THE GEOLOGICAL SURVEY OF WYOMING
Gary B. Glass, State Geologist

OVERVIEW OF THE HANNA, CARBON, AND COOPER LAKE BASINS, SOUTHEASTERN WYOMING

by

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Report of Investigations No. 48
1993

Laramie, Wyoming

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Front cover: Oblique aerial view of Como Bluff anticline, northern Albany County, Wyoming. View is to the northeast. Laramie Peak is on the skyline in the upper left of the photograph, U.S. Highway 30 and the Union Pacific Railroad are near the bottom of the photograph. Como Bluff is one of the several northeast trending, asymmetrical folds south of the Wyoming lineament. The prominent white beds near the highway are in the Upper Cretaceous Mowry Shale. (Photograph by R.W. Jones, March, 1985.)

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by

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Abstract

A compound basinal downwarp trends N70°W across south-central Wyoming and includes the Camp Creek syncline, Hanna Basin, Carbon Basin, and Cooper Lake Basin. The Hanna Basin is very deep—the top of the "Dakota Sandstone" (Cloverly Formation) is at least 25,000 feet (7,620 m) below mean sea level—for a small intermontane foreland basin. The location and depth of the basin is due in part to the interference by the northeast trending Wyoming lineament. The Hanna Basin is separated from the Carbon and Cooper Lake Basins by the large, northeast trending anticline, Simpson Ridge.

The basins involved in this compound downwarp developed during a period of broad folding of the crust that began in Late Cretaceous time and accelerated in the Paleocene. No well-defined marginal thrusting developed until post-Tiffanian time. The Hanna Basin was not caused by marginal thrusting, but rather by broad regional response of the crust to a compressive stress field.

Introduction

The Hanna Basin region of south-central Wyoming has been investigated by many geologists including: King (1876), Hayden (1883), Veatch (1907), Darton and Siebenthal (1909), Bowen (1918), Dobbin and others (1929), Lovering (1929), Beckwith (1941), Knight (1951 and 1953), Shelton (1968), Oliver (1970), and LeFebre (1988). A more complete list of previous investigations is given under **References;** specific studies are cited in the text.

The area first received attention upon construction of the Union Pacific Railroad in 1869. Coal mines were opened at Carbon, Wyoming (now known as Old Carbon), to provide fuel for steam locomotives but later the railroad was relocated northward and new mines were opened at Hanna. Interest in the coal reserves stimulated renewed investigation of the basin and its margins, but emphasis was placed on the central coal-bearing part of the basin, and its unusual depth. The writer believes that these investigators had too narrow a view, focused only on the great depth of the basin and its rather limited areal extent.

The writer has previously presented data on the Hanna Basin (Blackstone, 1983) but now proposes an interpretation that is broader in outlook and includes the minor Carbon Basin and the Cooper Lake Basin (**Figures 1** and **2**). In addition, an attempt will be made to explain crustal behavior in the area.

The dominant structural grain in south-central Wyoming is N70°W, as exhibited by the southeastward extension of the Wind River Range and bounding Wind River thrust fault, the Sweetwater arch and the Emigrant Trail thrust fault, and by the Seminoe-Shirley-Freezeout Mountains uplift and the related Bradley Peak and Shirley thrust faults (**Figures 1** and **2**).

A synclinal depression sub-parallel to the Sweetwater arch begins near Muddy Gap, Wyoming, as the Camp Creek syncline and plunges eastward into the profound Hanna Basin depression. The regional depression continues to the southeast across the Carbon Basin and into the Cooper Lake Basin. The outline of this downwarp is depicted by the outcrop pattern of the Cretaceous Mesaverde Group (**Figure 2**), and the structure contour map (**Plate 1**).

The writer reviewed the structural features of this region and demonstrated that the primary cause of the Laramide deformation was a compressional stress field (Blackstone, 1983). These features will not be reviewed again here. Instead, the writer has prepared a structure contour map (**Plate 1**) accompanied by both published and new cross sections (**Plate 2**). These data provide an overview of the gross anatomy of the basins.

The writer will develop the thesis that the Hanna Basin is not a discrete, local, and particularly deep basin but rather part of a major structural downwarp trending N70°W subparallel to the mountain uplifts along the north flank. The depression is modified by structures trending northeast that are associated with the Wyoming lineament (Ransome, 1915) and other northeast trending features (Maughan and Perry, 1986)

