marine strata. If roads are wet, four-wheel drive vehicles with good clearance may be necessary. Driving to most of the stops should not be attempted under soaked conditions. Rattlesnakes, by the way, are common during summer months at all localities to be visited.

Significant parts of our trip will cross privately owned lands. Access requires special permission from local ranchers. For mutual protection of all, we provide neither specific mileages nor detailed descriptions for travels on two-track roads that cross privately owned sections.

Home-base for our excursion is the village of Medicine Bow. Beginning mileages reported are from the intersection of U.S. Highway 287 (= U.S. Highway 30) and Wyoming State Highway 487, near the town's west end.

Actually getting to Stop 4 on the trip's first day raises a minor dilemma. Stop 4 is less than 1.5 map miles from Stop 1. Stop 4 can be reached on foot from Stop 1 without great difficulty, for those who are physically fit. Indeed, if local conditions are wet, it may be necessary to hike directly from Stop 1 to Stop 4. The two sites are separated by rugged topography, however, involving several repetitions of sharp climbs and descents. An especially steep final ascent would be necessary upon return from Stop 4 to the parking area near Stop 1. On the assumption of fine, dry conditions, we suggest that it is more cost-effective in time and personal energy to drive to Stop 4 from Stop 3, as described in the road log.

Day one of field trip

Stop 1–Vista of northeastern corner of Hanna Basin from "Tepee-ring Ridge" at brink of The Breaks

The discussion in the field begins near center SW of section 3, T23N, R80W.

Geographic introduction

This is among the best of viewpoints for gaining general geographic impressions of the northeastern corner of the Hanna Basin and diverse local uplands (see **Figures 2-4**). Looking to the north, immediately beyond the valley of the Medicine Bow River, is the south flank of the Freezeout Hills. Exposed is a sequence of complexly folded Paleozoic and Mesozoic strata (Taylor, 1996; **Figures 5-7**). The Precambrian basement is exposed only at the western extreme of the Freezeout Hills, on the western flank of Bald Mountain (Prucha and others, 1965; Van Ingen, 1978). Today's Stop 2 (Sledge Creek) is at the deepest canyon cutting through the generally south-dipping walls of the southern Freezeout Hills.

To the west of the Freezeout Hills is the broad, semi-forested, rather flat-topped southeastern quadrant of the Shirley Mountains. In contrast to the Freezeout Hills, the great bulk of the Shirley Mountains is eroded deeply into its Precambrian core (Bergh and Snoke, 1992). A veneer of Paleozoic and lower Mesozoic strata dips eastward along the east flank of the Shirley Mountains. The southern extreme of that veneer constitutes Stop 1 of Day 2. Immediately south of the southeastern corner of the Shirley Mountains can be seen a small white mesa, known as Chalk Bluff. This is an erosional remnant of the northern Hanna Basin's post-orogenic sedimentary record (Knight, 1951).

The rugged, relatively high peaks on the distant skyline west of the Shirley Mountains are parts of the Ferris Mountains. The Seminoe Mountains, situated between the Ferris and Shirley mountains, are not visible from this viewpoint, being hidden behind the Shirleys. The east-west elongated terrane involving the Ferris, Seminoe, Shirley, and Freezeout uplifts collectively forms the topographically most obvious components of the southeastern flank (and eastern nose of the Sweetwater arch.

A tectonically related but topographically less dramatic addition to this series of uplifts continues to the southeast from the Freezeout Hills, across the rolling landscape. Specifically, we refer to a series of *en echelon*, basement-involved, asymmetric, major anticlines, the axes of which have northeast-southwest alignments (**Figure 2**). The two largest, and most northerly of these include the Flat Top and Como Bluff anticlines (Dunbar, 1944; Blevens, 1984; Blackstone, 1983, 1993a). Como Bluff itself, renowned as a dinosaur graveyard (Ostrom and MacIntosh, 1966), is the exposed core of the Como Bluff anticline. The red-maroon bluff, composed principally of the Morrison Formation, can be seen just east of the village of Medicine Bow. Oil Springs anticline (Blevens, 1984; Blackstone, 1994) is a much smaller structure, which we will discuss as a tectonic special case. Its axis is oriented west-northwest to east-southeast. Oil Springs anticline is seen immediately north of the west end of Flat Top, with which it has oblique intersection. Oil Springs and Flat Top anticlines constitute Stop 1 of Day 3.

Between our present viewpoint and the west end of Flat Top anticline, the strike of steeply dipping strata of the Hanna Basin's northern margin begins a sharp turn to the southeast, and then to the south. This curve represents the true structural northeastern extreme of the Hanna Basin. Local Cretaceous stratigraphy at the curve's eastern flank was dramatically affected by the evolution of Flat Top anticline, as will be discussed at Stops 1 and 2 of Day 3. For purposes of orientation, the hike associated with Stop 2 of Day 3 will end at the piney ridge (north of Pine Draw), seen about three miles to the southeast of our present viewpoint.

On the eastern skyline can be seen the generally subdued profile of the Laramie Mountains, a direct continuation of more spectacular eastern components of Colorado's Front Range. The sharply defined high point toward the north end of the Laramie Mountains is Laramie Peak, situated roughly 60 miles southeast of Casper, Wyoming. Between the Laramie Mountains and the Freezeout Hills, and to the north of Como Bluff anticline, is the greater

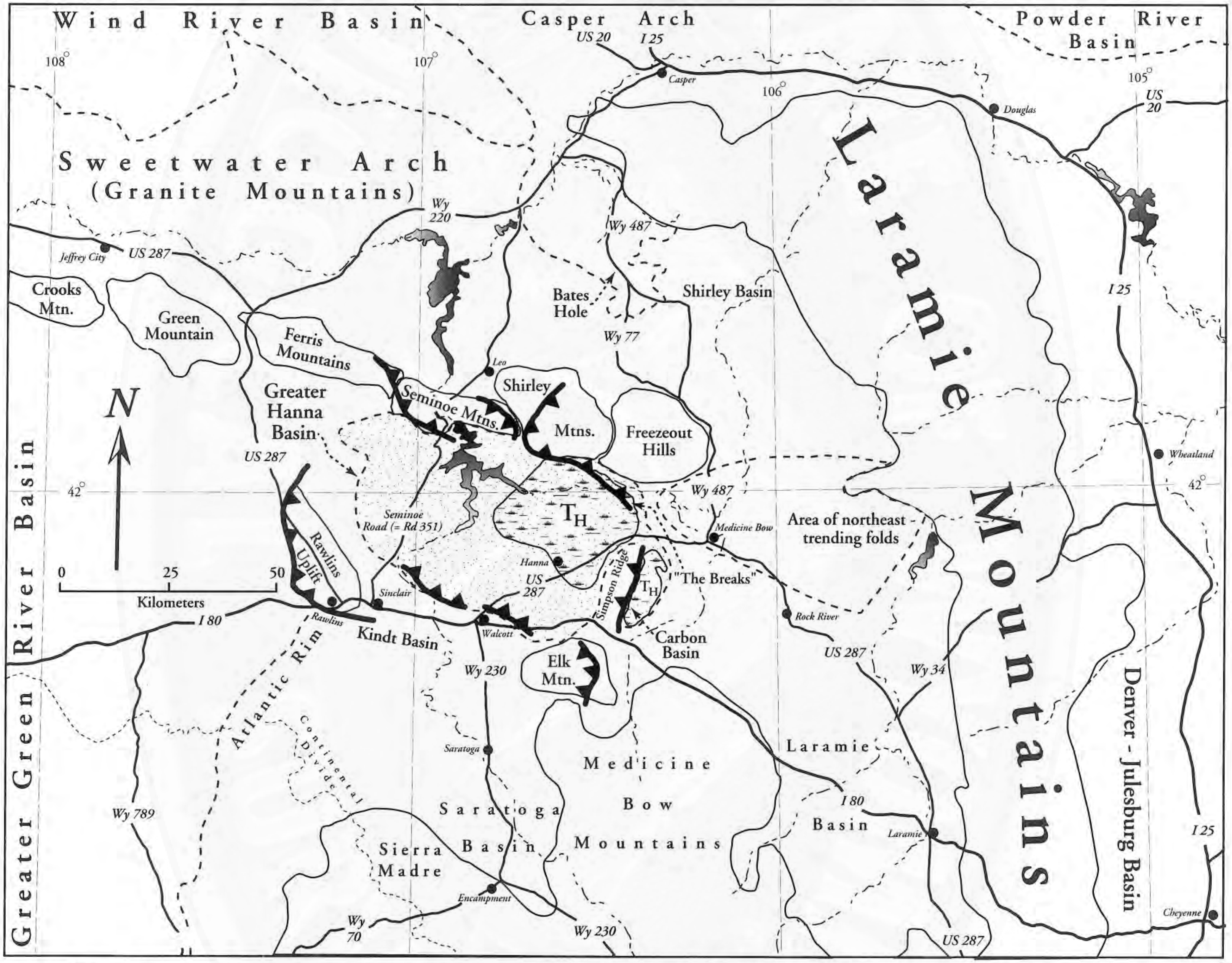


Figure 2. Reference map of central Wyoming, emphasizing principal tectonic features surrounding the focus of this trip. The map symbol applied to the Laramide-style thrust fault indicated along the southern flank of the Shirley Mountains expresses the standard interpretation of the "Shirley thrust;" one purpose of this excursion is to re-examine the nature of this fault-system. The map symbol T_H indicates approximate distribution of the mainly Paleocene Hanna Formation. Modified from Lillegraven (1994).

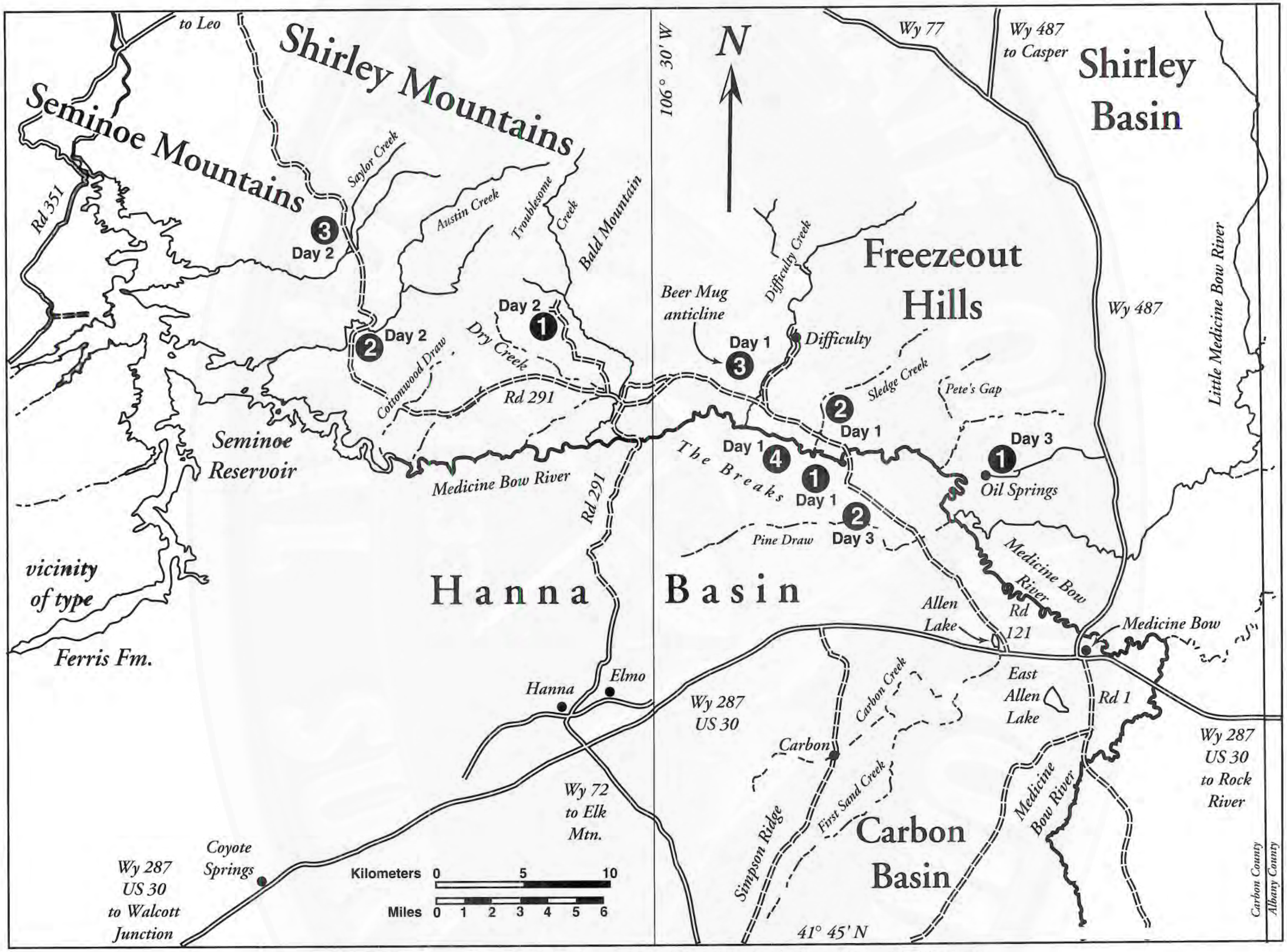
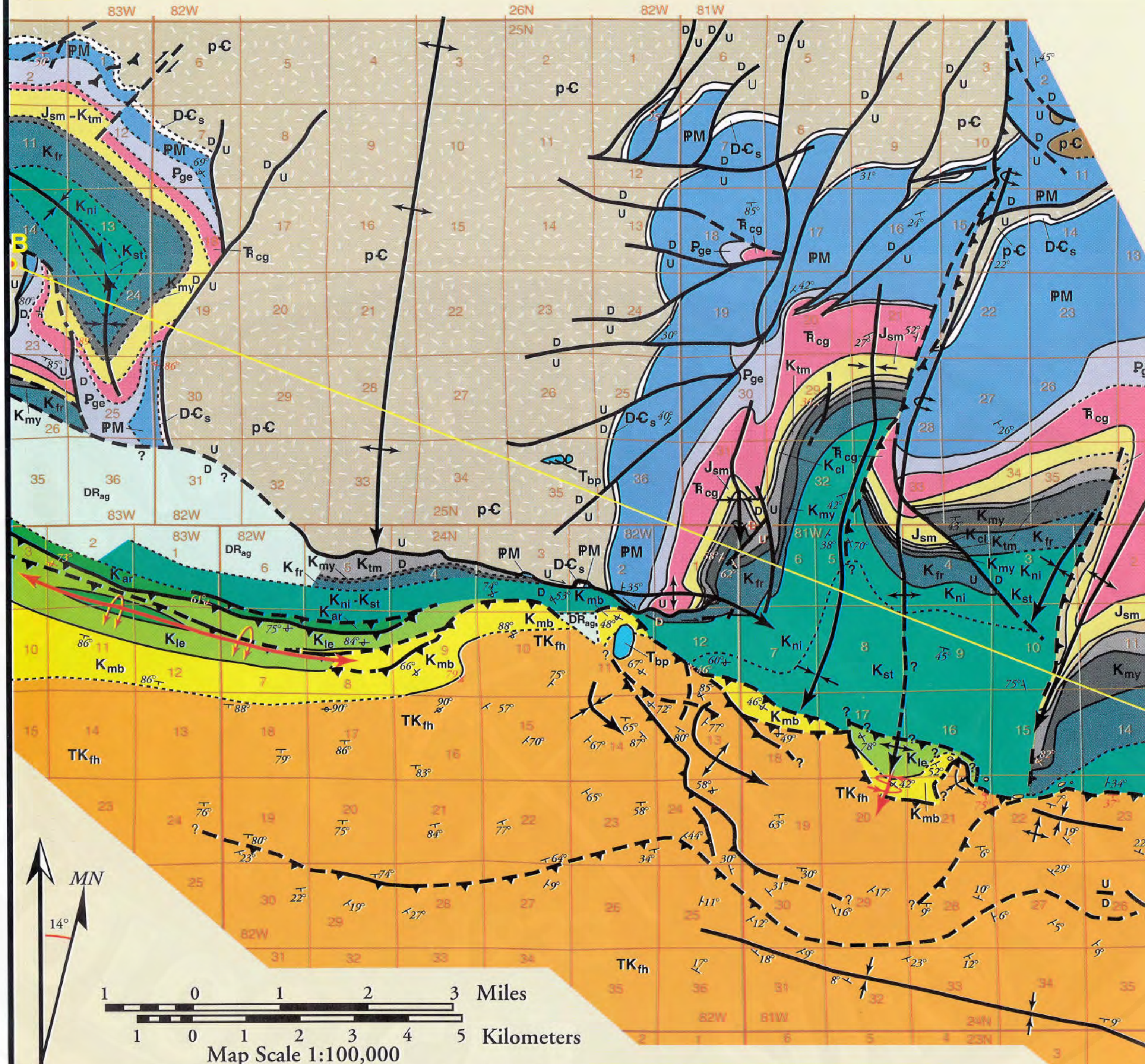


Figure 3. Geographic reference map and summary of day-by-day field trip stops discussed in this paper.