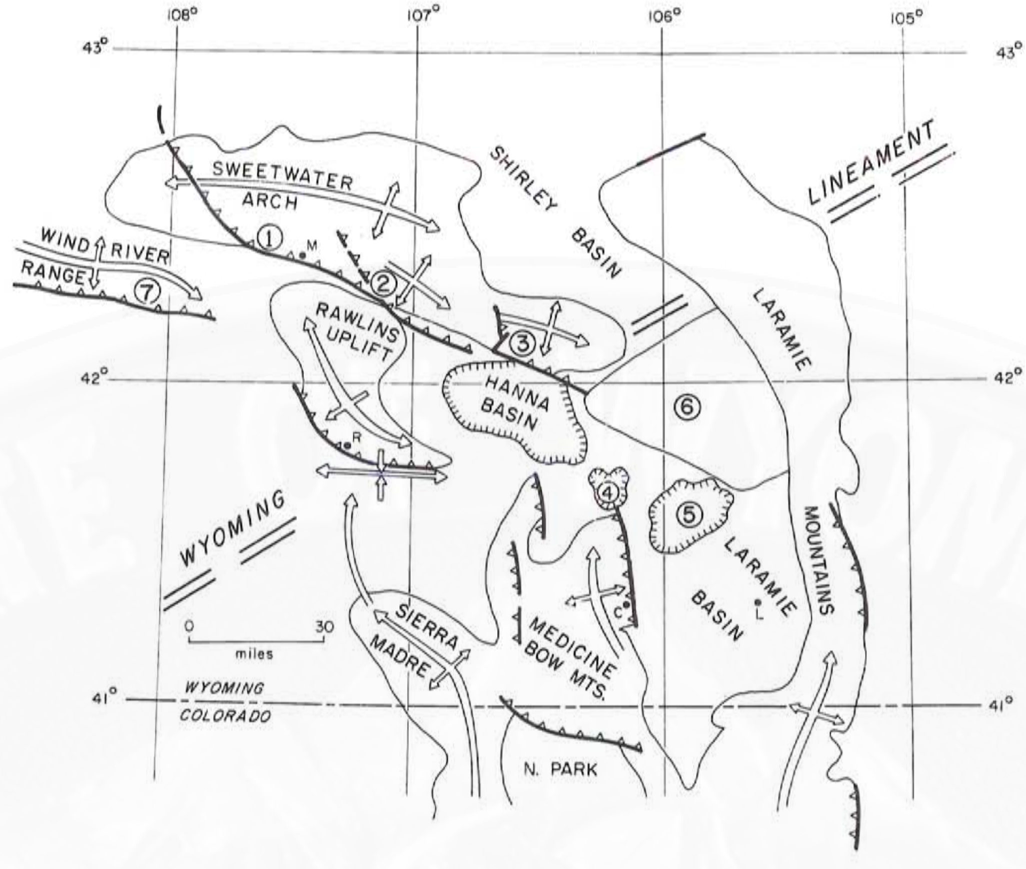

Figure 1. Tectonic map of the Hanna-Carbon-Cooper Lake Basin complex and surrounding area. 1. Emigrant Trail thrust fault; 2. Bradley Peak thrust fault; 3. Shirley thrust fault; 4. Carbon Basin; 5. Cooper Lake Basin; 6. Area of northeast trending folds; and 7. Wind River thrust fault. Towns shown as black dots: L=Laramie, C=Centennial, R=Rawlins, and M=Muddy Gap. Heavy lines are normal faults; heavy lines with sawteeth are reverse or thrust faults.

Location

The area includes approximately 4,824 square miles (12,328 square kilometers) in Albany and Carbon Counties, Wyoming. The area is traversed by the Union Pacific Railroad (UPRR), Interstate Highway 80, U.S. Highways 30 and 87, and by numerous county roads (**Figure 2**). The region is drained by the North Platte River and its tributaries.

Regional framework

The regional structural feature is a N70°W trending structural depression that extends from near Three Forks (Muddy Gap), Wyoming, as the Camp Creek syncline southeastward parallel to the Sweetwater arch, thence through the Hanna, Carbon, and Cooper Lake Basins. The depression is asymmetrical, steep on the northeast limb, and in general is fault bounded on the northeast by either reverse or thrust faults.

The major fault at the western end of the depression is the Emigrant Trail thrust fault (Love, 1970; Blackstone, 1990), which extends eastward to include

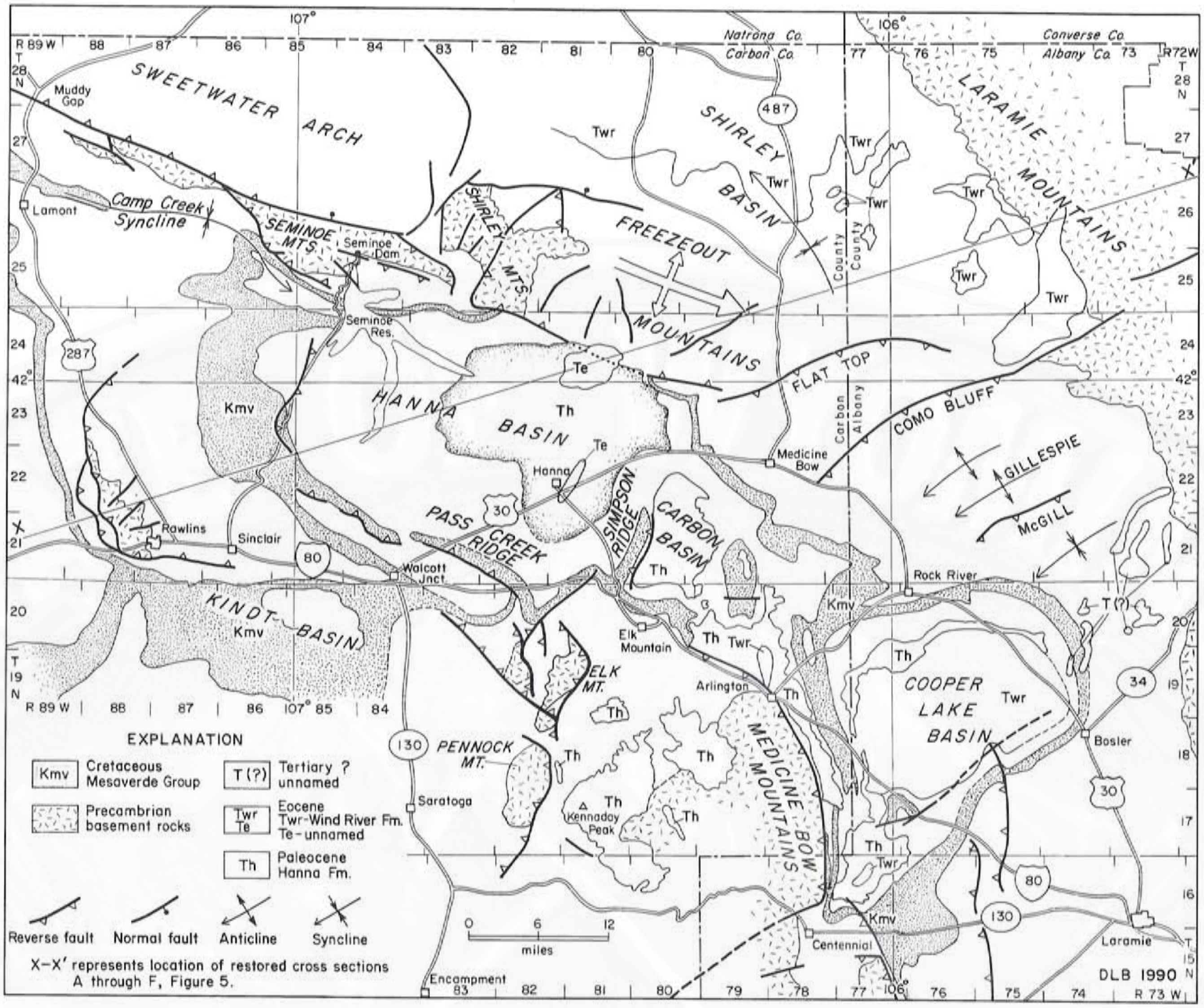

Figure 2. Generalized structure map of the Hanna, Carbon, and Cooper Lake Basins, Albany and Carbon Counties, Wyoming, showing outcrops of selected Tertiary formations, the Mesaverde Group, and the Precambrian basement.

what has been called the Seminoe and the Bradley Peak thrust faults. The fault system dips to the northeast, and tectonic transport was to the southwest.

West of the Emigrant Trail thrust fault, the southeastern part of the Wind River thrust fault has essentially the same trend and character with a parallel synclinal low (Blackstone, 1991). The COCORP reflection seismic line (Brewer and others, 1980) across the south end of the Wind River thrust fault and adjacent mountain mass provides the best data for interpreting the character of thrust faults in this part of the Rocky Mountain foreland. The basic fault dips 30° to the northeast and extends to a depth of 18 miles (30 km), flattening into a ductile zone in the crust.

Three structural units east of the Camp Creek syncline comprise the major trough and are discussed in order from northwest to southeast: Hanna Basin; Carbon Basin; and Cooper Lake Basin.

Hanna Basin

The Hanna Basin as depicted by Dobbin and others (1929) extends from the east flank of the Rawlins uplift and the northern flank of the Ft. Steele anticline eastward to the Simpson Ridge anticline (**Figure 2** and **Plate 1**). The western two-thirds of the basin is a broad eastward plunging syncline. This synclinal axis extends from west to east across T23N, Rs85 to 82W, inclusive.

The eastern third of the basin near Hanna, Wyoming (T22N, R81W) contains two synclines with divergent trends, expressed in outcrops of Paleocene and Eocene rocks. Neither of these synclines are expressed at the level of the "Dakota Sandstone" and do not appear on **Plate 1**. The southern syncline is centered two miles east of Hanna and contains numerous thick coal beds. This symmetrical syncline trends N30°E, with flank dips ranging from 10° to 12°. The fold axis can be traced for over 15 miles (24 km) across Ts22 and 23N, Rs81 and 82W. The boundary between Paleocene and Eocene age strata lies between the Hanna No. 1 coal bed and the 83-A coal bed (of Dobbin and others, 1929) at a locality near the town of Hanna, Wyoming (Blackstone, 1973, p. 38). The age determination is based on palynology.

A second syncline north of the previous syncline trends N55°W and is centered near section 1, T23N, R81W. The nature and extent of this syncline was described in part by Knight (1951). The fold is asymmetrical with dips on the southwest flank ranging from 10° to 12° northeast. Dips on the northeast flank are as high as 55° southwest, and the flank is overridden by the Shirley thrust plate. The strata in the trough of this syncline (T24N, R81W) are early Eocene in age on the basis of a fossil vertebrate, *Hyrachotherium* (J.A. Lillegraven, University of Wyoming, oral communication, 1991). The sequence appears in part to unconformably overlie the steeply dipping Hanna Formation. Possible structural relationships are shown on **Plate 2E**.

Carbon Basin

The name is derived from the now abandoned town of Carbon, Wyoming, on the original route of the Union Pacific Railroad, where coal was mined from shallow dipping coal seams in the Hanna Formation. The relatively shallow basin (**Plate 1**) is essentially discrete from the Hanna Basin proper; the two basins are separated by the Simpson Ridge anticline. The term "basin" rather than syncline has been applied because of terminology derived from the mining of coal in the Hanna Formation. The Hanna Formation lies with angular unconformity upon the Lewis Shale, Medicine Bow Formation, and the Ferris Formation on the margins of the basin and is, in turn, folded into a shallow syncline (**Plates 2G and 2H**) trending N10° to 15°E. The trend of the basin axis changes near Como Lake (Como Siding on the UPRR) and merges into the northern divergent syncline discussed above.

Cooper Lake Basin

The basin, centered around Cooper Lake (T19N, R75W), lies at the northern end of the larger Laramie Basin, and is defined by the extent of the Eocene (Wasatchian) Wind River Formation (**Figure 2**). The basin is shallow as shown on **Plate 2I**. The west flank of the basin includes a line of north-south trending anticlines—Rock River, Dutton Creek, Cooper Cove, and Seven Mile (Blackstone, 1963). The basin margin is defined by the contact between the Precambrian basement in the toe of the Arlington-Corner Mountain thrust fault complex and the underlying Phanerozoic sedimentary rocks.

Stratigraphy

The stratigraphy of the area is summarized in **Table 1**.

Marginal structures–Hanna Basin

The structural relief in the Hanna Basin based on the elevation of the top of the Precambrian basement is approximately 30,000 feet (9,150 m). The lowest point is in the trough of the Hanna Basin and the highest point is to the north at the crest of the adjacent Shirley-Freezeout Mountains uplift (Dobbin and others, 1929; Barlow, 1963; Oliver, 1970; and LeFebre, 1988). This amount of relief, plus the thick section of Late Cretaceous and Paleocene nonmarine rocks, is unusual for a basin of limited extent.

Table 1. Generalized stratigraphic section for the Hanna Basin area, south-central Wyoming. Ga = billion years.