Basemaps: (USGS) Shirley Basin, Wyoming (1981) and Medicine Bow, Wyoming (1980)

Geologic Map of Northern Hanna Basin and Adjacent Parts of Shirley Mountains and Freezeout Hills, Carbon County, Wyoming

1996

Compiled by Jason A. Lillegraven

(Geologic Data from D. M. Blevens, Jr., A. Braathen, J. A. Lillegraven, A. W. Snoke, D. A. Taylor, and

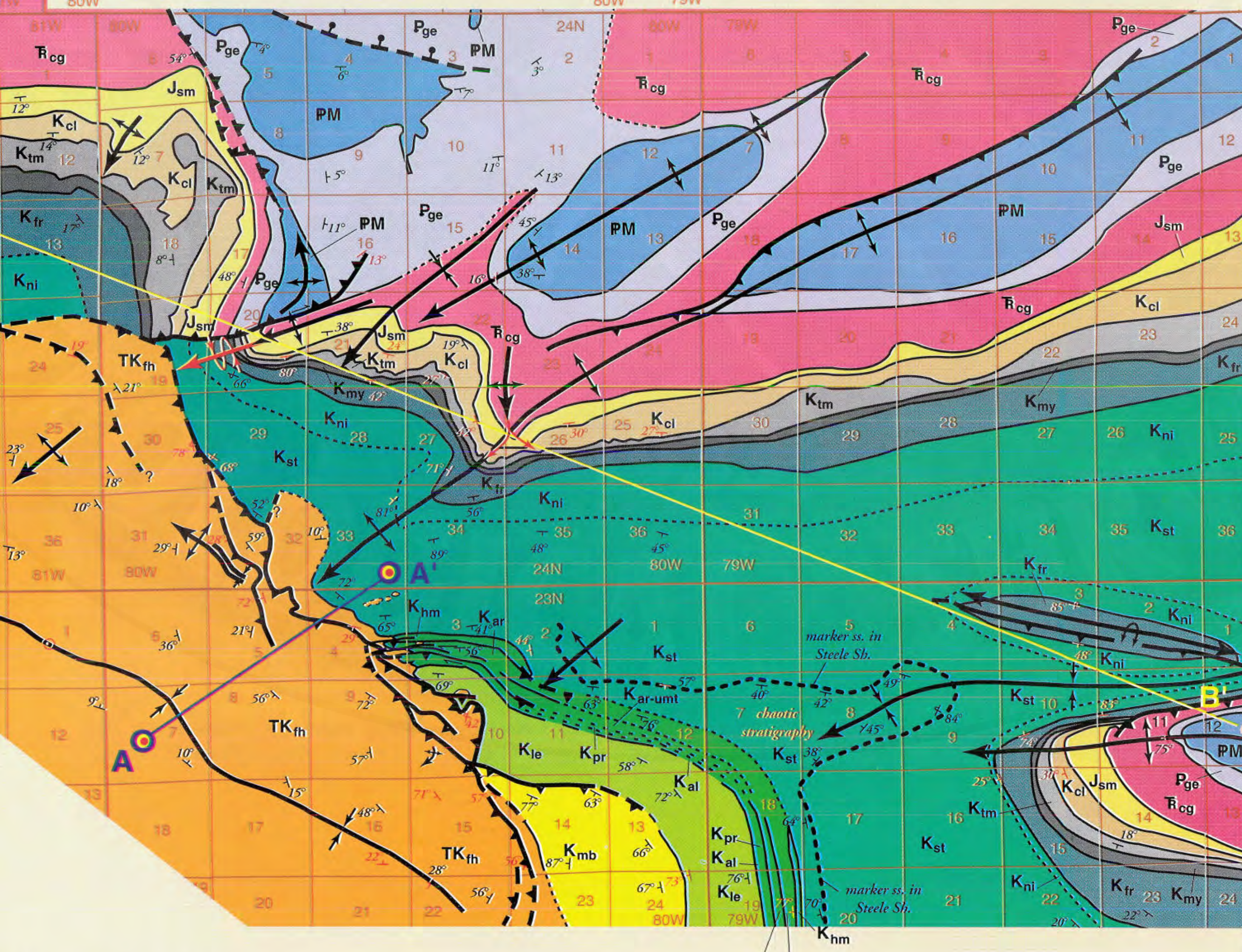
EXPLANATION

Rock Units:

	DR_{ag}	Area inadequately mapped
? Neogene	T_{bp}	? Browns Park Fm.
[C]retaceous & Paleogene	TK_{fh}	Ferris and Hanna fms., undivided
Cretaceous	K_{mb}	Medicine Bow Fm.
	K_{le}	Lewis Sh.
Mesaverde Group	K_{al}	Almond Fm.
Mesaverde Group	K_{pr}	Pine Ridge Ss.
Mesaverde Group	$K_{ar\text{-}umt}$	Unnamed marine tongue of Allen Ridge Fm.
Mesaverde Group	K_{ar}	Nonmarine facies of Allen Ridge Fm.
Mesaverde Group	K_{hm}	Haystack Mountains Fm.
	K_{st}	Steele Sh.
	K_{ni}	Niobrara Fm.
	K_{fr}	Frontier Fm.
	K_{my}	Mowry Sh.
	K_{tm}	Thermopolis Sh. and Muddy Ss., undivided
	K_{cl}	Cloverly Fm.
Jurassic	J_{sm}	Sundance and Morrison fms., undivided
Triassic	Ŧ_{cg}	Chugwater Gp., including Red Reak Fm., Alcova Ls., and Jelm Fm., undivided
Permian	P_{ge}	Goose Egg Fm.
Pennsylvanian / Mississippian	IPM	Madison Ls., Amsden Fm., and Tensleep Ss., undivided
Devonian or Cambrian	$D\text{-}C_{s}$	Fremont Canyon Ss. or Flathead Ss.
Precambrian	p-C	Precambrian rocks, undivided

Geologic Symbols:

- Stratigraphic contact, dashed where approximate
- Horizontal bedding
- 23° Strike and dip of bedding
- 90° Strike and dip of vertical bedding
- 67° Strike and dip of overturned bedding
- Trace of plunging anticline
- Trace of plunging synformal anticline
- Trace of overturned plunging anticline
- Trace of plunging syncline
- U D High-angle fault, dashed where approximate, relative sense-of-displacement indicated
- Thrust fault, dashed where approximate
- Normal fault, ball and bar on downthrown side



... B. Van Ingen III)

Period/Epoch	Thickness m	Thickness ft	Stratigraphic Unit	Group
? Neogene	310	1,015	? Browns Park Formation	
Paleocene - earliest Eocene	3,550	11,650	Hanna Formation	
Cretaceous - early Paleocene	1,980	6,494	Ferris Formation	
Cretaceous	2,054	6,737	Medicine Bow Formation	
Cretaceous	120	394	Fox Hills Formation	
Cretaceous	1,030	3,378	Lewis Shale	
Cretaceous	52	171	Almond Formation	Mesaverde Group (581 m)
Cretaceous	90	295	Pine Ridge Sandstone	Mesaverde Group (581 m)
Cretaceous	383	1,256	Allen Ridge Formation	Mesaverde Group (581 m)
Cretaceous	56	184	Haystack Mountains Formation	Mesaverde Group (581 m)
Cretaceous	1,676	5,500	Steele Shale	
Cretaceous	355	1,164	Niobrara Formation	
Cretaceous	272	892	Frontier Formation	
Cretaceous	75	246	Mowry Shale	
Cretaceous	7	23	Muddy Sandstone	
Cretaceous	30	98	Thermopolis Shale	
Cretaceous	22	72	Cloverly Formation	
Jurassic	68	223	Morrison Formation	
Jurassic	135	443	Sundance Formation	
Triassic	54	177	Jelm Formation	Chugwater Group (285 m)
Triassic	9	30	Alcova Limestone	Chugwater Group (285 m)
Triassic	222	728	Red Peak Formation	Chugwater Group (285 m)
Permian	89	292	Goose Egg Formation	
Pennsylvanian	243	797	Tensleep Sandstone	
Pennsylvanian	53	174	Amsden Formation	
Mississippian	79	259	Madison Limestone	
Devonian or Cambrian	30	98	Fremont Canyon Ss. or Flathead Ss.	
Archean	---	---	Precambrian basement	

Figure 5. Stratigraphically superposed occurrences of Phanerozoic formations, including approximate thicknesses, as they occur in vicinity of the northern Hanna Basin. Wavy lines indicate unconformities. Certain thickness measurements are original, and differ somewhat from estimates provided by Gill and others (1970); measurements for Paleozoic and lower Mesozoic parts of section are from Van Ingen (1978).

Shirley Basin (including the erosional area to the north called Bates Hole; Harshman, 1972). Relative to the northern Hanna Basin, the remaining stratigraphic section of Shirley Basin is thin. The greater Shirley Basin represents a structurally simple syncline between the Laramie Mountains and Freezeout Hills, with an axis that trends essentially north-south.

Important Early Proterozoic shear zones (Chamberlain and others, 1993; Resor and others, 1996) exposed in the Laramie Mountains near Laramie Peak were reactivated as faults during the Laramide orogeny. The influence of Precambrian structural discontinuities during Laramide contraction is manifested by the *en echelon* anticlines between the Laramie Mountains and eastern Hanna Basin. Furthermore, the reactivation of ancient Precambrian faults and structural trends probably played a role in the history of Laramide deformation in parts of the Hanna Basin itself.

Highlands east of the town of Laramie can be seen from this point. The Laramie Basin itself (Blackstone, 1975) is mostly obscured from our vantage point by topography of Pine Ridge. Outcrops at Pine Ridge are composed of eastern extremes of the Upper Cretaceous Mesaverde Group (see Gill and others, 1970; Martinsen and others, 1993), and can be used to define the otherwise broadly open, north end of the Laramie Basin.

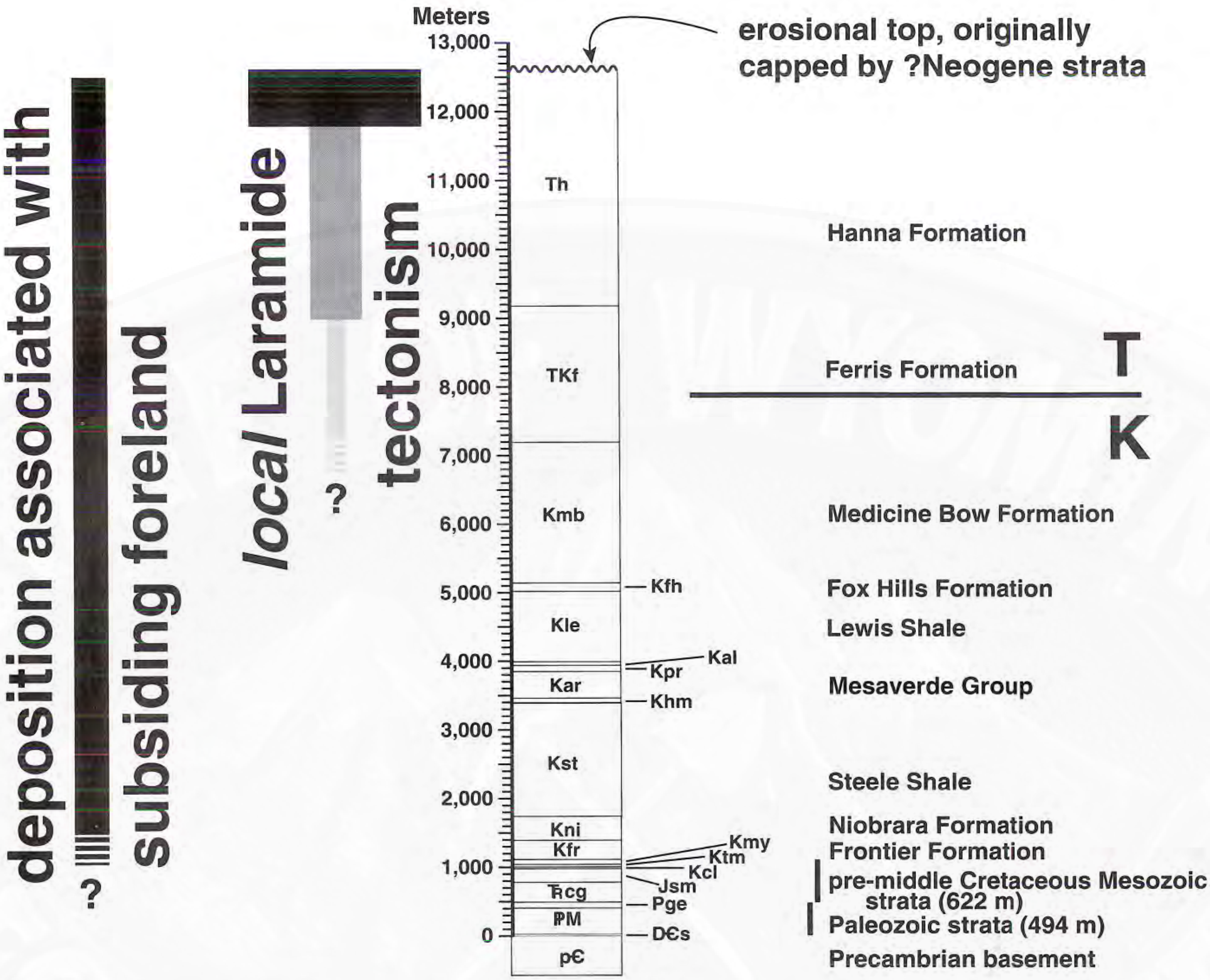


Figure 6. Phanerozoic sequence of sedimentary rocks, plotted in proportion to individual formational thicknesses, as it occurs in vicinity of the northern Hanna Basin. Notice that the pre-middle Cretaceous Mesozoic sequence, even when combined with the diversity of Paleozoic units, comprises only a thin veneer (not much more than a kilometer in thickness) above the Precambrian basement. In dramatic contrast, the sequence from the Frontier Formation (middle Cretaceous) upward through the Hanna Formation (mostly Paleocene) totals in excess of 12 kilometers. Most thickness measurements are original (see **Figure 8** for sources), and differ somewhat from estimates provided by Gill and others (1970). See **Figure 4** for identification of stratigraphic symbols.

The southern skyline is formed by northern parts of the Medicine Bow Mountains (Houston and others, 1968; Blackstone, 1987; Houston, 1993). Projecting northward toward us from near the middle of the range is a prominent north-plunging anticline, known as Simpson Ridge (or Saddleback Hills anticline). Simpson Ridge defines a structurally controlled boundary between the Hanna Basin's southeastern edge and a relatively small appendix, known as Carbon Basin (**Figure 2**). Recently revised mammalian biostratigraphy (Secord, 1996) in northern parts of Carbon Basin provides an excellent chronology of its Paleocene structural separation from original contiguity with the Hanna Basin per se (via folding and faulting of Simpson Ridge).

Elk Mountain (Beckwith, 1941), the large, relatively sharp pointed peak just northwest of the main bulk of the Medicine Bow Mountains, provides an excellent southern landmark that is visible from virtually any promontory in the Hanna Basin. As an indication of the small size of the Hanna Basin, individual vehicles often can be seen with the unaided eye, even from well north of our present viewpoint, as they travel U.S. Interstate Highway 80, built upon northern flanks of the Medicine Bow Mountains.

From our present position, all outcrops visible between the mountainous southern skyline and our parked vehicles belong to the heavily deformed Hanna Formation (Bowen, 1918; Glass and Roberts, 1980a, b; Hansen, 1986), the age of which is discussed below.

Introduction to the significance of the Freezeout Mountain anticline

The general southeastern flank of the Freezeout Hills (see **Figure 4**) is formed by a major anticline, the axis of which trends west-southwest. Following Maravich (1940), we refer to this structure as the "Freezeout Mountain anticline."

The Freezeout Mountain anticline is asymmetrically steepened on its northwestern side, and is broken there by a thrust fault. The southwestern flank of the anticline crosses the modern valley of the Medicine Bow River (**Figure 7**), where it forms integral structural and stratigraphic components of the Hanna Basin's northeastern corner. For example, the hill surrounding our present viewpoint at Tepee-ring Ridge is constructed of steeply south-dipping formations of the local Mesaverde Group and the underlying top of the Steele Shale (**Figures 5-9**; Gill and others, 1970). These Upper Cretaceous strata represent a superpositionally ordered, structural component of the Freezeout Mountain anticline.

Additional, stratigraphically still higher, steeply dipping elements of this same anticline can be recognized for at least a full mile to the south-southeast from our present position. The total section of exposed rocks composing the Freezeout Mountain anticline includes the Tensleep Sandstone (Pennsylvanian; at the anticlinal core within the Freezeout Hills) stratigraphically upward through lower parts of the Ferris Formation (here, probably of latest Cretaceous age; within the Hanna Basin). Near the northeastern corner of the Hanna Basin, only a thin, northwestwardly projecting, fault-truncated wedge of Ferris Formation persists (in NE corner of section 15 and western parts of sections 14 and 23, T23N, R80W; shown on the detailed map, page 20, but not distinguished from the Hanna Formation in **Figure 4**).

Figure 7. View to northeast, across valley of Medicine Bow River, toward Freezeout Hills at confluence of Sledge Creek and Freezeout Mountain anticlines. Ridge in foreground is steeply southeast-dipping, highly bentonitic Steele Shale. That ridge is capped with erosionally remnant, thin veneer of sandstones and pebble-conglomerates of Hanna Formation. Distant skyline ridge to right is made of highly resistant Cloverly Formation on the southeastern flank of Freezeout Mountain anticline. At that ridge's western base is the canyon through which Sledge Creek exits the Freezeout Hills, via the erosionally breached core of Sledge Creek anticline (see **Figures 16** and **17**). Photo taken from middle of section 4, T23N, R80W, by J. A. Lillegraven.

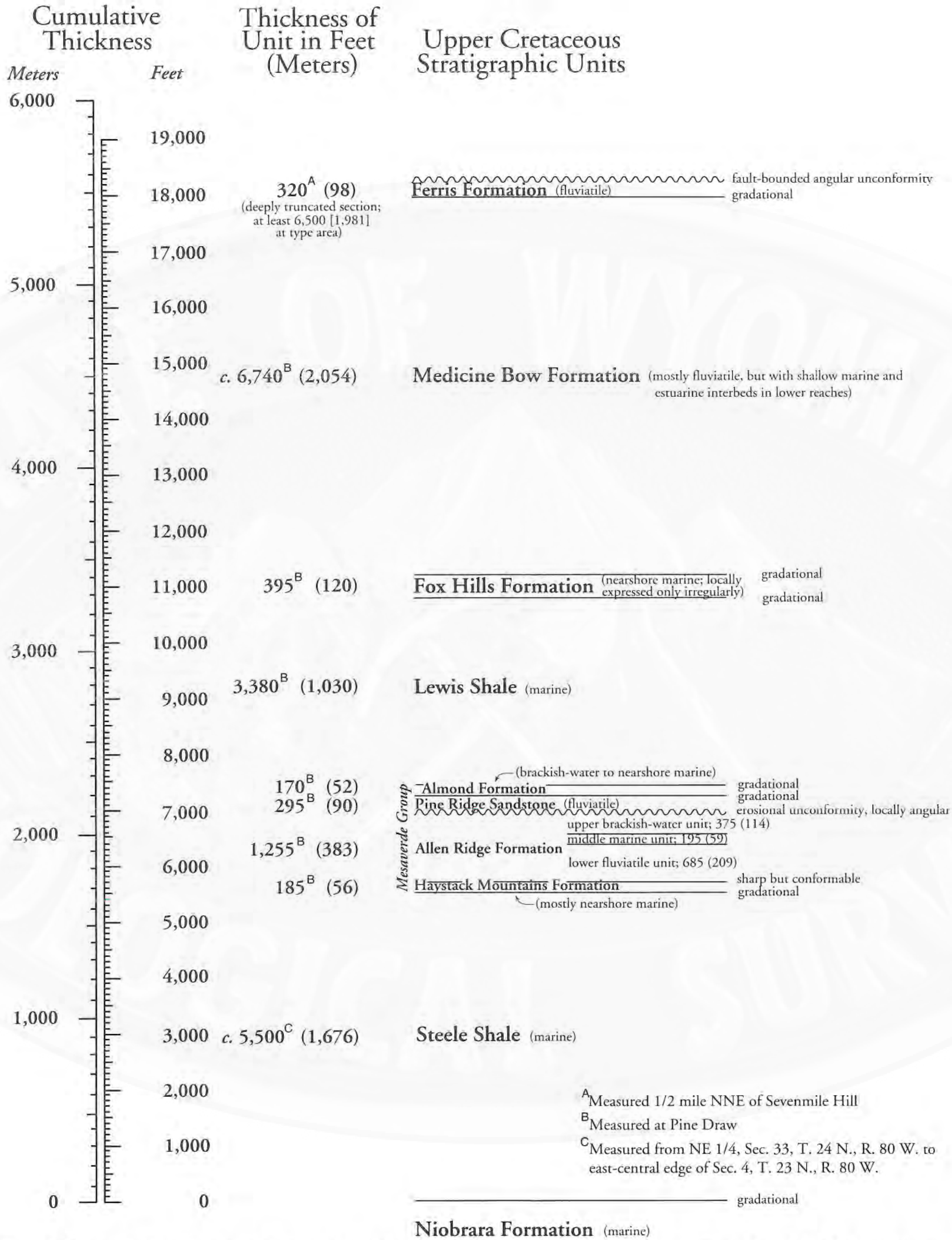


Figure 8. Summary of Upper Cretaceous stratigraphic relationships (above the Niobrara Formation) as they occur in vicinity of the northeastern Hanna Basin. Thickness measurements are original (by J. A. Lillegraven), and differ somewhat from estimates provided by Gill and others (1970).