Stratigraphic subdivisions			Formations or groups
CENOZOIC	TERTIARY		
	Neogene	Pliocene	not reported
		Miocene	Browns Park Formation
		Oligocene	White River Formation (locally present)
	Paleogene	Eocene	Wagon Bed Formation (in Shirley Basin to north)
			Wind River Formation
			unnamed Eocene unit(s)
			UNCONFORMITY
		Paleocene	Hanna Formation
			Ferris Formation
MESOZOIC	CRETACEOUS		
	Upper Cretaceous		Ferris Formation (lower part)
			Medicine Bow Formation
			Fox Hills Sandstone
			Lewis Shale
			Dad Sandstone Member
			Mesaverde Group
			Almond Formation
			Pine Ridge Sandstone
			Allen Ridge Formation/Rock River Formation
			Haystack Mountains Formation
			Steele Shale
			Niobrara Formation
			Frontier Formation
			Wall Creek Sandstone Member
			Mowry Shale
	Lower Cretaceous		Thermopolis Shale
			Muddy Sandstone Member
			Cloverly Formation ("Dakota Sandstone")
	JURASSIC		Morrison Formation
			Sundance Formation
			Jelm Formation
	TRIASSIC		Chugwater Formation
			Alcova Limestone Member
	TRIASSIC AND PERMIAN		
			Goose Egg Formation
PALEOZOIC	PERMIAN AND PENNSYLVANIAN		
			Tensleep Sandstone/Casper Formation
	PENNSYLVANIAN		Amsden Formation
	MISSISSIPPIAN		Madison Limestone
			UNCONFORMITY
	DEVONIAN		absent
	SILURIAN		absent
	ORDOVICIAN		absent
	CAMBRIAN		Buck Springs Formation/Flathead Sandstone
			UNCONFORMITY
PRECAMBRIAN	Middle Proterozoic		granite and mafic intrusions (1.4 Ga-1.2 Ga)
	Early Proterozoic		metasediments (2.5-1.7 Ga)
	Late Archean		metasedimentary and metavolcanic rocks (2.8-2.5 Ga) and gneiss (over 2.7 Ga)

The sharp folding of the thick sedimentary section has generated flexural slip deformation around the basin margin, creating "out of the syncline" reverse faults (Brown, 1984). Faults and related folds created by this type of deformation are found at Pass Creek Ridge, St. Marys Ridge, North Cedar Ridge, Lone Haystack Mountain, Austin Creek, and possibly Simpson Ridge. The problem relative to these structures is the fold termination or "roots" at depth: some faults appear to pass into the thick—4,000 feet (1,220 m)—section of Steele Shale. Also, how was the necessary stratal shortening accomplished? Examples of this style of deformation are demonstrated by cross sections (**Plate 2**) and the brief discussion that follows.

Pass Creek Ridge

Pass Creek Ridge on the southwest flank of the Hanna Basin trends N65°W and is defined on the surface by prominent hogbacks of the Cretaceous Mesaverde Group. Surface dips on the steep southwest limb of the asymmetric anticline range from 50°SW to overturned (Dobbin and others, 1929) but data from deep exploratory wells demonstrate that dips below a controlling thrust fault are in the range of 15°NE into the basin. The deepest test on Pass Creek Ridge anticline, Humble Oil and Refining No. 1 Pass Creek Unit, NE SW section 33, T21N, R82W, was drilled to a total depth of 16,854 feet, (5,138 m) and bottomed in the Jurassic Morrison Formation. An abrupt change in dip occurs at approximately 9,800 feet (2,740 m). The surface anticline lies above a northeast dipping reverse fault but data are inadequate to decide whether the fault roots in the basement or passes downdip into a bedding plane detachment (**Plate 2J**). Kaplan and Skeen (1985) interpreted the major fault to pass into a bedding plane detachment. Unfortunately, depths shown on the reflection seismic section published by Kaplan and Skeen (1985) do not agree well with the drilling data.

St. Marys anticline

St. Marys anticline is located in T21N, R84W on the southwest flank of the Hanna Basin (Dobbin and others, 1929; Chadeayne, 1966). The anticline is asymmetrical, bounded on the steep southwest flank by a northeast dipping reverse fault. The eastern flank is concealed by unconformably overlying Miocene Browns Park (?) Formation. The subsurface geology of the fold shown on **Plate 2K** illustrates the "out of the syncline" reverse fault.

Lone Haystack Mountain anticline

The Lone Haystack Mountain anticline is located in Ts23-24N, Rs85-86W, and is outlined by prominent hogbacks of the Late Cretaceous Pine Ridge Sandstone of the Mesaverde Group. The anticline has an arcuate form ranging in trend from east-west at the west end to N10°W at the south (Merewether, 1973). The fold is controlled by a complex of east dipping reverse faults of the "out of the syncline" type (**Plate 2B**).

Austin Creek anticline

A very tight fold exists in T24N, R83W, on the north flank of the Hanna Basin between massive ridge-forming sandstones of both the lower Medicine Bow Formation and the Mesaverde Group. The fold is well expressed by marine sandstones in the Lewis Shale. The fold trends N70°W, is asymmetrical to the northeast, and is bounded by a high angle reverse fault. Dips on the flanks of the fold range from 50° to 60°. Subsurface structure is constrained by four wells (Blackstone, 1983), one of which is shown on **Plate 2C**. The fold appears to have been generated by a force couple developed from differential movement (interbed movement) between the massive sandstones. The faulting is again the "out of the syncline" type.

The Breaks

An area of rugged badlands-type topography in the northeastern corner of the Como West 7 1/2-minute topographic quadrangle is known as The Breaks. A thick section of Hanna Formation composed primarily of mudstones and impersistent sandstone lenses crops out in T23N, R80W. The basal unit of the Hanna is conglomeratic and lies with marked angular unconformity (35°) on the Lewis Shale, Mesaverde Group, and Steele Shale. The Hanna Formation is, in turn, overlain unconformably by a younger unnamed unit (possibly Wind River Formation) described by Knight (1951).

The thick section of Hanna Formation behaves as an incompetent, almost ductile unit as shown by large, tight, kink folds along strike, in beds that dip at least 30°SW. The deformation is, in part, caused by the crowding from the northeast by the hanging wall plate of the Shirley thrust fault, and in part by "out of the syncline" crowding because of the steep dips (**Plate 2E**). The postulated position of the Mesaverde Group in the footwall of the Shirley thrust fault is shown on **Figure 3**.

The youngest strata (Eocene) are gently folded even though they unconformably overlie the steeply dipping Hanna and older formations. The younger folds may have been caused by differential interstratal

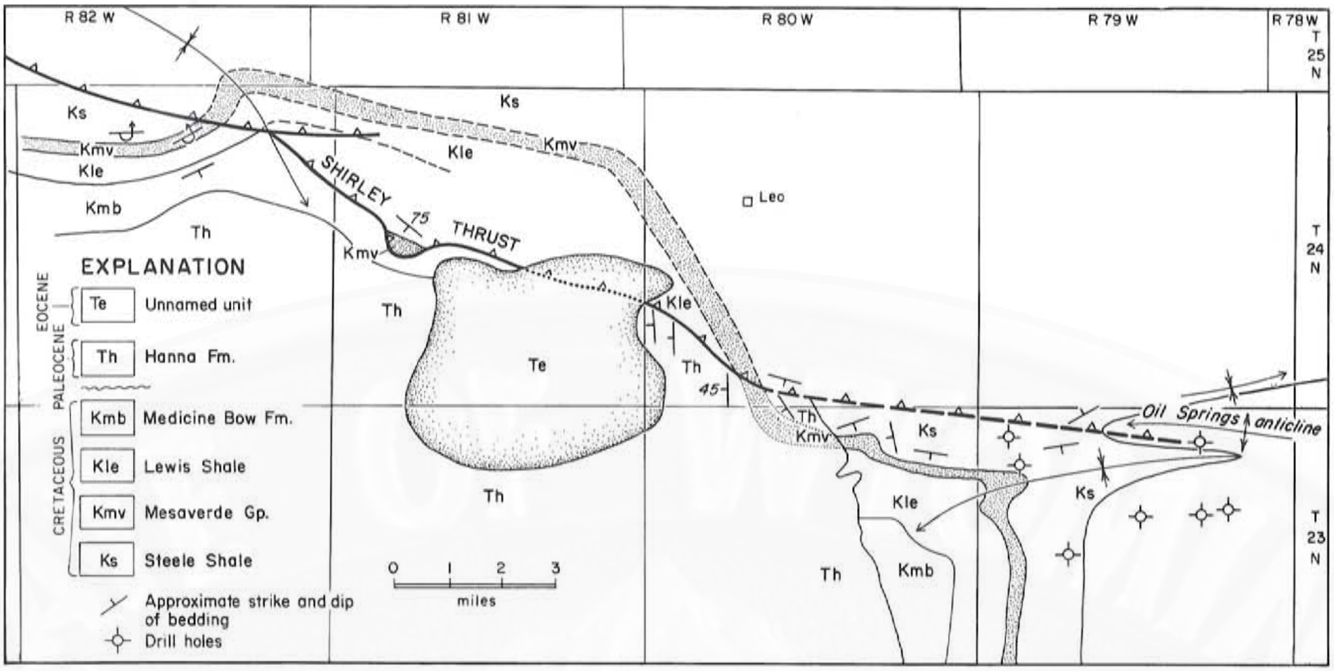

Figure 3. Subcrop map of the Shirley thrust fault, northeastern Hanna Basin, Carbon County, Wyoming. Solid lines are exposed contacts or faults, light dashed lines are inferred contacts beneath the Shirley thrust fault, heavy dashed lines are inferred locations of faults, and dotted lines are contacts or faults concealed beneath younger rocks.

motion of units in the underlying incompetent Hanna Formation.

Simpson Ridge anticline

The structural divide between the deep southern part of the Hanna Basin and the shallow Carbon Basin is the sharply folded, asymmetrical Simpson Ridge anticline, known topographically as the Saddleback Hills (Dobbin and others, 1929). An excellent map of the surface geology of the fold (Veronda, 1951) supplements the regional map of Dobbin and others (1929). Gas has been produced from sandstones in the Steele Shale at shallow depths; deep exploratory tests to the Pennsylvanian Tensleep Sandstone were failures but do provide control on the subsurface geology.

The anticline trends N25°E and on the basis of surface dips, the axial plane of the fold is near vertical in the upper levels of the fold. Overturned dips in the Lewis Shale on the east flank of the structure (Veronda, 1951) reflect the emergence of a southwest dipping reverse fault that is corroborated by drill hole records (**Plate 2H**). Three possible interpretations of the subsurface geology of the anticline are shown on **Figure 4**. It is obvious that the surface fold does not extend uniformly at depth. The writer favors the interpretation in **Figure 4B**.

Transbasin structures

A series of northeast trending structural features that exist in southeastern Wyoming includes major shear zones in Precambrian rocks, faulted anticlines in sedimentary rocks, and extensive fractures in the Laramie Mountains. Major features are the Wyoming lineament (Ransome, 1915); Cheyenne line (Karlstrom and Houston, 1984); Esterbrook shear zone (Snyder, 1984); and McGill, Gillespie, Como Bluff, and Flat Top anticlines (Blackstone, 1983).

Wyoming lineament

The name Wyoming lineament was applied by Ransome (1915) to a zone of deformation trending N50°-60°E across southeastern Wyoming (**Figure 1**). Most folds lying southeast of the lineament tend to verge to the northeast; reverse faults usually dip southwest or west and tectonic transport was to the northeast. Folds lying northwest of the lineament have an opposite sense of vergence and tectonic transport was to the southwest.

The lineament crosses the Laramie Mountains near Laramie Peak (T27N, R72W) and continues northeast along the northwest flank of the Hartville uplift. Northeast trending folds within the zone include Flat Top, Como Bluff, Gillespie, and McGill anticlines (**Figure 2**). Faults on the northwest flank of the Elk Mountain fold also reflect the effect of the lineament.

Maughan and Perry (1986) summarized data concerning lineaments in the Rocky Mountain region and proposed an orthogonal system of linear structural elements covering southern Montana, the western part of the Dakotas, Wyoming, and Colorado. The Hanna Basin lies near the intersection of approximately six lineaments, including what they describe as Ransome's lineament (Wyoming lineament). Much of the evidence for the proposed orthogonal pattern is the distribution of Paleozoic and Early Mesozoic sedimentary units.