Identifiable vertebrate fossils have not yet been discovered in strata identified as Ferris Formation of this immediate area. In the vicinity of the type Ferris Formation (Bowen, 1918) in west-central parts of the Hanna Basin, however, a detailed biostratigraphic zonation has been developed (Eberle, 1996; based mainly upon fossil mammals). Specifically, the type Ferris Formation of the western basin involves latest Cretaceous (Lancian North American Land Mammal "Age") through at least early Paleocene (Puercan "Age") time. Although admittedly tenuous as a means to correlation, lithologic details of the Ferris Formation at the northeastern corner of the basin are characteristic of Cretaceous parts of the Ferris type section in the western basin. Strata in both areas are characterized by common lenses of pebble conglomerates, representing highly diverse rock types that have no known local sources.

The Freezeout Mountain anticline was developed initially, and partially eroded, prior to deposition of Paleocene parts of the local Hanna Formation. In defense of that statement, later today (at Stop 4) we will examine the angular nature of the Hanna Formation's depositional contact upon an ancient surface eroded onto the Upper Cretaceous Steele Shale near the anticlinal axis.

A more compelling defense of the concept of pre-Hanna initial folding (Dobbin and others, 1929) of the Freezeout Mountain anticline can be seen on the large hill on which we stand (of which Tepee-ring Ridge is only a small part). On this hill one can observe, in correct stratigraphic order, deposition of the Hanna Formation onto an ancient erosional surface cut sequentially into the: (1) Steele Shale (**Figure 10**); (2) Haystack Mountains Formation (**Figure 11**); (3) Allen Ridge Formation; (4) Pine

Figure 9. View to west, showing steeply south-dipping sandstones of Upper Cretaceous Almond Formation (top of Mesaverde Group), in turn stratigraphically overlain by shales at base of Lewis Shale. At the pair of trees at right skyline is a veneer of cobble-conglomerates of early Paleocene Hanna Formation, deposited upon an erosion surface (expressed as an angular unconformity) cut into the Almond Formation. On left extreme of ridge in photo, one sees cobbles of Hanna Formation deposited upon the same erosion surface, there cut into Lewis Shale. A short distance to west (not within view in this photo) from top of the ridge, one can observe conglomeratic Hanna Formation deposited upon an erosional surface cut into the Pine Ridge Sandstone (Mesaverde Group), which underlies the Almond Formation. All three erosional components mentioned above represent the same surface, expressed upon three stratigraphically superposed components of the southeastern flank of Freezeout Mountain anticline. Furthermore, although the relationships have been obscured somewhat by late Laramide faulting, the general erosional surface shown in this photograph is simply a higher stratigraphic expression of the same interval of Paleocene erosion shown in **Figures 10** and **11**. View is near southwestern corner of SW of section 3, T23N, R80W. Photograph by J. A. Lillegraven.

Ridge Sandstone; (5) Almond Formation (**Figure 9**); and (6) and Lewis Shale. That is, one can follow a single, general erosional surface that was cut during Paleocene time onto superposed strata of the southeastern flank of Freezeout Mountain anticline. The interval of Paleocene erosion sequentially exposed younger components of the anticline's Upper Cretaceous stratigraphy; onto that surface were deposited progressively higher strata of the Hanna Formation. Various stratigraphic levels of that ancient erosional unconformity, including depositional contacts of the Hanna formation, are being exposed by the present cycle of erosion.

One might expect to find similar erosional-depositional relationships near the stratigraphic top of the Freezeout Mountain anticline, between the Medicine Bow/Ferris and Hanna formations. However, all surviving contacts between the Hanna Formation and Medicine Bow/Ferris strata at the northeastern corner of the Hanna Basin represent surfaces of major out-of-the-basin thrusts. These faults comprise directly traceable eastern components of "The Breaks fault system," discussed at today's Stop 4.

General features of the Hanna Formation in vicinity of The Breaks

The extensive area of rugged badlands seen inside the northeastern corner of the Hanna Basin is known on existing maps as The Breaks. The badlands themselves are dominated by superb exposures of heavily deformed Hanna Formation (**Figure 12**). A detailed measured section (see generalized summary in **Figure 13**) of the Hanna Formation in vicinity of The Breaks shows a total thickness in excess of 11,600 feet. Preliminary analysis of abundant mammalian fossils from lower reaches of the section suggests a late early Paleocene age (late Torrejonian or, more probably, early Tiffanian North American Land Mammal "Ages"; Archibald and others, 1987; Woodburne and Swisher, 1995). The local top of the Hanna Formation is dated on the basis of fossil horses (Lillegraven, 1994) as latest Paleocene or earliest Eocene (early Wasatchian Land Mammal "Age").

The Hanna Formation is a nonmarine rock unit, dominated in vicinity of The Breaks by carbon-

Figure 10. Angular unconformity between essentially vertical Steele Shale and overlying, southwest-dipping local base of Hanna Formation. View is to northwest in NW section 4, T23N, R80W. At this point, the Hanna Formation was deposited upon a profound, sharply defined erosion surface cut during Paleocene time onto the steeply plunging southwestern extreme of the Freezeout Mountain anticline near the northern structural margin of the Hanna Basin. Several million years later, after deposition of the Hanna Formation, the anticline was deformed further, leading to the 32° SW dip of the basal Hanna Formation. Very little ancient weathering is discernible at the unconformity, suggesting rapid secondary burial following erosion. On the basis of mammalian fossils from superjacent strata, the base of the Hanna Formation at this place probably is of early Paleocene age. Photograph by J. A. Lillegraven.

aceous mudstones. The mudstones are interrupted, however, by minor sheets and stringers of siltstones and generally fine-grained sandstones, with even fewer conglomeratic components. Conglomerates in the lower half of the formation are dominated by rounded clasts (mainly in the size-range of small pebbles, but grading to small boulders) that almost certainly were derived from erosion of exposures of the Mowry Shale, Cloverly Formation, and Tensleep Sandstone along the southern flanks of the Freezeout Hills. Sandstones and siltstones in the lower two-thirds of the formation are composed principally of quartz, with lesser contributions of mostly non-feldspathic rock fragments.

Figure 11. Midlength of hammer-handle indicates erosional surface between white sandstones of underlying, Upper Cretaceous Haystack Mountains Formation (base of Mesaverde Group) and overlying, pebble- to small cobble-conglomerates of early Paleocene parts of Hanna Formation. This erosion surface is the same one shown in **Figure 10**, only expressed upon a slightly higher stratigraphic level on the southeastern flank of Freezeout Mountain anticline. Stratigraphically still higher parts of this same erosion surface are shown in **Figure 9**. View to south, near middle of SE of section 4, T23N, R80W. Photograph by J. A. Lillegraven.

In marked contrast, however, the upper third of the Hanna Formation along the northern border of

Figure 12. View to southeast, showing steeply southwest-dipping, mudstone-dominated section of Hanna Formation. The highest hill is in east-central part of SE of section 5, T23N, R80W. Photograph by J. A. Lillegraven.

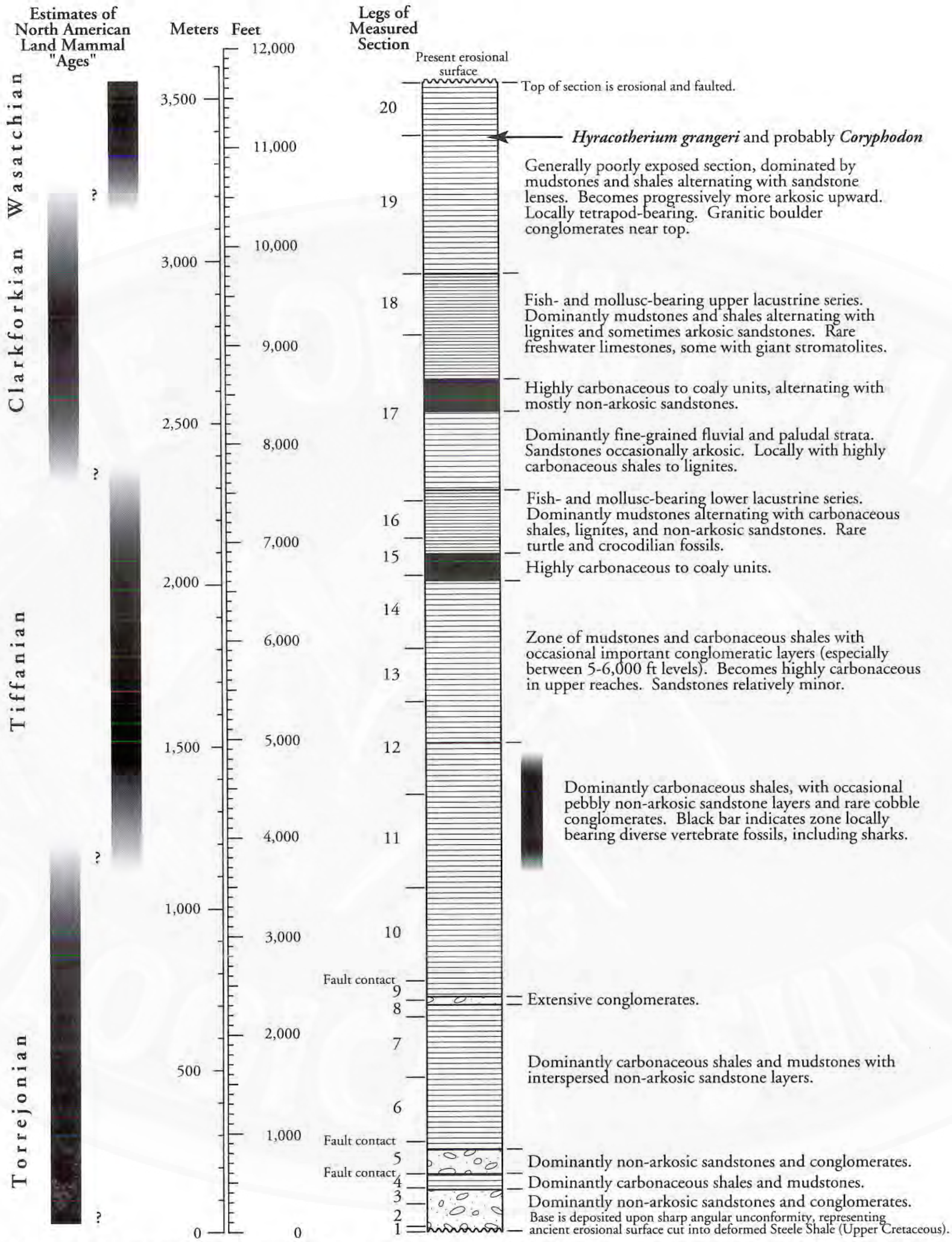


Figure 13. Generalized composite section of Hanna Formation as it occurs in vicinity of The Breaks, northeastern Hanna Basin. Most of the legs of the transect along which the section was measured are shown in **Figure 14**; stratigraphy encompassed is indicated here by numbers to left of column. Contacts between legs 4-5, 5-6, and 9-10 are separated by younger-onto-older faulting, involving uncertain amounts of missing section. Discovery of dental remains of an ancient horse (*Hyracotherium grangeri*) near the top of the section indicates an age of early Wasatchian (North American Land Mammal "Age") which, on current time-scales, is variously correlated with latest Paleocene or earliest Eocene epochs of Europe. Identifications of a much greater diversity of fossil mammals known from lower parts of the section (see vertical black bar) are preliminary, but suggest that the local base of the Hanna Formation most probably was deposited during the Torrejonian (correlated with early Paleocene epoch of Europe). Extensively revised from Lillegraven (1994).

The Breaks becomes progressively more coarse-grained and arkosic. Granite-dominated boulder conglomerates (Knight, 1951) can be seen near the top of the section (best exposed in section 22, T24N, R81W). The arkosic sands and granitic boulders clearly were derived from sources other than the central core of the Freezeout Hills. Sources probably included the eroding core of the Shirley Mountains, perhaps involving additional contributions from central parts of the Sweetwater arch (= Granite Mountains) located north of the Shirley Mountains.

Stratigraphically intervening between the mud-dominated lower reaches of the Hanna Formation and its upper arkosic levels (*i.e.*, the approximate 6600-9700-foot interval) is a complexly alternating sequence of very carbonaceous shales, thick coals, and mollusc-rich and fish-bearing lacustrine deposits. Collectively, this interval records unusually watery conditions during Paleocene time in the northern Hanna Basin (see Lillegraven and Ostresh, 1988, figure 7).

Contrary to the interpretation by Knight (1951), we recognize no major unconformity in the northern Hanna Basin that separates the Hanna Formation *sensu stricto* from an overlying unnamed early Eocene ("Wind River") unit. Rather, only insensible gradations in lithology, and their respective attitudes, separate gross elements of the column as represented in **Figure 13**.

Paleogeographic considerations related to such a thick Hanna Formation

The nature of the present-day, exposed map contact between the Hanna Formation and older strata along northern margins of The Breaks is unequivocal. The existing zero-isopach line of the Hanna Formation is erosional in origin, reflecting Holocene beveling down to the angular (but depositional) unconformity of Paleocene age with underlying Cretaceous strata (**Figure 10**). Immediately to the south and southwest of the zero-isopach line, however, the Hanna Formation thickens enormously.

With those relationships in mind, it seems undeniable that the Hanna Formation in later Paleocene time must have extended well to the north of its present limits, probably high onto simultaneously eroding flanks of the Freezeout Hills. In fact, it seems quite probable that the Freezeout Hills became buried by prograding sediments of upper reaches of the Hanna Formation. Distribution of conglomeratic clasts within the local Hanna Formation is compatible with such an interpretation. No confirmatory remnants of Hanna Formation, however, have been discovered on the rapidly eroding, existing terrain of the Freezeout Hills. Nevertheless, a previously unrecognized, thin veneer of Hanna conglomerates and coarse sands persists as erosional remnants capping the modern ridge of Steele Shale in NE of section 4, T23N, R80W (**Figures 4, 7**, and **14**).

Relatedly, and representing a concept deserving further consideration, is the thought that most of the presently exposed Laramide deformation involving the local Hanna Formation of the northern basin occurred at some depth, perhaps approaching three miles below the land surface during Paleogene time. LeFebre (1988) approached this concept via analyses of water content of basinal coals and data from basinal fission-track counts, as clues to calibration of the ancient geothermal gradient.

Late Laramide structural complexities in vicinity of Stop 1

The general hill that surrounds Tepee-ring Ridge (as a component of the Freezeout Mountain anticline's southeastern flank) exposes numerous examples of extensive faulting. Many individual faults are seen to cut the Hanna Formation and older strata alike (*e.g.*, **Figure 15**). It is clear, therefore, that the deformation occurred subsequent to deposition of the Hanna Formation upon the anticlinal flank. In local terms, this deformation can be thought of as late Laramide.

In at least five separate places across this general hill, one can observe instances in which the Hanna Formation (deposited with angular unconformity upon an erosional surface cut into Cretaceous strata) is tectonically overlain by Cretaceous strata. Detailed mapping suggests that: (1) the planes of these faults strike essentially east-west and are steeply dipping (generally paralleling the bedding planes of Cretaceous strata); and (2) the senses of motion along these faults were either with right-lateral or out-of-the-basin components, or both.

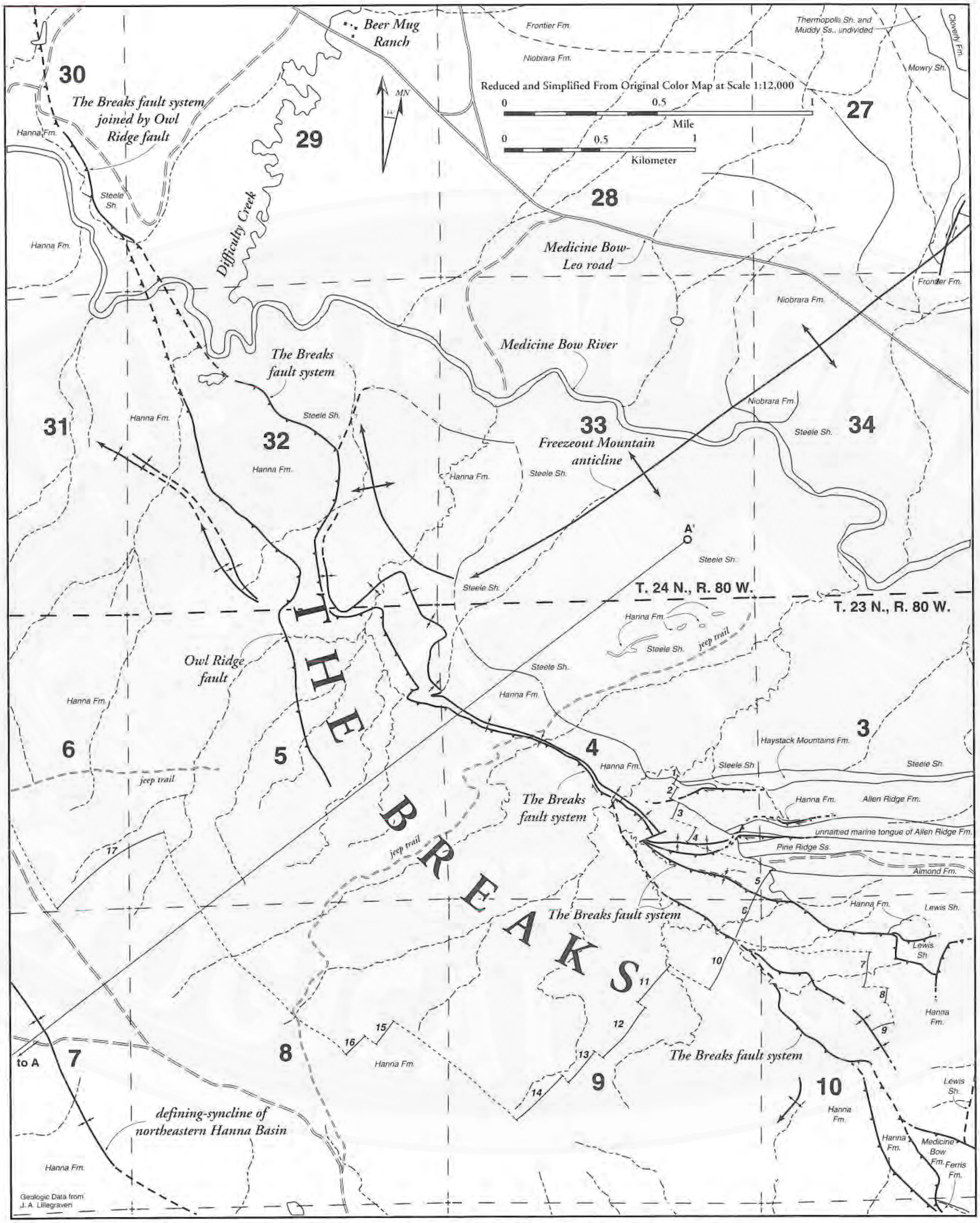


Figure 14. Geologic map, vicinity of The Breaks, northeastern Hanna Basin. Part of the transect used to compile interpretive geologic cross-section A-A' (**Figures 4** and **20**) is shown. Segments 1-17 (of 20 total) of the measured section used in compilation of **Figure 13** also are plotted. Segments 6-8 were cut away by faulting between adjacent ends of segments 5 and 9 because of out-of-the-basin stratigraphic separation along The Breaks fault system; younger strata were thereby faulted upon older strata. Geologic symbols as in **Figure 4**.