Cheyenne line

The Cheyenne line is a major Precambrian structural element trending N50°-55°E across the Cooper Lake Basin and the Laramie Mountains. The shear zone was originally called the Mullen Creek-Nash Fork shear zone (Houston and others, 1968) but was subsequently renamed the Cheyenne line (Karlstrom and Houston, 1984). The northeast extension of the Cheyenne line bounds the southeast flank of the Hartville uplift and crosses the Medicine Bow Mountains south of Medicine Bow Peak.

Alignment of Pennock, Coad, and Elk Mountain

Pennock Mountain, Coad Mountain, and Elk Mountain and their satellites Bear Mountain and Sheepshead Mountain are Precambrian-cored anticlinal uplifts lying on the northwestern flank of the Medicine Bow Mountains (Beckwith, 1941). The mountain masses are bounded on their east flanks by reverse faults and tectonic transport was to the east. The general trend of the uplifts is N20°W, changing to north-south at the southern end (**Plate 1**). The Elk Mountain fault, a major reverse fault, terminates the complex at the north end of Elk Mountain (Beckwith, 1941; Blackstone, 1983).

The Elk Mountain fold terminates at the southwest corner of T20N, R81W, at the Elk Mountain fault, but the structural grain continues northward in the footwall of the fault in two anticlines—Bloody Lake to the west and Simpson Ridge to the east. Both folds flare up plunge to the south and tighten down plunge to the north.

The change of vergence of structures also occurs at the Elk Mountain fault. The Pennock-Coad-Elk Mountain structural segment moved tectonically to the east, and vergence is to the east. The major structure beneath Simpson Ridge anticline is asymmetrical to the west. Of three possible interpretations of the structure at the top of the Precambrian basement beneath Simpson Ridge anticline, the writer favors **Figure 4B** as the most probable.

Present status–geophysical data

The Hanna Basin region is essentially aseismic. Only one seismic event of greater than 5 magnitude and only three events of magnitude less than five occurred in historic time (Woollard, 1939).

Woollard (1939), Malahoff and Moberly (1968), and Oliver (1970) reported gravity values for the region. The gravity anomaly map of the conterminous United States (Society of Exploration Geophysicists, 1982) demonstrates a major gravity anomaly (in excess of 275 milligals) roughly circular in outline beneath the Hanna Basin. A zone of negative anomalies extends northwestward beneath the Great Divide Basin and joins with a large negative anomaly on the east side of the Green River Basin.

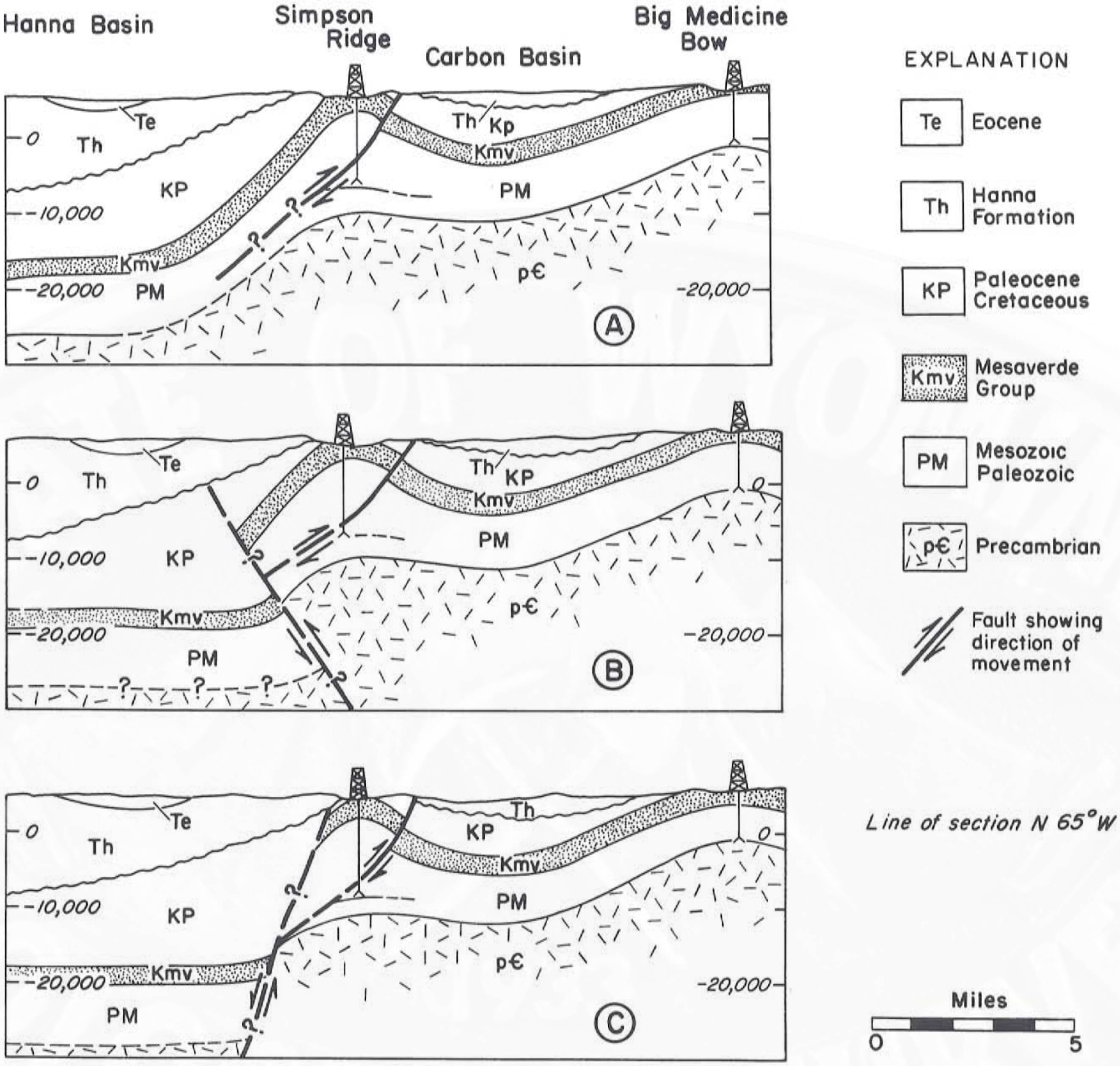

Figure 4. Three possible cross section interpretations from Hanna, Wyoming, across Simpson Ridge to Big Medicine Bow anticline. No vertical or horizontal exaggeration. Location of cross section shown on **Plate 1**.

The large negative gravity anomaly beneath the Hanna Basin reflects the thickness of sedimentary rocks in the basin rather than a local condition in the Precambrian basement. The steep gravity gradient on the north margin of the basin reflects the major overthrusting on the Shirley thrust fault.

The composite magnetic anomaly map of the United States (U.S. Geological Survey, 1982) shows no distinctive pattern of magnetic anomalies for the region here considered. A strong local magnetic anomaly (1,600 gammas) shown in the Seminoe Mountains is caused by the large body of Precambrian banded iron formation that is exposed at the surface here (Lovering, 1929). The northeast grain of lithologic units in the Laramie Mountains is also very evident on this map.

No hot springs exist in the area. The basin is underlain by aquifers in which the water temperature is higher than 120°F (Breckenridge and Hinckley, 1978; Heasler and others, 1983), which is normal for Wyoming basins.

Basin evolution

Structural basins (crustal depressions) have many forms. The interior regions of the North American craton are characterized by large, relatively shallow "basin and swell" type basins such as the Michigan, Illinois, and Williston Basins. Basins also develop in zones of active crustal subduction under compressional regimes and on the rifted margins of continents during extensional tectonism. "Pull apart" basins form in regions of large scale strike slip movement.

Rocky Mountain foreland basins are characterized by long wavelength and relatively short amplitude and usually are bounded on one margin by reverse or thrust faults that produced crustal shortening.

The physical dimensions of the Hanna-Carbon-Cooper Lake Basin complex were derived from several sources. Values for the mean sea level elevation of the Precambrian basement in the Hanna Basin proper range from -25,000 feet (7,620 m) to -30,000 feet (9,150 m) (Dobbin and others, 1929; Knight, 1951; Oliver, 1970; Sacrison, 1978; Shelton, 1968). The writer accepts an elevation of at least -20,000 feet (6,100 m) for the top of the "Dakota Sandstone" directly under the town of Hanna, Wyoming (**Plate 1**), based on the gravity survey by Oliver (1970).

The Rocky Mountain foreland had a long history of marine sedimentation during the Paleozoic and most of the Mesozoic Eras. During the Paleozoic, central Wyoming was the site of shallow, shelf type deposition at the same time that western Wyoming (Overthrust Belt) was the site of miogeosynclinal deposition. During most of Cretaceous time, much of central and eastern Wyoming lay beneath or on the western edge of the Western Interior seaway (Gill and others, 1970) and deposition proceeded at a slow rate.

The cratonic crust beneath the Rocky Mountain foreland during the interval from Cambrian to Late Cretaceous was stable with very little localized deformation. However, by the close of the Cretaceous, two broad, northwest trending troughs were evident in Wyoming (Blackstone, 1963; Love, 1960). These troughs continued to subside and act as sediment traps for material derived from the rising positive areas.

In the Hanna Basin, subsidence accelerated through the deposition of the Fox Hills Sandstone and the Medicine Bow Formation during early Maastrichtian time and the deposition of the lower part of the Ferris Formation during the Latest Cretaceous (Lancian).

Restored cross sections

Restored stratigraphic-structural cross sections shown on **Figure 5** summarize the writer's interpretation of the evolution of the Hanna Basin through time. A similar set of cross sections for the Cooper Lake Basin was presented by Blackstone (1973). Slow subsidence and slight marginal uplift of the area occurred through the Late Cretaceous and early Tertiary (**Figures 5A-D**). At the inception of the Laramide orogenic episode, there was no localized loading of the crust, but broad intra-continental warping allowed marine waters to invade the craton.

The region emerged from a marine environment in Maastrichtian time and has remained above sea level to the present. The last episode of marine deposition resulted in the Fox Hills Sandstone. Brackish water conditions continued to a limited extent during the deposition of the Medicine Bow Formation (Lancian) as demonstrated by Fox (1971).

An isopach map of the total thickness of post-Precambrian and pre-Medicine Bow sediments in Wyoming defines the configuration of the top of the