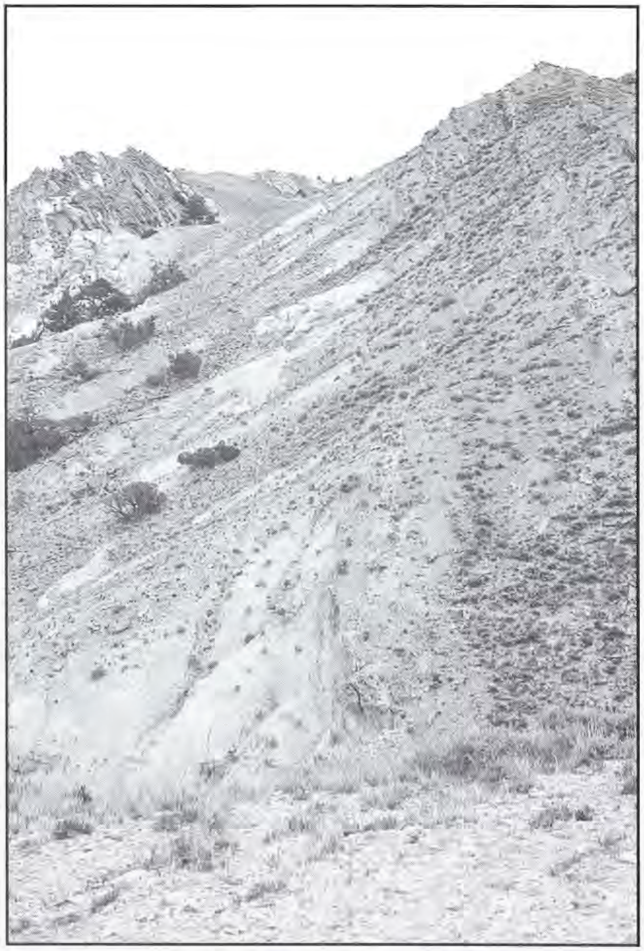


Figure 15. View to east, showing steeply south-dipping, light gray strata (dominating left half of photo) of Hanna Formation (here early Paleocene in age) tectonically overlain by darker, dinosaur-bearing strata of Allen Ridge Formation (Mesaverde Group). Close examination of contact between the two rock units shows a one- or two-meter-thick zone of intense deformation. This fault, and several others like it in this general vicinity, exhibit important components of right-lateral or out-of-the-basin separation, or perhaps both. These faults can be traced into structural confluence with The Breaks fault system, which had mainly out-of-the-basin separations. As late expressions of the local Laramide orogeny, faulting of the Allen Ridge Formation seen in photo appears to have brought the unit westward (*i.e.*, toward the camera), and cut stratigraphically upward relative to the much younger Hanna Formation. Focal point of photo is near center of SE of section 4, T23N, R80W. Photograph by J. A. Lillegraven.

Ordinarily, confirmation of the existence of strike-slip faulting depends upon recognition of some sort of unique geologic feature (*i.e.*, a "piercing-point") on both sides of the fault, such that the fault's opposite walls can be realigned palinspastically back to pre-faulting positions. On this particular hillside, however, traditional piercing points have not been identified, and probably could never be definitively recognized in actual practice. Nevertheless, the rather simple progradational relationships, described above, of the Hanna Formation's deposition upon the eroding, stratigraphically ordered, Paleocene southeastern flank of the Freezeout Mountain anticline are readily recognizable on the modern hillside. Reconstruction of a reasonable Paleocene erosional-depositional surface on the southeastern flank of Freezeout Mountain anticline demands relative fault motions having some combination of components of right-lateral or dip-slip, out-of-the-basin separation. Oblique-slip separations, involving both vertical and right-lateral components, fit well the spatial relationships of surviving stratigraphy.

As a working hypothesis, we suggest that the late Laramide faulting seen in the vicinity of Stop 1 developed during formation of the great curvature of the northeastern corner of the Hanna Basin. Quite probably, the faulting occurred in conjunction with evolution of the western end of Flat Top anticline, just to the east. We will revisit this concept in the discussion for Stop 2, Day 3.

At Stop 4 today (Day 1) we will examine probable relationships between the faulting seen here in vicinity of Stop 1 and extensive north-directed, out-of-the-basin thrusting discovered along most of the Hanna Basin's northern margin.

Stop 2–Sledge Creek

The discussion in the field begins in SW of section 26, T24N, R80W.

The purposes of this stop are to acquaint you with the classic Mesozoic stratigraphy of south-central Wyoming (**Figure 16**) and to view the structural style of a foreland anticline. The area of our traverse was studied most recently by David A. Taylor (1996), and **Figure 17** was derived from his geologic mapping. We will traverse various Mesozoic units along the drainage of Sledge Creek.

As discussed below, Sledge Creek exposes the core of one anticline as it becomes confluent with another, much larger anticline. At this point along our traverse, Sledge Creek exposes rocks as old as the Lower Triassic Red Peak Formation; still older strata (*e.g.*, Permian Goose Egg Formation and Pennsylvanian Tensleep Sandstone) are exposed to the north and northeast. Our traverse crosses rock units ranging from the Red Peak through Frontier formations, although we do not approach them in

Figure 16. Lower Mesozoic stratigraphy exposed near the axis of Sledge Creek anticline in Sledge Creek canyon. The stratigraphically lowest rocks exposed in this view are the Lower Triassic Red Peak Formation overlain by the ledge-forming, Middle Triassic Alcova Limestone and, in turn, the slope-forming Upper Triassic Jelm Formation. The prominent off-white exposures in the center of the photograph are sandstones of the Middle Jurassic Sundance Formation. These rocks are sequentially overlain by slope-forming, Upper Jurassic Morrison Formation and ridge-forming, Lower Cretaceous Cloverly Formation. A regional unconformity separates the Morrison and Cloverly formations. Photograph by A. W. Snoke.

strict stratigraphic order. **Figure 17** shows specific localities along the traverse. The stratigraphic key to these localities follows: ***A*** = Middle to Upper Cretaceous Thermopolis, Muddy, Mowry, and Frontier formations; ***B*** = Lower Triassic Red Peak Formation; ***C*** = Middle Triassic Alcova Limestone; ***D*** = Upper Triassic Jelm Formation; ***E*** = Middle Jurassic Sundance Formation; ***F*** = Upper Jurassic Morrison Formation; and ***G*** = Lower Cretaceous Cloverly Formation.

The geometric form of the anticlinal structure at Sledge Creek (the Sledge Creek anticline *sensu* Taylor, 1996) is geographically and stratigraphically variable. To the north, its cross-section appears as a chevron-like fold, defined by the Alcova Limestone. Farther to the south, near the beginning of our traverse (at the mouth of the canyon), the southward-plunging anticlinal form converts to a box-like geometry, defined by the ridge-forming Cloverly Formation. Consequently, the axial surface of the southern parts of the Sledge Creek anticline bifurcates from a single axial surface at deeper stratigraphic levels to a conjugate set at higher stratigraphic levels. The southeast-striking axial surface becomes unrecognizable at stratigraphic levels above the Cloverly Formation. The southwest-striking axial surface, in contrast, continues to help define a prominent fold that is recognizable on the surface for at least two miles beyond our stop.

The Sledge Creek anticline intersects southwestern parts of a much larger, faulted anticlinal feature, the Freezeout Mountain anticline, as identified and described above. Strata of the southeast flank of the Freezeout Mountain anticline not only define the southeastern structural corner of the Freezeout Hills, but constitute an integral component, as discussed above, of the northeastern Hanna Basin itself. Determination of the relative antiquity of the Sledge Creek and Freezeout Mountain anticlines awaits further study.

Stop 3–South flank of Beer Mug anticline

This field discussion begins near center of section 20, T24N, R80W.

The Beer Mug anticline is a spectacular, asymmetric fault-propagation fold with a core of Pennsylvanian Tensleep Sandstone (**Figures 18, 19a,**

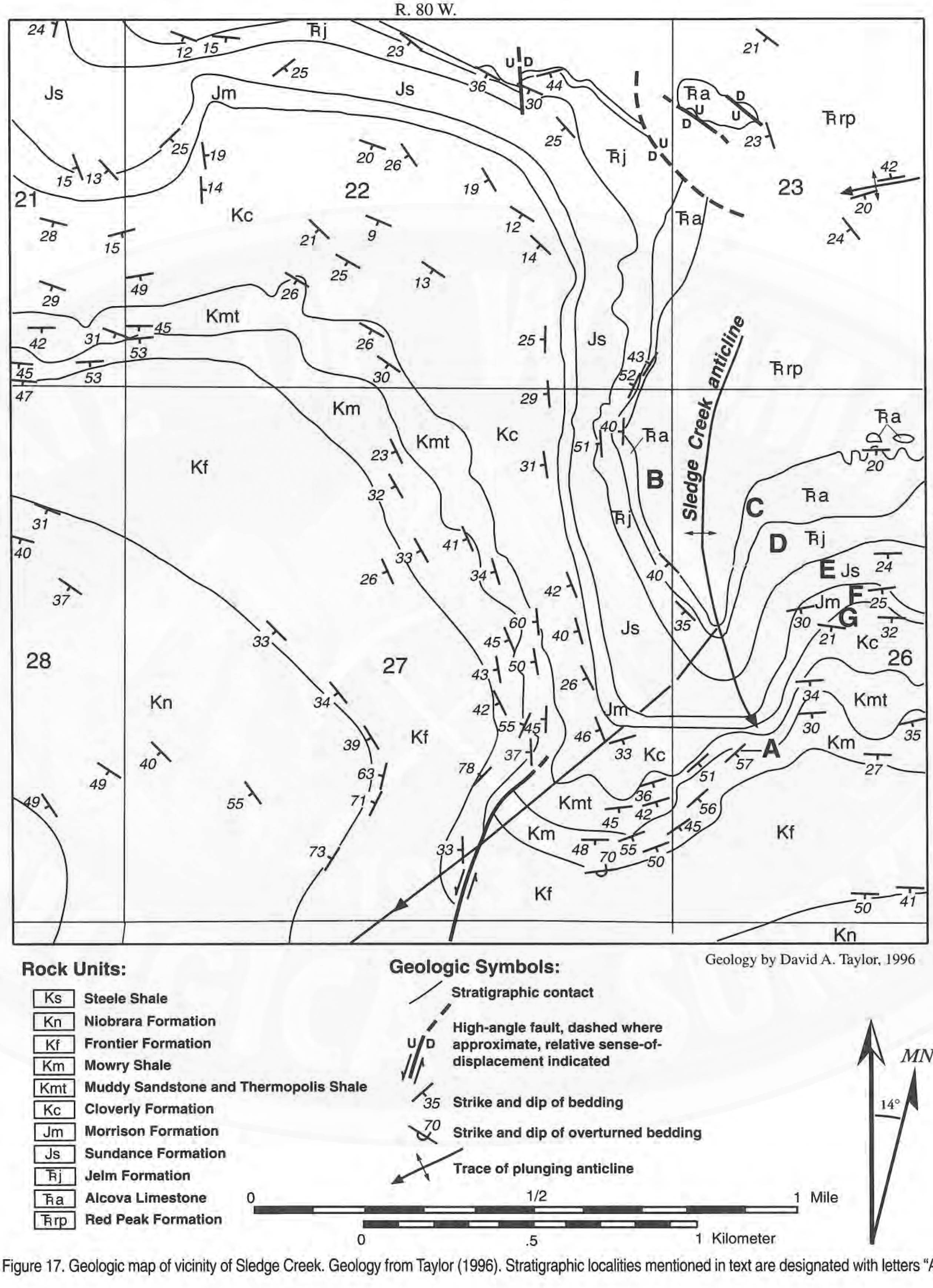


Figure 17. Geologic map of vicinity of Sledge Creek. Geology from Taylor (1996). Stratigraphic localities mentioned in text are designated with letters "A-G."

Figure 18. A view of the asymmetric, eastward vergent Beer Mug anticline from near the Leo-Difficulty road looking northward. The prominent exposures that define the fold are Pennsylvanian Tensleep Sandstone. Note that the fold has an angular aspect characterized by several distinct dip domains. The fold is truncated along its southern end by the right-lateral, oblique-slip Indian Spring fault (see **Figure 19a** and **19b**), and the synformal Ellis Ranch anticline forms the footwall of the fault. Photograph by A. W. Snoke.

and **19b**). The Indian Spring fault strikes approximately east-west, and forms the southern boundary of the Beer Mug anticline (Taylor, 1996). The anticline dies out to the north (**Figure 19b**). The Indian Spring fault is a right-lateral, oblique-slip fault. South of the Indian Spring fault is a separate, southwest-plunging anticline (Ellis Ranch anticline), having an exposed core of strata of the Chugwater Group. As the axial surface of the Ellis Ranch anticline is traced to the southwest, the folded bedding in various formational units plunges beyond vertical, and thus the fold becomes synformal in map view.

Recently, Stone (1993) interpreted the Beer Mug anticline as a "trapdoor structure" (his figure 31). In this interpretation, the Indian Spring fault is a "tear fault" that connects with an inferred, exposed thrust fault on the eastern flank of Beer Mug anticline. Geologic mapping by Taylor (1996), however, did not recognize the inferred thrust fault that Stone's model requires (**Figure 19b**). Taylor (1996) interpreted the Beer Mug anticline as a fault-propagation fold, associated with a basement-rooted thrust fault. The Indian Spring fault is a right-lateral, oblique-slip fault that cuts across and terminates the fault-propagation fold. The Indian Spring fault is thus kinematically linked to development of the Beer Mug fold, but occurred late in structural development of the fold.

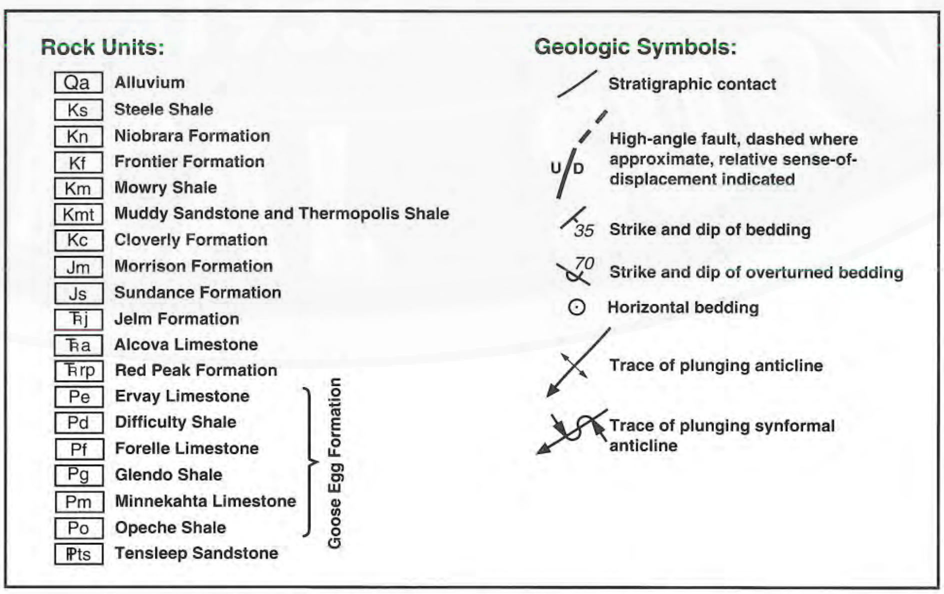


Figure 19a. Geologic symbols to accompany **Figure 19b**.

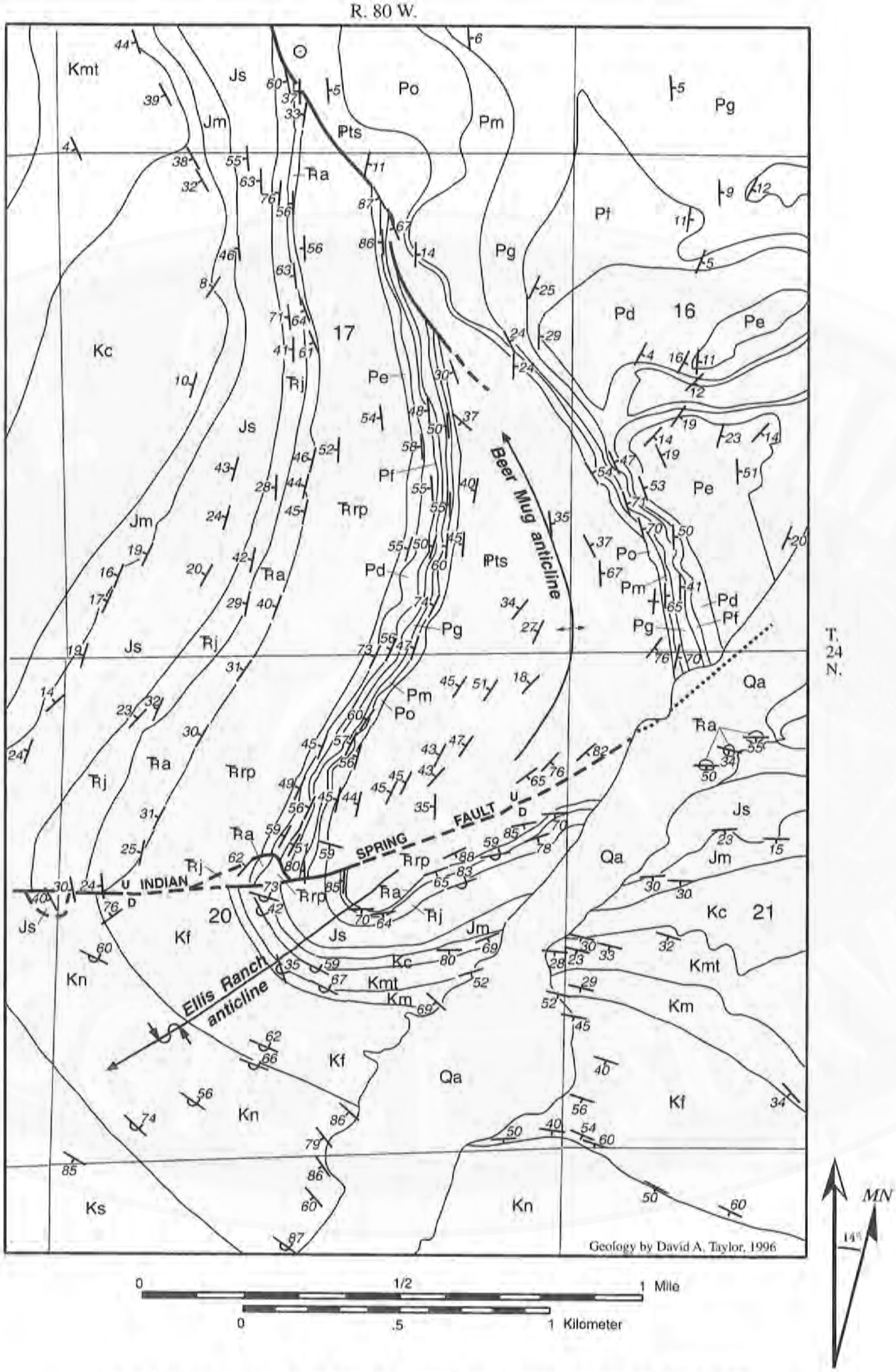


Figure 19b. Geologic map of the Beer Mug anticline and environs. Geology from Taylor (1996).

We will walk directly to a fault contact (Indian Spring fault), which separates Middle Triassic Alcova Limestone (footwall) from Pennsylvanian Tensleep Sandstone (hanging wall), exposed in a small saddle. At this locality, an overview of part of the footwall fold (Ellis Ranch anticline), as outlined by Alcova Limestone, is afforded. Also, this locality provides a chance to examine sedimentological and structural features of the Tensleep Sandstone, including the well-preserved cross-stratification characteristic of this unit. On the return hike, we will traverse various Mesozoic units (most are poorly exposed), including a distinctive brown-weathering, pelecypod-bearing limestone of the Middle Jurassic Sundance Formation. Eventually we will climb onto a knob that exposes "out-of-place" Alcova Limestone. This is a fault slice that occurs along the trace of the Indian Spring fault.

Stop 4–Jeep road into The Breaks

The discussion in the field begins along west-central edge of section 4, T23N, R80W.

Distribution of fossil vertebrates in the local Hanna Formation

We are parked on lower reaches of the Hanna Formation, stratigraphically about 3500 feet above its local base. Our present position is essentially at the bottom of a roughly 1200-foot-thick zone that commonly preserves fossilized bones and teeth of terrestrial and fresh-water vertebrates (**Figures 13** and **14**). Despite intensive prospecting, very few identifiable bones or teeth have been discovered in vicinity of The Breaks stratigraphically below our present level. Similarly, only a few sites stratigraphically above this 1200-foot-thick section in the Hanna Formation (not including an abundance of fish-bearing, lacustrine strata) have yielded identifiable, biostratigraphically useful remains of ancient tetrapod vertebrates. The thick band of fossiliferous strata above our present position, therefore, is critically important to interpreting age relationships of the local Hanna Formation (Lillegraven, 1993).

The 1200-foot-thick band of vertebrate-bearing strata can be traced along strike northwestward from here for at least a mile and a half, and to the southeast (and south) for roughly four miles. Strata above and below this band, however, apparently have been diagenetically stripped of their original content of fossil vertebrates. In terms of gross lithology, there exist no recognizable differences between parts of the local Hanna Formation that do, or do not, retain a record of vertebrate fossils. We believe, therefore, that local distributions of fossil remains may provide important clues to the evolution of Paleocene groundwater chemistries in the northeastern Hanna Basin.

Many of the local fossil-bearing sites are composed of channel deposits, most of which contain stringers of water-worn pebble conglomerates. Commonly, these conglomerates include individual well preserved, but reworked, Cretaceous shark teeth. Among the most abundant clasts are pebbles derived from local deposits of the Cretaceous Mowry Shale. The Mowry is famous for its common inclusions of disaggregated scales, bones, and teeth of marine fishes. Interestingly, one can expect to find bone-bearing clasts of Mowry Shale within the 1200-foot-thick Paleocene vertebrate-rich band of the Hanna Formation. Stratigraphically above and below that band, however, in channel deposits that otherwise appear to be identical, one finds only the impressions of scales and bones in clasts derived from the Mowry Shale; reworked shark teeth also are absent. These observations provide strong evidence for a secondary, most unfortunate diagenetic loss from the great bulk of the local Hanna Formation of what must have been at least an incipient record of fossil vertebrates.

Introduction to "The Breaks fault system"

Strata up-section from this point are relatively undeformed, except for their rather consistent 40°-70° dips to the southwest (**Figures 4, 12,** and **20**). Strata down-section from here, in marked contrast, become progressively more deformed, characterized by pervasive stratal dismemberment of weak, mud-rich rocks, until they encounter a dramatic structural feature, here named "The Breaks fault system." Although heretofore this fault system has not been described or even precisely located, its general zone of associated deformation (aligned generally northwest-southeast) has made appearance on older maps (*e.g.*, LeFebre, 1988, plates I-II) as an eastern component of the "Shirley thrust."

The Breaks fault system is structurally distinct from the so-called Shirley thrust. The Breaks fault system is one of many, previously unrecognized out-

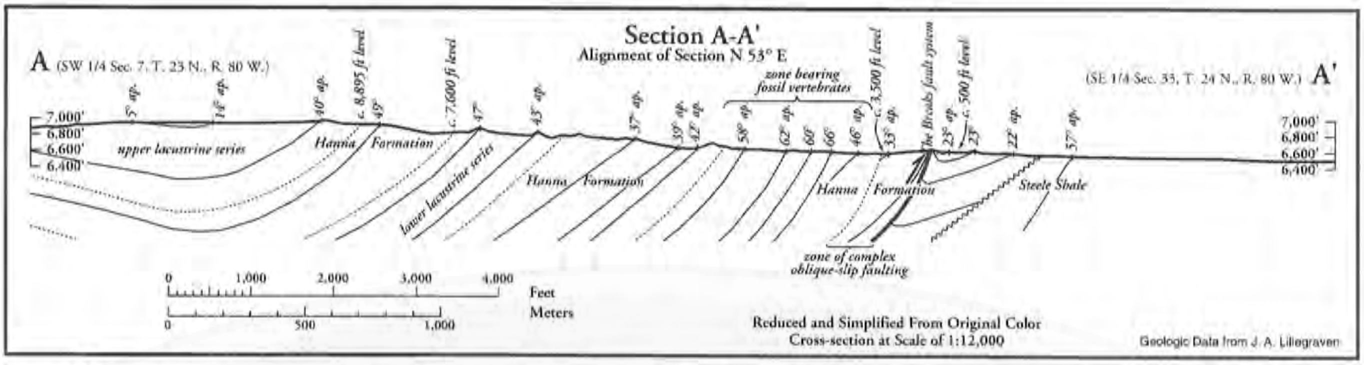


Figure 20. Interpretive geologic cross-section A-A' through The Breaks, northeastern Hanna Basin (see **Figures 4** and **14** for alignment; no vertical exaggeration). At least 2000 feet of stratigraphic separation exists across The Breaks fault system (out-of-the-basin) at this section. Basic stratigraphic elements of the Hanna Formation can be related to **Figure 13**. "ap." = apparent dips.

of-the-basin thrusts that we have identified through recent mapping along the northern and northeastern margins of the Hanna Basin. This particular fault seen at Stop 4 is traceable on the surface for several miles. At our present position, the structure is identifiable as a single fault. To the southeast, however, the single fault seems to become transformed, through bifurcation, into a system of several coalescing faults.

Local field evidence suggests that The Breaks fault system should be considered as a series of oblique-slip thrust faults. The principal sense of motion along The Breaks fault system was out-of-the-basin (*i.e.*, to the northeast). Components of probable right-lateral separation (reflecting more westerly-directed motion of the hanging wall), however, also are indicated by a consistency of bending directions, observable at several scales, as preserved in fold segments along the bases of the length of the fault system's hanging walls. The components of right-lateral separation observed within The Breaks fault system, we suggest, represent genetic continuations of similar senses of oblique-slip motion recognized across the general hillside discussed earlier today (Day 1) at Stop 1. Indeed, from the western end of each major fault identified on the hill in the vicinity of Tepee-ring Ridge, intense deformation can be traced westward directly into readily mappable traces of The Breaks fault system.

Here, at the beginning of Stop 4, we are standing on lower parts of the hanging wall of The Breaks fault system. The entirety of the Hanna Basin to the south of this point can be considered to represent the remainder of the fault's hanging wall. Notice the intensity of local deformation in this part of the Hanna Formation, and the masses of excellently exposed trace fossils (interpreted as burrows of Paleocene crayfish by Hasiotis and Honey, 1995) in otherwise tortuously kinked walls of fine-grained sandstones and siltstones. Such trace fossils are common throughout The Breaks, from the base of the local Hanna Formation up to the level of the first major coals (c. 6500-foot stratigraphic level) seen below the lower lacustrine series. Although relatively uncommon, these burrow-like trace fossils also can be recognized in the fluvial section (c. 7500-8300-foot levels of **Figure 13**) between the two bands of largely lacustrine strata.

Examination of "The Breaks fault system"

A short hike to the north brings us to the crest of a northwest-trending ridge, located just north of the midline of the boundary between sections 4 and 5, T23N, R80W. The spectacular crest of this ridge is dominated by vertical walls of well-indurated, fine-grained sandstones of the Hanna Formation, some of which are packed with the burrow-like trace fossils. A zone of deformation along the crest of the hill (**Cover photograph** and **Figure 21**) represents local expression of The Breaks fault system.

The vertical sandstones that form walls along the northeastern margin of the ridge have stratigraphic "up" to the northeast (**Figure 20**). As determined from direct measurement, those sandstones are only a few hundred feet above the local base of the Hanna Formation; they represent the top of the footwall of The Breaks fault system. The vertical nature of these sands resulted from drag along the base of the hanging wall of the fault. Within a remarkably short distance to the northeast of the ridge, the ver-

Figure 21. View to east along crest of ridge dominated by main trace of The Breaks fault system. See **Cover photo**, text, and **Figures 14** and **20** for explanation. Center of ridge in foreground is in west-central parts of SW SW of section 4, T23N, R80W. Massive hill on center skyline includes areas shown in **Figures 9**, **11**, and **15**. Photograph by J. A. Lillegraven.

tical strata switch to horizontal attitudes (forming the consistently expressed axis of a minor footwall syncline), and then convert to a southwesterly dip of 30° or less all the way to the formational contact with the underlying Steele Shale. The general footwall in most instances is not dramatically deformed, except at the drag zone immediately adjacent to the fault.

In sharp contrast, the vertical sandstones that form walls along the southwestern margin of the ridge have stratigraphic "up" to the southwest. As determined through tracing of laterally equivalent strata, those sandstones are more than 3000 feet above the local base of the Hanna Formation; they represent the base of the hanging wall of The Breaks fault system. Across the 20- to 30-foot-wide ridge crest, therefore, the opposing walls of sandstones represent a stratigraphic separation across the fault approaching 2000 feet.

Again, as determined through detailed mapping of laterally equivalent stratigraphic levels, it is clear that total stratigraphic separation across The Breaks fault system decreases from this point to the southeast, and increases to the northwest. Not far to the northwest (in the northern half of section 32, T24N, R80W), the fault's hanging wall completely overrode the local base of the Hanna Formation (*i.e.*, the footwall), to rest directly upon Steele Shale. Notice that the ultimate effect of these sorts of motion is to superpose younger strata atop older strata. To explain this phenomenon as locally expressed, it becomes necessary to recognize that as The Breaks fault system evolved it cut stratigraphically down-section. Through our recent mapping, such younger-over-older fault-relationships are now recognized as common in association with out-of-the-basin thrusts present along the Hanna Basin's northern and northeastern margins. This point will be reinforced at Stop 2, Day 2.

Notice from **Figure 14** that another out-of-the-basin thrust, here named the Owl Ridge fault, appears to become confluent with The Breaks fault system just to the north of the Medicine Bow River (in SE of section 30, T24N, R80W).

Also notice, in map view (**Figure 14**), that The Breaks fault system (as well as its associated, largely parallel, footwall syncline) exhibit occasional sharp kinks. Additionally, both structures are, themselves, faulted. We suggest that such peculiarities developed either very late in the history of The Breaks fault system's own out-of-the-basin displacements, or shortly after its principal displacements.

Structural-depositional relationships of the local base of the Hanna Formation

From the faulted ridge, hike a short distance northeast (to the center of section 4, T23N, R80W), to an exquisitely exposed contact of the basal Hanna Formation upon Steele Shale (**Figure 10**). Although somewhat south of its axis, we are close to the southwestern extreme of the Freezeout Mountain anticline (including the merged Sledge Creek anticline) as it is expressed on the surface. The Steele Shale at this point is almost vertical, reflecting the greatly steepened axis of the anticline at the margin of the Hanna Basin. The Steele Shale is cut by a sharply defined, ancient erosion surface. The erosionally beveled shales and upwardly projecting fins of thinly bedded sandstones of the Steele Shale are overlain and filled in by the more shallowly dipping Hanna Formation. Except for a zone of sideritization less than two feet thick, little evidence of consequential weathering or ancient soil formation appears at the contact. Indeed, the contact looks as though it was eroded rapidly, then quickly buried once again by sediments of the Hanna Formation.

Equally important, this contact (and others like it observable to the southeast) shows clearly that an early version of the Freezeout Mountain anticline existed prior to deposition of the local base of the Hanna Formation. Note the existence of 20°-30° dips in the basal Hanna Formation, combined with nearby arcuate changes in its strike as the basal Hanna Formation wraps around the crest of the anticline. These features suggest significant structural refinement of at least basin-margin parts of the anticline following deposition of the Hanna Formation.

As an aside, the erosional surface seen here represents localized removal of a prodigious thickness of pre-existing, Upper Cretaceous strata. Specifically, a minimal estimate of the amount removed would be in the order of 15,000 feet. This point was recognized long ago by Veatch (1907) and Bowen (1918).

Day two of field trip

Stop 1–Eastern termination of Shirley fault, and Smith Creek anticline

The field discussion begins in the southwestern extreme of section 6, T24N, R81W.

Standard interpretation of the "Shirley thrust"

Virtually all pre-existing literature on the Laramide tectonic evolution of central Wyoming makes reference to the "Shirley thrust." As typified in geologic maps and cross-sections presented by Blackstone (1983, 1993a), the Shirley thrust has been visualized as a relatively low-angle fault (dipping c. 30° to the northeast) that bordered most of the northern Hanna Basin (see **Figure 2**). Practically all relevant geologic maps illustrate the Shirley thrust extending southeastward, often as a surface feature, as far as the northeastern corner of the Hanna Basin, or even beyond. Motion along the fault plane during the Laramide orogeny is presumed to have brought a Shirley Mountains-Freezeout Hills terrane in a southwestward direction. Through a combination of vertical uplift and southwestward translation, Precambrian and younger rocks of the terrane were thought to have overridden strata of the northern Hanna Basin. The Wind River thrust of west-central Wyoming, where it is known to have overridden the northern Green River Basin, has been used as a model for general interpretation of the Shirley thrust (see, for example, Van Ingen, 1978).

Introduction to a more limited Shirley fault

Our geologic mapping indicates that major revision of the standard interpretation of the "Shirley thrust" is required. In particular, we suggest that the basement-involved fault now exposed at the surface is a steeply dipping reverse fault, not a low-angle thrust fault. Furthermore, parts of the previously mapped "Shirley thrust" are actually out-of-the-basin thrust faults; their senses of motion were directed northward, rather than southward as in the standard interpretation of the "Shirley thrust."

Stop 1 begins near the eastern end of the Smith Creek anticline (**Figure 22**). Its main axis extends from west to east, beginning at the extreme southeastern corner of exposed Precambrian rocks of the Shirley Mountains. The eastern end of the Smith Creek anticline curves southeastward, and plunges in that direction. As a feature recognizable on the surface, the Shirley fault terminates near the eastern end of the Smith Creek anticlinal axis, in the Frontier Formation, where we presently stand. Specifically, stratigraphic separation of just a few feet can be seen on a highly diagnostic, stratigraphically useful horizon here referred to informally as the "brown sparkly marker sandstone." The well-exposed Wall Creek Sandstone Member constitutes the top of the Frontier Formation; just to the southeast is a sharp bend in its contact with the overlying Niobrara Formation, clearly defining the axis of the southeast-plunging Smith Creek anticline.

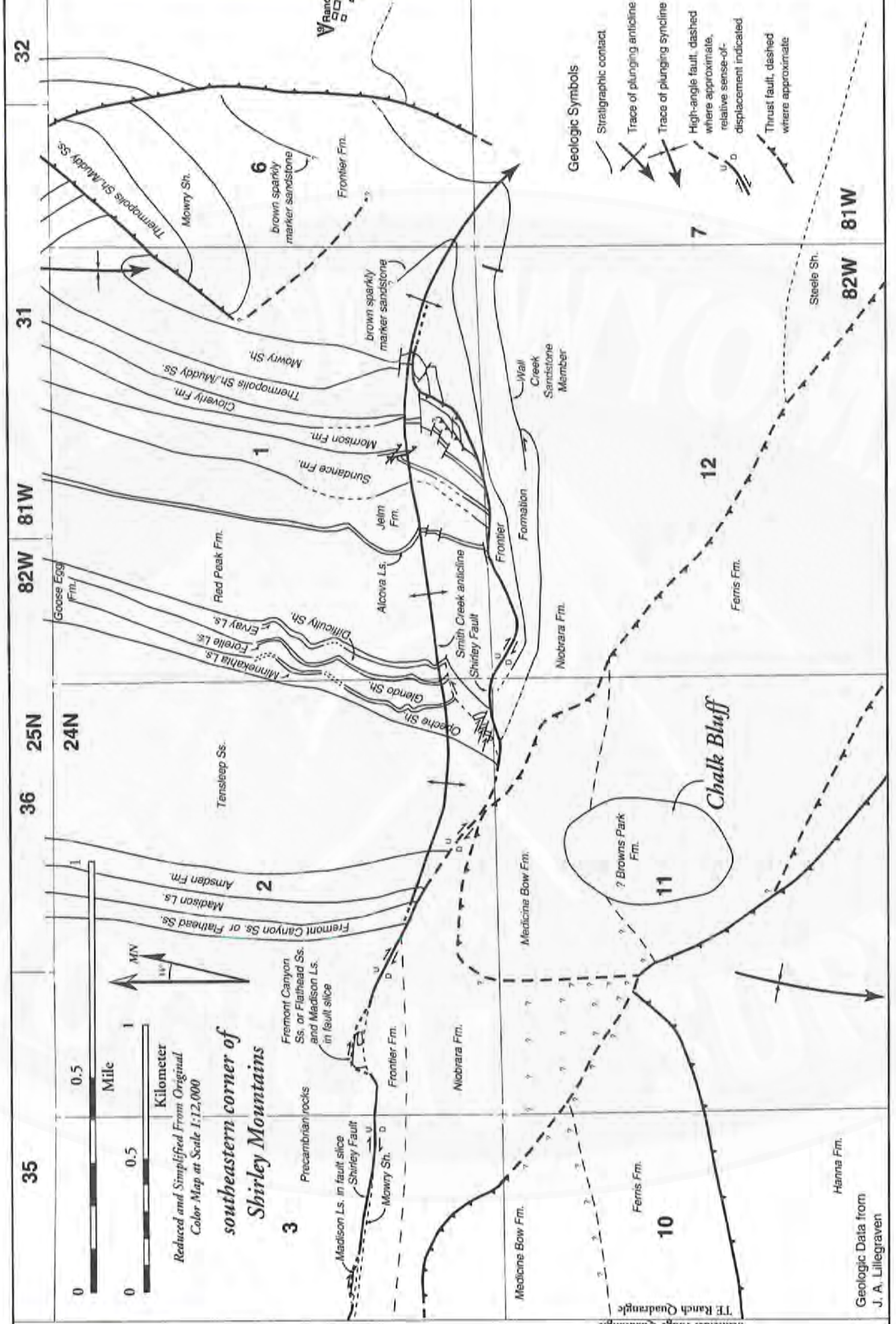


Figure 22. Geologic map of the southeastern corner of Shirley Mountains and adjacent parts of the northern extreme of the Hanna Basin. The Shirley fault (restricted definition, as discussed in text) expresses its terminal structural separation in the southern part of the SE of section 1, T24N, R82W, and is interpreted as becoming a blind fault as it passes into the NW of section 7, T24N, R81W, associated at that point with a fault-propagation fold.

As a surface phenomenon, we stand at the point of termination of the Shirley fault. Because the Shirley fault is rooted in the Precambrian basement, the fault's separation progressively increases westward, reaching a magnitude of several thousand feet just a few miles to the west. Thus we can visualize the dramatic bend in strata southeast of this eastern extreme of the Shirley fault as representing a fault-propagation fold. The hanging wall of the Shirley fault is to the north. Because of the Shirley fault's increasing stratigraphic separation westward, one would expect to see evidence along the trace of the fault, both in the hanging wall and footwall, for separations involving right-lateral oblique-slip motions. Indeed that is the case, and evidence such as drag of bedding, right-lateral separation of fragmented strata, slickenside orientations, smearings within a gouge zone, and even a system of Riedel shears (R-shears) occurs associated with the fault trace. A mile-long hike westward along the trace of the Shirley fault allows observation of all these features.

What is the orientation of the plane of the Shirley fault?

The attitude of the plane of the Shirley fault as it occurs at the modern surface can be seen clearly along the southwestern edge of section 1, T24N, R82W. A small side-canyon is cut sharply northward into fundamentally east-dipping redbeds of the Jelm Formation (Upper Triassic). A fault cutting through the Jelm is well-exposed on the eastern wall of the side canyon (**Figure 23**). On the south side of the fault (footwall) exist steeply south-dipping black shales of the Frontier Formation (middle Cretaceous). An obvious meter- or two-thick gouge zone intervenes between the Jelm and Frontier formations. The plane of the fault at this point, estimated by our measurement within the gouge zone, strikes east-west and dips northward at about 75°. Within the gouge zone at the east wall of the side canyon, one can find fragments of fossil belemnites, almost surely derived by drag from hanging wall strata of the Sundance Formation, exposed farther to the east.

Figure 23. View to east showing surface expression of Shirley fault (see **Figure 22**). Person stands on roughly 2-m-thick gouge zone between east-dipping, brilliant red mudstones of Upper Triassic Jelm Formation (hanging wall, on left) and steeply south-dipping (essentially vertical), black mudstones of mid-Cretaceous Frontier Formation (footwall, on right). As measured at this outcrop, the plane of the Shirley fault strikes east-west and dips northward at about 75°. Photograph is at south-central edge of section 1, T24N, R82W, by J. A. Lillegraven.

The Shirley fault at the surface in this vicinity must be considered as a high-angle reverse fault (up to the north). Planes of many Laramide faults inferred to be low angle at depth, however, exhibit steep dips at the surface (*e.g.*, Rattlesnake Mountain; see Brown, 1984; Erslev, 1986, 1993). Is it probable that what we call the Shirley fault here becomes markedly listric (as a thrust) with greater depth? An answer to this question can be pursued to the west of Stop 1, in light of revised geologic mapping along the remainder of the southern flank of the Shirley Mountains (especially in sections 2-5, T24N, R82W; **Figure 4**).

Within sections 2-5 (as cited above), at the northern extreme of the present-day Hanna Basin, the generally poorly exposed Cretaceous strata are dominantly somewhat overturned, or in some cases dip steeply to the south. When standing in southern parts of sections 2-5, one can look northward and see a well-defined trace of the Shirley fault on southern flanks of the Shirley Mountains, as expressed through differential erosion (**Figure 24**). Topographically above that trace one encounters Archean pink granites and darker metamorphic rocks of the core of the Shirley Mountains. Topographically below the same line exists strongly deformed (overturned, stretched, and fractured), albeit very poorly exposed Phanerozoic strata.

Under the standard interpretation of the Shirley thrust (see above), the trace of the fault along the south flank of the Shirley Mountains has been interpreted as an expression, as though seen in cross-sectional view, of an eroding, shallowly north-dipping fault plane. The Precambrian rocks of the Shirley Mountains (hanging wall), thereby, were interpreted as having been faulted southward along a shallow fault during the Laramide orogeny to a present position atop Phanerozoic strata (footwall) of the Hanna Basin. If that scenario were true, one would expect (in map view) to observe overriding of progressively younger footwall strata from east to west along the trace of the fault.

The above-described, expected relationships between fault-trace and stratigraphy of the footwall were not observed in the revised mapping of sections 2-5 (**Figure 4**). Indeed, progressively older (not younger) strata of the footwall are observed along the trace of the Shirley fault from east to west. In short, geologic relationships along the south flank

Figure 24. View to north, showing southern flank of Shirley Mountains, at extreme northern edge of Hanna Basin. Sharp horizontal line about halfway up flank of hill is modern erosional trace of Shirley fault. Topographically above the fault trace one finds locally well-exposed Archean granites and metamorphic rocks. Although poorly exposed, topographically below the fault trace (*i.e.*, southward from it) exist heavily deformed, stretched, vertical to overturned, Lower Cretaceous strata. Revised mapping in this vicinity strongly suggests that the Shirley fault is not a low-angle, north-dipping thrust, but rather is best thought of as a steeply north-dipping, high-angle reverse fault. At several discrete sites along the trace of this fault exist isolated, heavily deformed outcrops of resistant Paleozoic units (see **Figures 22** and **25**), preserved as fault-bounded slivers torn free along the Shirley fault from originally intact strata. Highest hill in center of photo is west of center of section 3, T24N, R82W. Photograph by J. A. Lillegraven.

of the Shirley Mountains provide no support for the traditional concept of a Shirley thrust having a shallowly north-dipping plane. No evidence exists within the new mapping for significant overriding of the northern Hanna Basin by the Shirley Mountains. To the contrary, presently available evidence suggests that most, if not all, of the east-west component of the Shirley fault was in reality a high-angle reverse fault. This interpretation is at least compatible with published seismic evidence available from this general area (see Kaplan and Skeen, 1985, figure 2).

Miscellany relevant to the Shirley fault and local post-Laramide geologic history

Our re-investigation of the Shirley fault led to discovery of large but deformed outcrops of resistant Paleozoic strata within the actual trace of the Shirley fault. These previously overlooked outcrops (see western part of **Figure 22** and **Figure 25**) typically are constructed of Madison Limestone (Mississippian) and quartzites or pebble-conglomerates of Upper Devonian Fremont Canyon Sandstone or Cambrian Flathead Sandstone. The outcrops, and sometimes large isolated clasts derived from the same formations, occur at the elevation of the fault at irregular intervals along the south flank of the Shirley Mountains for a distance of 3 miles. Clearly, these fragmentary outliers represent fault-bounded slivers, ripped loose from the footwall and/or hanging wall during the faulting of originally intact outcrops.

Notice on **Figures 4** and **26** that we have considered the southern Shirley Mountains themselves as a highly asymmetrical anticlinal structure, having an axis oriented essentially north-south. This new interpretation is based upon the observation that steeply-dipping Paleozoic strata exist both on the southwestern and southeastern flanks of the Shirley Mountains. On the southwestern flank the strata are overturned, and Precambrian rocks unquestionably are faulted over them by a west-directed fault. Existing maps (*e.g.*, Bergh and Snoke, 1992) usually show the west-directed fault as a continuation of the "Shirley thrust."

The present surface of Little Basin (Bohn, 1990; = Seminoe-Shirley syncline of Finnell, 1951), the arcuate synclinal area lodged between the western Shirley Mountains and eastern Seminoe Mountains, is largely covered by poorly exposed, post-Laramide

Figure 25. View to west-northwest, along southern flank of southeastern part of Shirley Mountains. The two relatively dense stands of trees on lower slope of hills to left are watered from seeps just below Shirley fault. The triangular hill seen just above and to the left of distant end of two-track road is a previously unrecognized, heavily fractured and slickensided, generally east-dipping, fault-bounded sliver of resistant strata of Upper Devonian Fremont Canyon Sandstone or Cambrian Flathead Sandstone and Mississippian Madison Limestone, with smearings of softer redbeds of Amsden Formation (see **Figure 22**). This is the largest, most easterly, and most intact of several similar fault-bounded slivers of Paleozoic strata trapped within trace of Shirley fault. This string of fault-bounded slivers extends to the west in the trace of Shirley fault for nearly three miles. Triangular hill is west of center of SW of section 2, T24N, R82W. Photograph by J. A. Lillegraven.

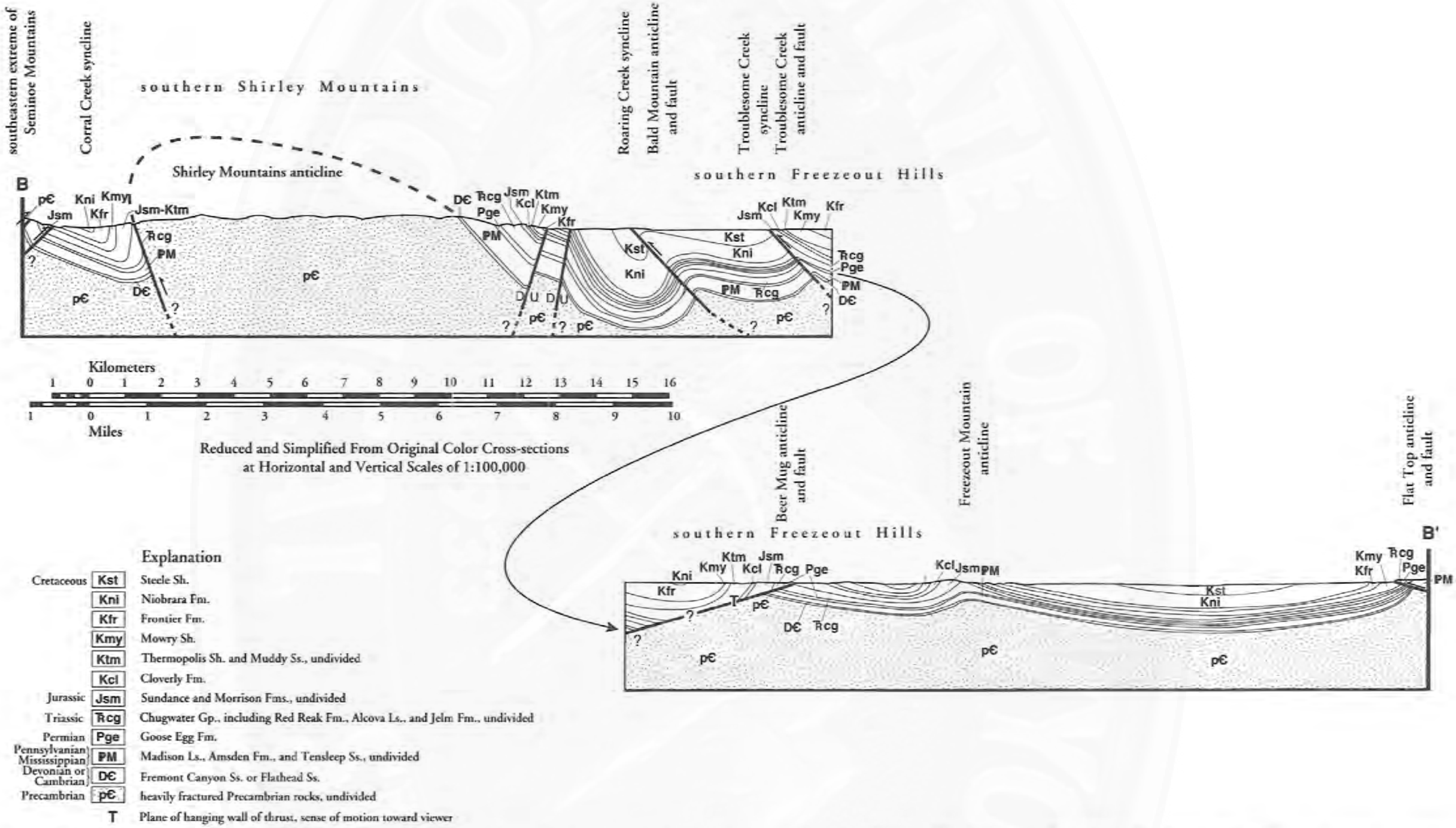


Figure 26. Interpretive geologic cross-section (along line B-B' of **Figure 4**; no vertical exaggeration), extending from eastern tip of Seminoe Mountains to northern flank of Flat Top anticline. The purpose is to suggest the degree of basement-involvement, and a possible main mechanism of uplift, of the southern Shirley Mountains and Freezeout Hills relative to the northern Hanna Basin. In all probability, a huge number of smaller faults (not shown here) occur within the basement to allow the kinds of folding observable on the surface and restored here at depth. In no case is the actual dip of the indicated faults known with certainty.

volcaniclastic strata and freshwater limestones. This cover was shown as Kortes formation by Flanagan and Montagne (1993, figure 9). The post-Laramide, essentially flat-lying strata of Little Basin continue southeastward well beyond the limit indicated by Flanagan and Montagne, to border and partly cover the southwestern corner of the Shirley Mountains (not shown in **Figure 4**). Lithologically, these strata are greatly similar to those of Chalk Bluff, set immediately south of the southeastern corner of the Shirley Mountains (**Figure 27**). Remarkably, additional small patches of freshwater limestones exist high on the southeastern Shirley Mountains (**Figure 4**; also see Love, 1963, figure 1), approximately 800 feet topographically above the top of present-day Chalk Bluff. The high-elevation limestones on the Shirley Mountains are indistinguishable lithologically from those on Chalk Bluff.

We tentatively identify the above-described strata as Browns Park Formation. For the present, we reject application to these outcrops of the informal name Kortes formation (of Flanagan and Montagne, 1993; "Tuffaceous conglomerate at Kortes Ranch" of Love and others, 1993). The principal section of the Kortes formation, which is found at markedly lower elevation north of the Seminoe Mountains is much more conglomeratic. Collectively, these strata probably represent tiny erosional remnants of what was once a vast sedimentary sheet, originally extending across the Hanna Basin to similar rocks known today from the southern Hanna (Ingle, 1977) and northern Saratoga (Montagne, 1991) basins.

Aside from root-casts and heavily silicified wood, no fossils have yet been discovered in any of the post-Laramide outcrops in vicinity of the northern Hanna Basin. Closer age refinement beyond "post-Laramide" therefore remains problematic. Most investigators (*e.g.*, Knight, 1951; Love, 1963) have suggested Miocene or Pliocene ages. LeFebre (1988), on the basis of limited fission-track samples, suggested an Oligocene age.

Except for these few tantalizing hints, what must have been a fascinating post-Laramide Tertiary history of the Hanna Basin will be left unconsidered on our trip.

Figure 27. View to east, showing west side of the northern end of Chalk Bluff. This is a small erosional remnant of post-Laramide strata (? Browns Park Formation), locally deposited upon overturned Upper Cretaceous, nonmarine strata of Medicine Bow and Ferris formations (see **Figure 22**). The caprock is a white, stromatolitic, freshwater limestone exhibiting secondarily in-filled desiccation cracks. Lithologically identical remnants, deposited directly upon the eroded Precambrian core of the Shirley Mountains, have been discovered to the north (see **Figure 4**), roughly 800 feet topographically higher than Chalk Bluff. Probably, these small remnants represent a minimally 1000-foot-thick sequence of volcaniclastic and epiclastic post-Laramide strata that formerly extended southward across the Hanna Basin to its southern extreme, and to Saratoga Basin. Strata of Chalk Bluff dip generally to the southeast (up to 24°), suggesting minor continuations of local deformation after completion of Laramide orogeny. North summit of Chalk Bluff is near midpoint of NE of section 11, T24N, R82W. Photograph by J. A. Lillegraven.

Re-evaluation of standard interpretation of the "Shirley thrust"

As discussed above, evidence gained from our new geologic mapping of the northern Hanna Basin and adjacent parts of the Shirley Mountains and Freezeout Hills has caused us to reevaluate the standard interpretation of the "Shirley thrust." Specifically, we no longer consider the feature to be a low-angle, northeast-dipping fault as exposed at the surface. Furthermore, we no longer recognize a surface trace, or an inferred surface trace, of the previously delineated "Shirley thrust" as extending southeastward from the southeastern corner of the Shirley Mountains to the southern flank of Oil Springs anticline (*i.e.*, approximately as shown in **Figure 2**).

Part of the rationale for the above conclusions was raised, albeit indirectly, at stops during Day 1 of this excursion. Specifically, recall the stratigraphic continuity of the southeastern flank of Freezeout Mountain anticline as it crosses the modern valley of the Medicine Bow River (from the Freezeout Hills into the northeastern Hanna Basin). Several existing geologic maps illustrate a "Shirley thrust" cutting, as a feature that reaches the surface, across that specific part of the modern landscape; we see no evidence for surface expression of such a fault. Also recall that at The Breaks we demonstrated the dominance of northward directed, out-of-the-basin thrust faults. Although these specific faults never before had been recognized, some of the general zones of deformation have been mapped erroneously as part of the "Shirley thrust." We demonstrated at our present stop that the surface trace of the Shirley fault is limited, and that its fault plane has a steep dip. It is clear, therefore, that the standard interpretation of a low-dipping, thrust fault exposed at the Earth's surface forming the boundary between the Shirley Mountains-Freezeout Hills and adjacent Hanna Basin requires significant revision.

Nevertheless, the existence of a deep, master, basement-involved, low-angle fault along the southern flank of the Sweetwater uplift that does not actually reach the surface is a concept that could be supported by several regional observations. For example, the map by Blackstone (1993b) delineates major structural relief between Precambrian basement rocks exposed on the Shirley Mountains (at elevations greater than 9000 feet above sea level) and their buried counterparts in the center of the Hanna Basin (at depths surpassing 30,000 feet below sea level). This magnitude of structural relief is nearly the same as differences observable between high parts of the Wind River Range and the northern Green River Basin, across the Wind River thrust. Furthermore, to the northwest of our study area near Bradley Peak (Blackstone, 1965; Bayley, 1968) and along southern flanks of the Ferris Mountains (Veronda, 1951; Bayley, 1968; Bowers, 1993) exists a low-angle, northeast-dipping, basement-involved thrust. Perhaps this represents a component of an exposed master fault that extends as far southeast, at depth, as the Freezeout Hills.

In other words, possible reconciliation of relationships involving greatly displaced elevations of the basement (see **Figure 4**) with our revised interpretation of the exposed Shirley fault could be gained by postulating existence of a blind, deep Shirley thrust. Under that scenario, the steeply dipping Shirley fault (in the sense of this paper, and seen to be of limited extent) might represent only a splay off a master, blind fault (*i.e.*, a new sense of a Shirley thrust). Similarly, the Indian Spring fault (visited during Day 1 of the excursion) could be interpreted as another splay off a master, blind Shirley thrust. In an analysis of the southern flank of the Sweetwater uplift, which employed subsurface data in addition to surface geologic mapping, Homan (1988) concluded that blind, basement-involved faulting constituted an important element during structural development and uplift of the Ferris-Seminoe mountains.

There are, however, other structural models that could be used to explain the geometric relationships manifested on **Figure 4**. It is possible, for example, that the principal cause of uplift of Flat Top anticline, the Freezeout Hills, and Shirley Mountains was not by way of southwestward motion along a deep, blind, northeast-dipping thrust fault. As an alternative, much of the uplift of the Precambrian core of Flat Top anticline, the Freezeout Hills, and Shirley Mountains relative to the northern Hanna Basin might have occurred through contractional strain related to development of the fan-like array of faulted anticlines that characterize those present highlands. Specifically, this model relates principal uplift of Flat Top anticline, the Freezeout Hills, and Shirley Mountains to basement-involved, west- and northwest-directed thrusts and asymmetric folds that are known to form the southeast-plunging nose of the Sweetwater uplift.

Spatial relationships of the alternative hypothesis can be visualized by way of our cross-section (B-B'; **Figures 4** and **26**) that extends in a straight line east-southeastward from the eastern tip of the Seminoe Mountains to the north flank of Flat Top anticline. The scenario illustrated there would require significant left-lateral transfer of the Shirley Mountains-Freezeout Hills terrane relative to the northern margin of the Hanna Basin, possibly along traces of the out-of-the-basin thrusts. This is an hypothesis that is readily testable in the field, although we have not yet done so.

The two hypotheses presented above are not mutually exclusive. Indeed, evidence exists to support the concept that both scenarios played important roles in structural development of the Seminoe-Shirley mountains, Freezeout Hills, and Flat Top anticline in relation to the northern Hanna Basin.

Stop 2–Out-of-the-basin thrusts between Schneider and Horseshoe ridges

The field discussion begins in the north-central part of section 12, T24N, R83W.

Introduction to local stratigraphy

Our parking place is in a valley between two more-or-less parallel ridges that trend essentially east-west (**Figure 28**). All strata within sight of here represent the Upper Cretaceous, and most of the section is essentially vertical or overturned. Stratigraphic "up" in this area generally is to the south, although complex folds within the valley itself provide interesting exceptions to that rule. The more southerly ridge (Schneider Ridge), except at its northern base, is composed of shallow marine and terrestrial strata of the Medicine Bow Formation. The marine components of the lower Medicine Bow Formation represent the youngest known incursions of the Western Interior Seaway into central Wyoming (see Lillegraven and Ostresh, 1990); in many references, that distinction is ascribed to the underlying Lewis Shale. In this particular part of the Hanna Basin there exists no consistently expressed, lithologically distinctive "Fox Hills Sandstone" between the Lewis Shale and Medicine Bow Formation, although the term on occasion has been used (Fox, 1971).

The more northerly ridge (Horseshoe Ridge) is heavily faulted, and near Stop 2 is variously constructed from lower parts of the Lewis Shale, formations of the Mesaverde Group (especially, faulted slivers of the Almond Formation and more substantial components of the Allen Ridge Formation), and top of the Steele Shale.

Nature and significance of the Austin Creek anticline

Stop 2 is toward the north end of the semi-agricultural valley of Austin Creek. Exposed Cretaceous rocks of the valley are principally Lewis Shale. Despite its initial appearance of simplicity, the valley of Austin Creek, and particularly its eastern extreme, is extraordinarily complex in a structural sense. As a good place to gain basic understanding of the situation, look immediately west of the road from our parking place. At the road's edge one can see anomalously east-dipping sheets of lower sandstones of the Lewis Shale on the axis of an asymmetrical, east-plunging anticline (Austin Creek anticline, as illustrated by Blackstone, 1983, figure 5). The anticline, which has steeper dips on its northern flank, exists in the valley between sets of essentially vertical strata of the Lewis Shale.

Modern erosion at the crest of the anticline exposes peculiar fluvial sandstones and finer-grained strata of the Mesaverde Group. We use the term "peculiar" because the exposed older strata are uncharacteristic of the Almond Formation, which is the element of the Mesaverde Group that would be expected immediately below the base of the Lewis Shale. An intervening fault may exist, although this possible explanation has not been pursued adequately. From the eroding axis of the anticline, one can walk northward up-section through the Lewis Shale until a well-defined fault is encountered. Step across the fault, continue northward, and one begins to move down-section through lower reaches of the Lewis Shale.

Blackstone (1983, p. 6) interpreted the Austin Creek anticline, and we believe correctly so, as hav-

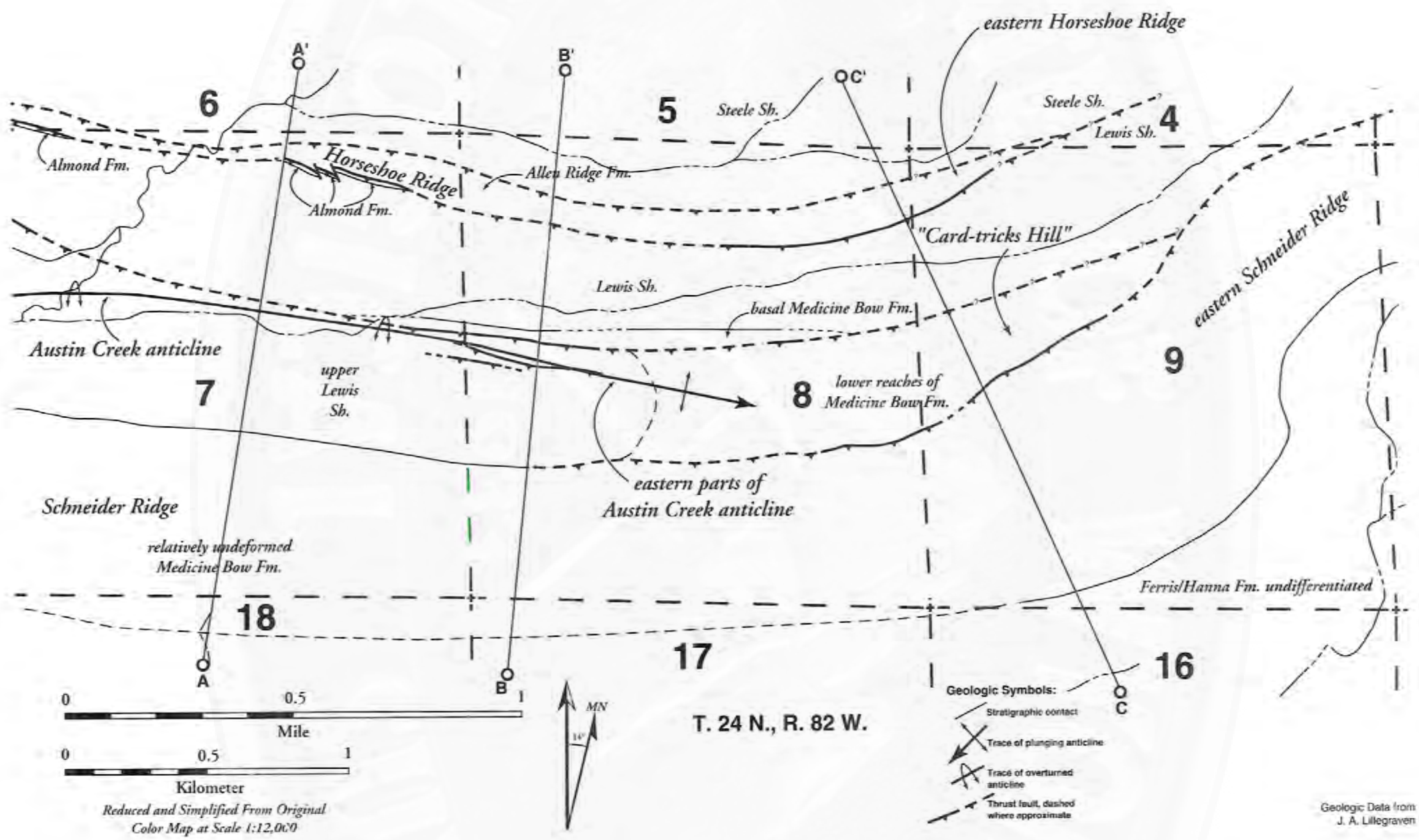


Figure 28. Geologic map of vicinity of eastern parts of the valley of Austin Creek, between Horseshoe and Schneider ridges. Principal features include: (1) eastern end of the Austin Creek anticline; (2) the overriding of eastern Schneider Ridge upon the eastern extreme of the anticline; and (3) a series of additional, previously unrecognized out-of-the-basin thrusts that served to cut away important parts of the Mesaverde Group along eastern parts of Horseshoe Ridge. Restored, interpretive geologic cross-sections A-A' through C-C' are presented in **Figure 30**.

ing resulted from ". . . a bedding plane fault and interstratal slippage between the massive sandstones of the Mesaverde and Medicine Bow Formations." As recognized from renewed efforts in geologic mapping, we add that the Austin Creek anticline is but one relatively minor, albeit well-exposed, example of a multitude of complexly oriented, out-of-the-basin thrust faults that dominated the Laramide tectonic history of most of the Hanna Basin's northern margin.

Added tectonic complexities observed near eastern ends of Schneider and Horseshoe ridges

By looking eastward from Stop 2, one can see that the valley of Austin Creek becomes narrowed to the east. Mapping performed in 1995 (**Figure 28**) confirms that the Austin Creek anticline and its associated bedding-plane fault, as recognizable structures, continue eastward from Stop 2 for more than two miles. Throughout that distance, the anticline continues its generally eastward plunge. One effect of the continuing plunge is that the modern surface of erosion becomes expressed stratigraphically upward through the anticline to the east, exposing progressively higher strata of the Lewis Shale. Continuing still further to the east, lower strata of the Medicine Bow Formation eventually are attained, as integral components of the Austin Creek anticline. Stratigraphic levels rising into the basal Medicine Bow Formation are encountered near the center of section 8, T24N, R82W.

At about that same longitude, the northern base of Schneider Ridge itself exhibits the origin of a new out-of-the-basin fault that can be traced to the east and northeast for at least two miles. Hinge-like motion along that fault served to have the eastern end of the Austin Creek anticline overridden by northward translation of the eastern end of Schneider Ridge. During that process, lower levels of the Medicine Bow Formation of the Austin Creek anticline became overthrust by lower levels of that same formation as they existed on Schneider Ridge. The relatively incompetent strata on the easternmost observable crest of the Austin Creek anticline (*i.e.*, the footwall of the thrust; located in east- and west-central adjacent parts of sections 8 and 9, T24N, R82W, expressed as an odd topographic feature that we call "Card-tricks Hill") became incredibly folded, and riddled with minor faults (**Figure 29**). Surely this intense deformation occurred during the process of north-directed overthrusting of Schneider Ridge. The eastward narrowing of the present-day valley of Austin Creek reflects that Laramide deformation.

The massively faulted nature of eastern Horseshoe Ridge

Elements of the Mesaverde Group on Horseshoe Ridge to the north and east of Stop 2 also were profoundly modified by bedding-plane faults (**Figures 28** and **30**). For example, along the southwestern border of section 6 (T24N, R82W) only a thin sliver of Almond Formation persists, and it clearly is in fault contact with upper levels of an inordinately thin section of Allen Ridge Formation. The normally intervening, lithologically distinctive Pine Ridge Sandstone has been lost through faulting. Similarly, the abnormally thin Allen Ridge Formation exists in section 6 in direct fault contact upon the Steele Shale; again, the normally intervening Haystack Mountains Formation appears to have been lost through faulting. A more complete representation of expected formations of the Mesaverde Group exists on Horseshoe Ridge to the west of Stop 2, and the topographic width of the ridge itself increases markedly westward.

Stratigraphic relationships at the eastern extreme of Horseshoe Ridge (western border between sections 4 and 9, T24N, R82W) are particularly interesting. Even though exposures of the generally soft strata are poor, it is virtually certain that the Lewis Shale has been faulted directly upon the Steele Shale. Normally intervening, relatively indurated strata of the Mesaverde Group, therefore, must have been cut completely away.

Orientations of local fault-planes– now, and when they formed

As mentioned above, Blackstone (1983) suggested that the fault associated with the Austin Creek anticline principally represents slippage between bedding planes. We agree with that interpretation, and apply it to nearly all of the recently recognized faults in this area. We add the obvious qualifier, however, that evolving faults occasionally had to have cut significantly across stratigraphic horizons

Figure 29. View to north, showing hill ("Card-tricks Hill") composed of tectonically repeated, intensely faulted and folded section of basal Medicine Bow Formation. White sandstones near center of photograph form one of several tight chevron folds observable on "Card-tricks Hill." We interpret the extreme deformation as representing off-scrapings of lower Medicine Bow Formation that formed as strata (which today form eastern extremes of Schneider Ridge) were thrust northward (out-of-the-basin) across the east-plunging end of Austin Creek anticline (see **Figure 28**) during the Laramide orogeny. See text for further information. The top-left of the hill is near the southwestern corner of NW of section 9, T24N, R82W. Photograph by J. A. Lillegraven.

to allow explanation of existing peculiarities of observed stratigraphic relationships.

Most of the strata in vicinity of Stop 2 are nearly vertical to overturned. It follows, therefore, that most of the fault-planes also must dip at very high (to overturned) angles (**Figure 30**). For mechanical reasons alone, however, it seems a virtual certainty that most of the structural (and stratigraphic) separation along these faults occurred while the strata, and thereby the fault-planes themselves, possessed much shallower dips. At that time, as suggested by new evidence derived from most of the length of the Hanna Basin's northern border, fault separations principally occurred from south to north (*i.e.*, out-of-the-basin). On the assumption that this concept is correct, we applied to our maps the ordinary geologic symbol for thrust-faults (*i.e.*, toothed lines) to represent fault-planes that today might have vertical to inverted orientations.

It is interesting to note in vicinity of Stop 2 (and at many other places along the northern and northeastern margins of the Hanna Basin) that mapped stratigraphic relationships commonly suggest fault placement of younger strata on top of older strata. Additionally, and somewhat puzzlingly, strata showing younger-on-older fault relationships commonly exhibit closely similar attitudes above and below the fault-planes. Is there a plausible explanation for such relationships that does not involve stratigraphic down-ramping during the process of faulting? As a miscellaneous and very much expected point, the hanging wall of these faults typically is significantly more deformed than the footwall (the situation at Card-tricks Hill is an obvious exception; **Figure 29**).

Invitation to speculate upon local tectonic evolution

At Stop 2 we stand within the bowels of an enormously thick Cretaceous section that is character-

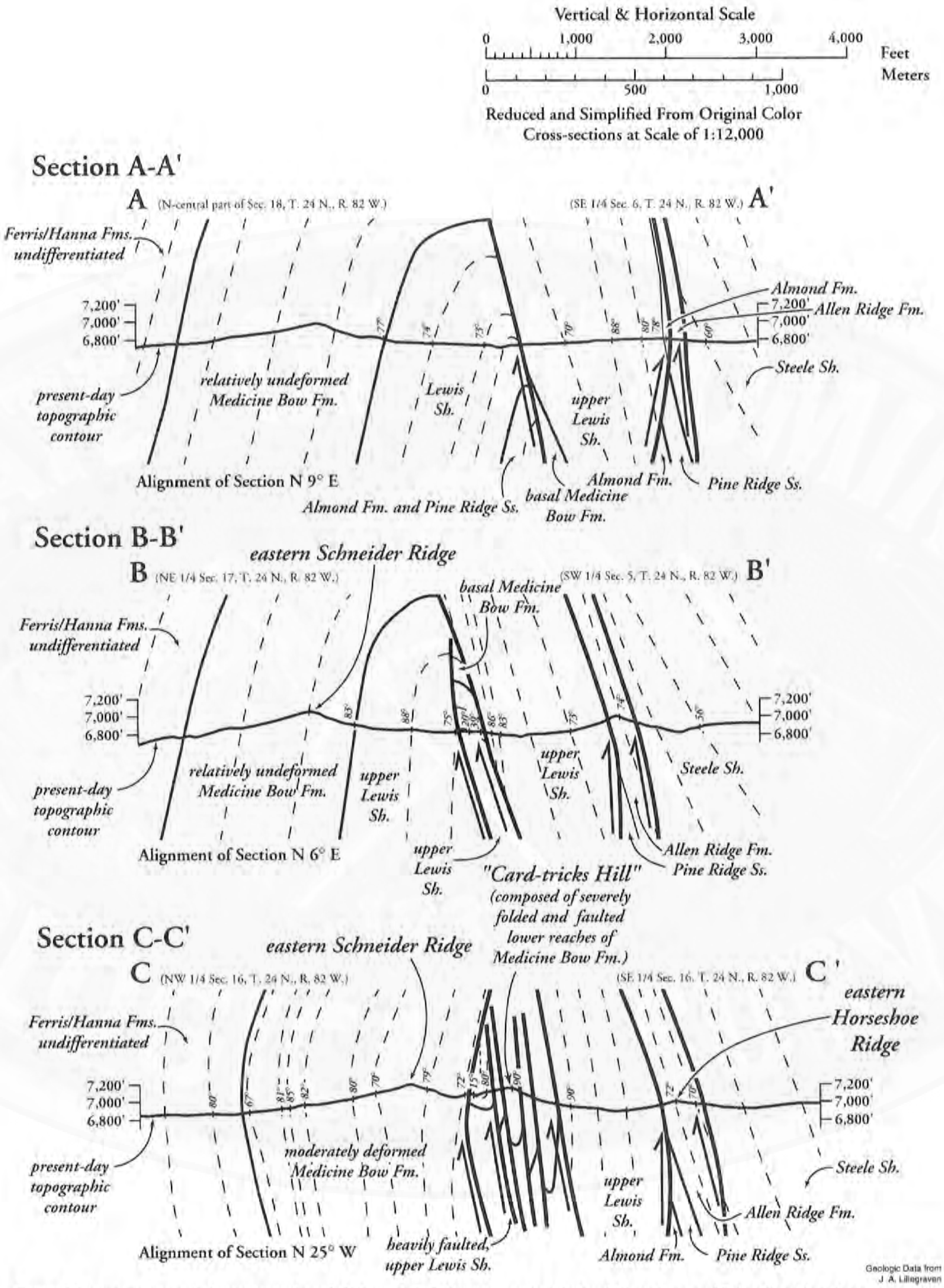


Figure 30. Interpretive geologic cross-sections A-A' through C-C' between eastern limbs of Horseshoe and Schneider ridges (see **Figure 28** for alignments; no vertical exaggeration), restored across existing topography. Because most of the faults probably are oriented close to stratigraphic bedding-planes, most of them are restored here as nearly vertical to somewhat overturned. In all probability, most displacements (indicated by arrows) along these out-of-the-basin faults occurred prior to vertical tilting of the general stratigraphic section as observed in vicinity of Austin Creek. Note that several of the thrusts are interpreted to have cut stratigraphically down-section.

ized by dips consistently approaching (and even exceeding) vertical. Southward travel from this point requires stratigraphic gain of approximately 15,000 additional feet to reach levels deposited during closing phases of the Paleocene. Throughout that great stratigraphic extent, observed dips are seen to decrease southward gradually, only incrementally, and multi-scaled indicators of interstratal sliding are ubiquitous.

Most of this deformation, we argue, occurred late in the local history of the Laramide orogeny (*i.e.*, during, and perhaps continuing after, deposition of the top third of the Hanna Formation). Furthermore, the thought of bending such a colossal sedimentary heap to present attitudes in the absence of extensive basement-involved deformation seems ludicrous. Less than 2 miles north of Stop 2, at the Shirley fault, is encountered the deeply eroded Precambrian core of the large-scale, asymmetrical anticline known as the Shirley Mountains; recall our suggestion that the anticline, cut by the Shirley fault, plunges southward at depth. Perhaps now is the time to speculate upon uplift mechanisms and/or models that could be used to explain the patterns of deformation observed within the prodigious late Mesozoic-Paleogene section of the northern Hanna Basin.

Stop 3–Eastern end of the Seminoe Mountains–basement-cover relationships

The discussion in the field begins in the east-central part of section 14, T25N, R83W.

At this stop we are situated in a broad topographic saddle between the western Shirley Mountains and eastern Seminoe mountains (**Figures 3** and **4**, **31** through **33**). Immediately to the northwest, this topographic low has been referred to as Little Basin (see Bohn, 1990, for geologic mapping). Structurally, the saddle between the Shirley Mountains and Seminoe Mountains represents a complexly deformed, arcuate syncline that reflects opposite senses of uplift between the two ranges during the Laramide orogeny (**Figure 26**).

The Seminoe Mountains are bounded on the northeast by the North Bennett Mountain fault, a southwest-dipping, Laramide-age reverse fault (Finnell, 1951; Blackstone, 1983; **Figure 31**). Along strike of this fault to the northwest, a Neogene normal fault (locally referred to as the Kortes normal fault by Blackstone, 1965) is superimposed upon this zone of Laramide contraction. This complex fault zone forms the eastern terminus of the South Granite Mountains fault system of Love (1970), along which collapse of the Granite Mountains graben occurred during late Neogene time. Across the topographic low (*i.e.*, southeast extension of Little Basin) to the east and northeast, the Shirley fault merges into a northeast-striking, steeply dipping, oblique-slip fault (Bergh and Snoke, 1992). The fault is manifested topographically by the canyon of Saylor Creek, and defines the faulted southwestern margin of the Shirley Mountains.

The southeastern end of the Seminoe Mountains affords an excellent down-plunge view of a basement-involved, Laramide, faulted fold as well as evidence of multiphasic faulting (**Figures 32** and **33**). Traverse approximately south-southwest from our parking spot to exposures of Late Archean granitic rocks (granite of Seminoe Dam after Dixon, 1990), which form the hanging wall of an up-faulted basement block exposed in the eastern core of the Seminoe Mountains (locally referred to as Bennett Mountain). The granitic rocks exhibit variable deformation, ranging from nonfoliated to foliated, even to mylonitic (Dixon, 1990; Bohn, 1990).

The contact between the Late Archean granitic rocks and Madison Limestone is a reverse fault that strikes north-south, manifested topographically by a saddle along the ridgeline. The north end of this fault is truncated by the North Bennett Mountain fault. The north-south reverse fault also is truncated to the south by the northwest-striking Beaver Jimmy Creek fault (Homan, 1988; Braathen and Snoke, 1994).

Climb eastward above the saddle onto resistant exposures of Mississippian Madison Limestone. From this point, one enjoys good views of Horseshoe Ridge (Mesaverde Group), Schneider Ridge (Medicine Bow Formation), and northern parts of Hanna Basin. Elk Mountain (11,162 feet) is the prominent peak about 165° (north = 0°) from our viewpoint. The Sierra Madre (~190°) is on the southern skyline. Also, a prominent, southeast-trending arm of Seminoe Reservoir is visible at ~200°, reflecting the original valley of the Medi-

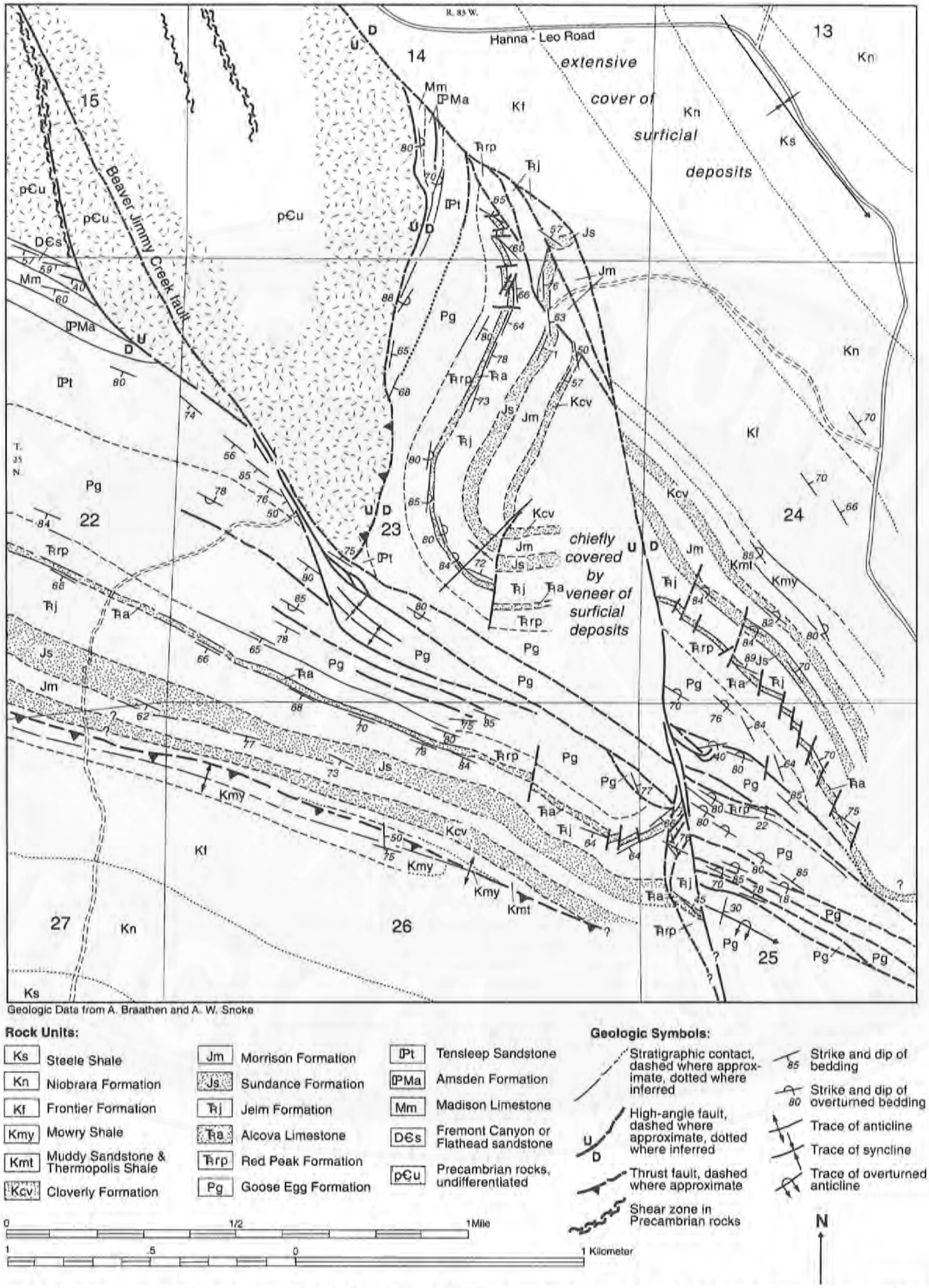


Figure 31. Preliminary geologic map of eastern end of the Seminoe Mountains and southeastern parts of Little Basin. Base map included the following U.S. Geological Survey 7.5-minute quadrangles: Seminoe Dam NE, Beaver Creek, Seminoe Dam SE, and Schneider Ridge. Geology by Alvar Braathen and A. W. Snoke.

Figure 32. View to west toward eastern end of the Seminoe Mountains. The prominent, light-colored exposures near the center of the photograph are steeply dipping to subvertical Pennsylvanian Tensleep Sandstone in apparent steep fault contact with Permian Goose Egg Formation (footwall; see **Figure 31**). The higher ground behind the exposures of Tensleep Sandstone is comprised chiefly of Late Archean granitic rocks, although a thin wedge of Pennsylvanian-Mississippian Amsden Formation and Mississippian Madison Limestone occurs between the Tensleep exposures and Archean granitic rocks. The contact between the Madison Limestone and Archean granitic rocks is a north-south-striking reverse fault that dips steeply westward. The low ground in front of the Tensleep exposures is composed of Permian Goose Egg Formation and various lower Mesozoic stratigraphic units that become progressively younger toward the camera. Photograph by A. W. Snoke.

cine Bow River. Directly below our vantage point, the Middle Triassic Alcova Limestone, a prominent resistant marker layer, defines part of the faulted fold system at the southeastern end of Bennett Mountain.

Traverse downhill to the southeast from the saddle, crossing progressively younger strata (Mississippian through Lower Cretaceous) that define the southeast-plunging, eastern terminus of the Seminoe Mountains. This distinctive sedimentary sequence is truncated by an unnamed, north-northwest striking, steep fault that appears to merge into the North Bennett Mountain reverse fault. The unusual strike of the unnamed fault suggests a complex deformational history, involving an important dip-slip component (west side up) coupled with a probable strike-slip component. Small-scale strike-slip faults are common in this area, exhibiting both right-lateral and left-lateral separations; these strike-slip faults appear to constitute a conjugate set. Additional geologic mapping and kinematic studies are required to better understand the significance of the unnamed north-northwest-striking fault.

Day three of field trip

Stop 1–Oil Springs/Flat Top anticlines

The discussion in the field begins along the northern flank of the Oil Springs anticline, near its eastern end in section 2, T23N, R79W.

The Oil Springs anticline, as exposed at the surface, is a tight anticline that trends N 70° W, with an overturned northern limb (Blevens, 1984; Blackstone, 1994; **Figure 34**). The anticline has been defined by wells drilled down plunge both at its western and eastern extremities. The fold is the essential feature of the Oil Springs Field, which is the northernmost oil field in the Hanna Basin. The Oil Springs Field is outlined by the Wall Creek Sandstone Member of the Frontier Formation. The Wall

Figure 33. View to southeast from eastern end of Seminoe Mountains toward the southwest corner of the Shirley Mountains, with Horseshoe and Schneider ridges and the northern margin of the Hanna Basin in the far background. In the center of the photograph, part of the plunging core of a faulted anticline is well exposed. The core of the fold consists of much faulted and deformed, red-weathering, Permian Goose Egg Formation. Homan (1988) reported hydrocarbon-stained limestone in the Goose Egg Formation from near the crest of the anticline. To the left of this core area are several low ridge-forming units including (in stratigraphic order from right to left): Middle Triassic Alcova Limestone, Middle Jurassic Sundance Formation, Lower Cretaceous Cloverly Formation, and Upper Cretaceous Mowry Shale. Photograph by A. W. Snoke.

Creek Sandstone is repeated on the south limb of the anticline by a south-dipping reverse fault. The reverse fault appears to pass into a bedding-plane fault at depth, although it may reach basement (Blevens, 1984; Blackstone, 1994).

A major aspect of the Oil Springs anticline is the apparent discrepancy between fold expressions of the Wall Creek Sandstone and the top of the Jurassic Sundance Formation, as seen at the surface and in the subsurface, respectively. Blackstone (1994) based his interpretation of subsurface relationships upon data from sixteen wells, and concluded that the fold as seen at depth is not as tight as at the surface. According to seismic reflection data made accessible to us by Sinclair Oil Company (via the courtesy of Mark Rogers and Carl F. Pirner), the tight surface fold that defines the Oil Springs anticline is interpreted to be detached in the subsurface.

From well data, Blackstone (1994) suggested existence of a thrust, as indicated by repetition of the Lower Cretaceous Cloverly Formation (data from Sharples 1-A Govt., in SE of section 6, T23N, R79W). Blackstone further proposed that the fault represents the eastern end of the "Shirley thrust."

The Ohio Oil Company drilled an initial test on the Oil Springs anticline in 1918 (No. 1 Federal, in section 2, T23N, R79W). The well was drilled to a total depth of 1048 feet (451 m), to upper sandstones of the "Dakota" (= Cloverly Formation), encountering minor shows of gas. The discovery well was the Cunningham Oil Company No. 1 (UPRR-Cronberg, in section 3, T23N, R79W), drilled in 1938 to a total depth of 2350 feet (716 m) into sandstone of the Middle Jurassic Sundance Formation. Initial production was 55 million cubic feet of natural gas per day. The Northern Gas Company ac-

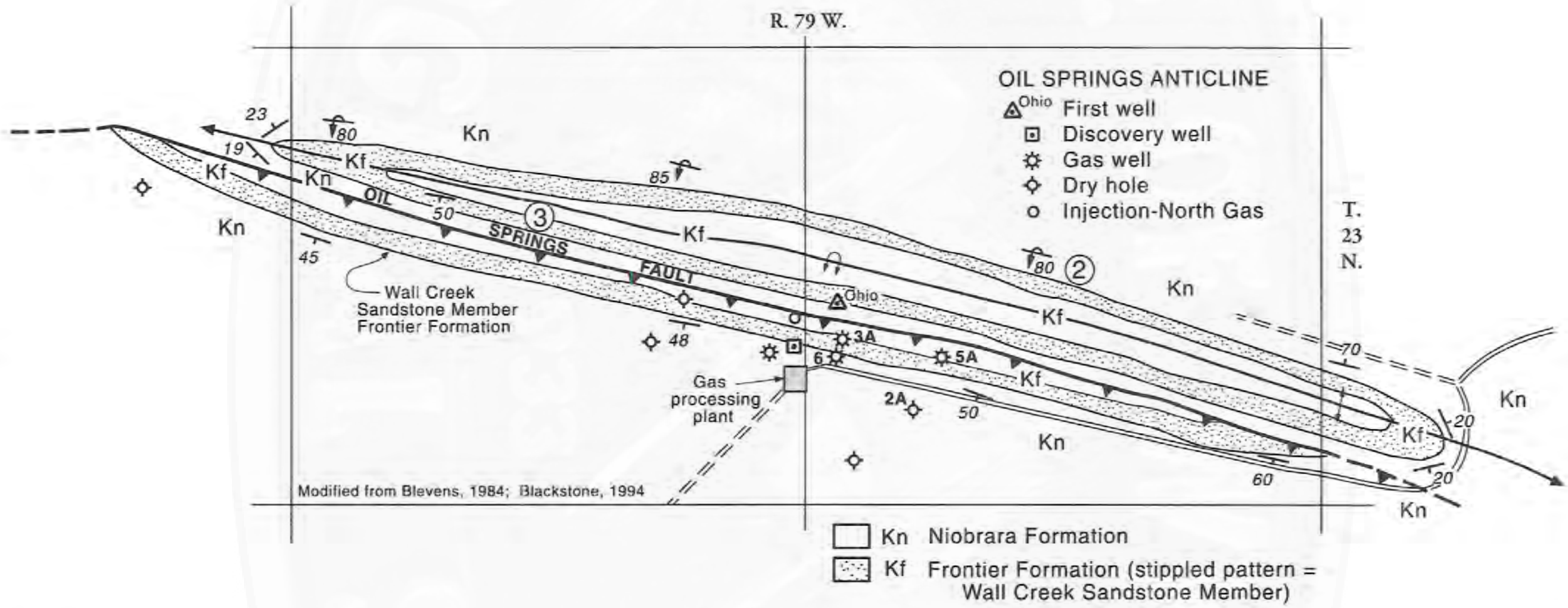


Figure 34. Geologic map of Oil Springs anticline, derived from Blackstone (1994, figure 4), which in turn was developed from geologic mapping by Blevens (1984). Outcrop pattern of Wall Creek Sandstone Member of the Frontier Formation is stippled to depict basic geometry of the structure.

quired the field in 1952, and now uses it to store gas in transit.

Stop 2–Relatively undeformed Upper Cretaceous section at Pine Draw

The discussion in the field begins near the west-central edge of section 20, T23N, R79W.

Purposes of final stop

This last stop of the excursion has three main purposes. The first is to consider the tectonic significance of Flat Top anticline (as well as others nearby) in relation to general structure of the northeastern corner of the Hanna Basin. The second purpose is simply to observe relatively undeformed, interleaved marine/nonmarine components of the Mesaverde Group. This will be done by way of a short hike stratigraphically up-section, to a viewpoint at which the vastness of the total Upper Cretaceous section of the northeastern basin can be more fully appreciated. Finally, near the viewpoint, within the setting of a long-abandoned Native American village, the trip leaders will invite general, informal discussion amongst the participants on the relevance of this area to interpreting the Laramide evolution of the Rocky Mountains. We consider this open discussion to represent the single most important purpose of the entire excursion.

Tectonic influence of Flat Top anticline

Before beginning the hike, look northeastward across the foreground toward the steeply dipping, thin sheets of marine sandstone within upper parts of the Steele Shale. These sands are readily traceable in the field, and thus provide useful markers for following strata around the largely vegetated northeastern corner of the Hanna Basin.

Notice on **Figure 4** that these marker sands in the Steele Shale do not follow the general northwestward curve at the Hanna Basin's northeastern corner as defined by strikes of formations of the overlying Mesaverde Group. To the contrary, the part of the Steele Shale bearing the marker sands seems to become detached from strata of the Mesaverde Group, and continues independently to the east-northeast for nearly 2 miles. The marker sands become overturned near their eastern extreme. The outcrop pattern then effects a sharp bend back to the northwest, and finally the upper beds of the Steele Shale turn due west to return to their expected stratigraphic position at the base of the Mesaverde Group.

As shown on **Figure 4**, outcrops of the above-described, independent eastward loop of the upper Steele Shale define a small syncline. We interpret this structure as a westward continuation of the Flat Top syncline of Blevens (1984). The syncline rests upon the northern flank of the steep, west-plunging nose of Flat Top anticline. We suggest that detachment of the upper Steele Shale from the overlying Mesaverde Group is a consequence of tectonic development of Flat Top anticline, involving northwest-vergent folding with a westward plunge.

The basement-involved stress field responsible for Flat Top anticline's northwest-directed folding (including associated thrust-faulting along parts of the anticline's northern flank), in combination with the westward plunge of the anticline, must have profoundly influenced structural evolution of the northeastern corner of the Hanna Basin. Prior to formation of Flat Top anticline, strikes of the presently southeastward curving Upper Cretaceous sequence at the northeastern corner of the Hanna Basin would have continued more directly eastward. In other words, the presently obvious northeastern structural corner of the Hanna Basin was less clearly defined prior to evolution of Flat Top anticline. Additionally, relative to the Freezeout Hills, net motion of the immediate Laramide landscape resulting from development of western elements of Flat Top anticline would have involved right-lateral oblique slip. All the various tectonic features observed at Stops 1 and 4 during Day 1 of this trip (recall The Breaks fault system and faults with components of right-lateral and/or oblique out-of-the-basin separation on the hill in vicinity of Tepee-ring Ridge) are compatible with the kinds of deformation expected in relation to the folding and faulting of Flat Top anticline.

The sequence of asymmetrical anticlines with axes trending northeast-southwest between the eastern Hanna Basin and Laramie Mountains (*i.e.*, Flat Top, Como Bluff, Gillespie, and McGill anticlines; see Blackstone, 1993a, figure 2) is not covered by younger strata that might allow direct dating of anticlinal folding. Perhaps the local anticlinal evolution can be constrained indirectly, however, by recognizing the timing of related structural events, as described above, within the northeastern corner of the Hanna Basin itself. Specifically, we suggest that the principal folding of Flat Top anticline occurred sometime after deposition of the lower two-thirds of the Hanna Formation–that is, not before late phases of Paleocene time.

Traverse of the Mesaverde Group to a viewpoint for a final discussion

Excellent photographs and descriptions of local rock types for the section of the Mesaverde Group at Pine Draw were presented by Gill and others (1970), and need not be repeated here. The exposures of all consequential units are superb and, except for the steep westward dips, the section is relatively undeformed. No better exposures exist in vicinity of the eastern Hanna Basin to gain impressions of local Upper Cretaceous stratigraphy (**Figure 8**).

After reaching our viewpoint at the top of the piney ridge (near the western border of NE of section 19, T23N, R79W), one gains a magnificent view to the west across the great thicknesses of the Lewis Shale and Medicine Bow Formation. An unusually well-exposed section of what can be considered as Fox Hills Sandstone intervenes between the Lewis Shale and Medicine Bow Formation; recall that such a lithologic distinction could not be made along the north flank of Schneider Ridge. Stratigraphy of the inside of the Hanna Basin's northeastern corner can be seen very well from our piney viewpoint. Two levels of "Dad Sandstones" (Perman, 1990) are seen to be well exposed within the curvature of the Lewis Shale.

Note the abundance of tepee-rings in relatively sheltered sites along the crest of the piney ridge.

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Notes

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