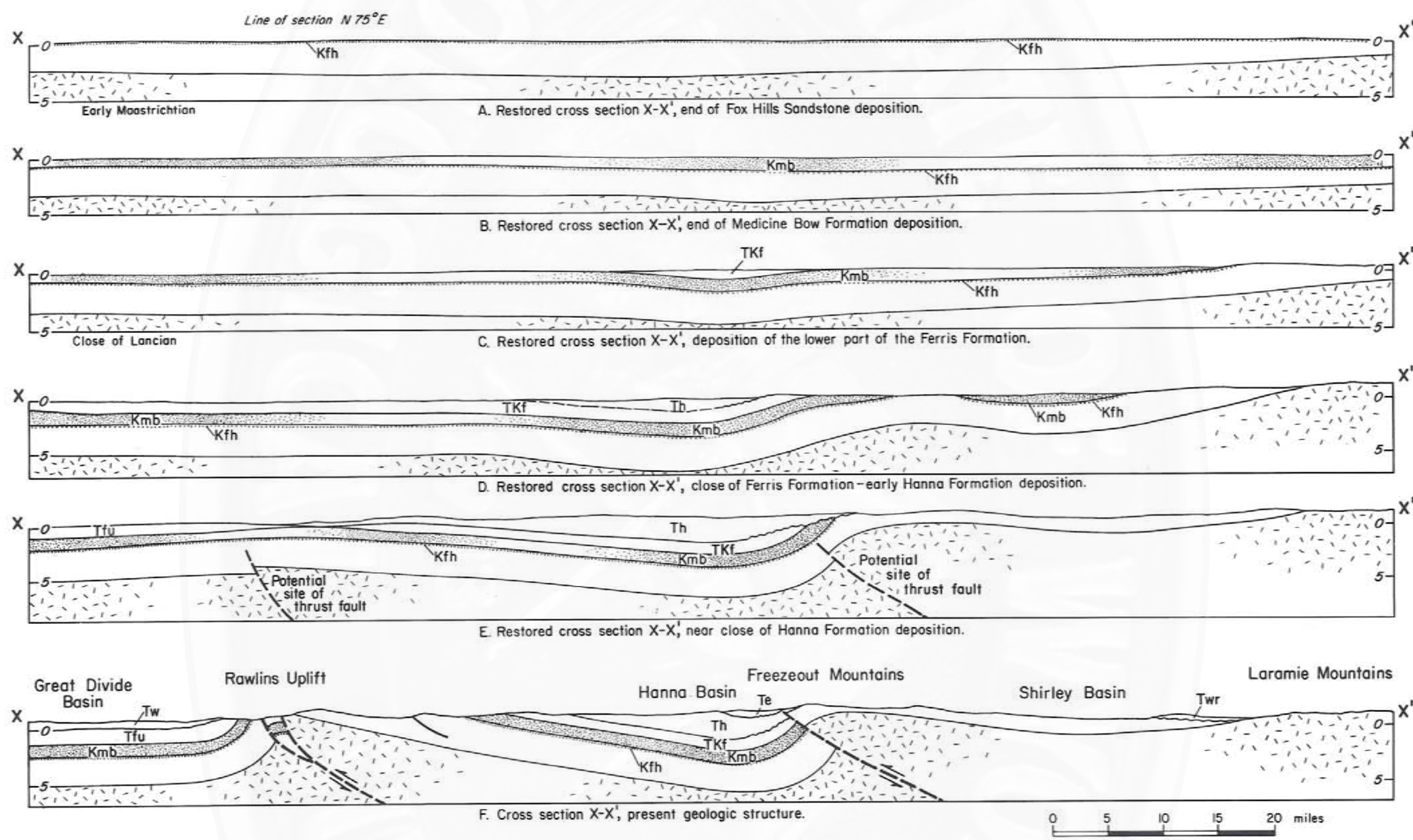

Figure 5. Restored cross sections for the Hanna Basin and surrounding area. Location of cross section X-X' shown on **Figure 2**. See **Plate 2** for explanation of most symbols and patterns; Tfu = Fort Union Formation (Paleocene) and Tw = Wasatch Formation (Eocene) on cross sections E and F.

Precambrian basement at the end of Cretaceous deposition (Blackstone, 1963). Blackstone's (1963) map documents the existence of two structural "lows" trending N70°W across Wyoming. One of these troughs is in the present position of the Hanna Basin. Love (1960) reported two troughs in latest Cretaceous time essentially on the same sites. These data show that at the close of Cretaceous marine deposition in the Rocky Mountain foreland region, the Precambrian crust was warped into broad open folds with no well-defined local deformation.

The definition of the modern Hanna-Carbon-Cooper Lake Basin complex began with the deposition of the Cretaceous (Lancian) Medicine Bow Formation and continued until at least 4,000 feet (1,219 m) of sediment accumulated. Subsidence continued during the deposition of 6,000 feet (1,829 m) of the Cretaceous-Paleocene Ferris Formation.

Late Cretaceous and early Tertiary depositional history

A review of the Late Cretaceous, Paleocene, and Eocene sedimentary record demonstrates the structural evolution of the Hanna-Carbon-Cooper Lake Basin complex.

Thicknesses of Late Cretaceous and early Tertiary formations are difficult to establish, partly because well-described measured sections are lacking and partly because of the criteria used to choose stratigraphic boundaries. The thicknesses reported by Bowen (1918) are frequently "recycled" without any new, detailed descriptions. Knight's (1951) measured sections are too generalized to be definitive and LeFebre's (1988) descriptions of a part of the section lack great detail.

Knight (1951) described two measured sections in T24N, R82W, on the northwest flank of the Hanna Basin, beginning at the Lewis Shale-Medicine Bow Formation contact and continuing upward to the Hanna Formation. No detailed descriptions of the sections are given but major conglomerates are noted. Knight (1951) stated that the Hanna Formation is conformable with the underlying Ferris Formation but subsequent mapping by the writer and R.W. Jones (Geological Survey of Wyoming, oral communication, 1991) demonstrates that this is not the case. In this area, the Ferris Formation strikes essentially east-west and dips 70°S and is overlain unconformably by Hanna Formation of similar strike but dipping only 10°S. Knight's (1951) conclusion has lead to problems in interpreting the basin evolution.

Lewis Shale and Fox Hills Sandstone

The Lewis Shale and overlying Fox Hills Sandstone are both marine deposits formed during Maastrichtian time. The age of these units, based on the standard Western Interior ammonite zonation, corresponds to *Sphenodiscus*, Zone No. 27, (Gill and others, 1970). The Lewis is 2,600 feet (793 m) thick and the Fox Hills is about 600 feet (183 m) thick. Broad regional uplift to the west (Love and others, 1963) resulted in eastward regression (withdrawal) of marine waters and deposition of the Fox Hills Sandstone along the receding shoreline (**Figure 5A**).

Medicine Bow Formation

The development of extensive coastal plains and swamps in much of central Wyoming led to the deposition of the Medicine Bow Formation. Marine conditions existed locally but in general, brackish waters were the rule (Fox, 1971). The region was at or near sea level and the Hanna Basin was slowly subsiding (**Figure 5B**). The basal unit of the Medicine Bow Formation is approximately 1,500 feet (457 m) thick; it contains a few foraminifera, brackish water invertebrate fossils, fossil wood, coal beds, and dinosaur bones. The rocks are dominantly mudstones, sandstones and lenticular sandstones, and coal beds. According to Ryan (1977), the distribution of cross beds in the formation "offers no suggestions as to local source."

Barlow (1963) recognized 4,800 feet (1,460 m) of Medicine Bow Formation west of the Rawlins uplift and indicated a sediment source to the west. Strata of equivalent age (the Lance Formation) are widespread in Wyoming and crop out as far east as Goshen Hole, about 100 miles (160 km) east of the Hanna Basin.

The Medicine Bow Formation at the type locality (Bowen, 1918) is approximately 6,200 feet (1,890 m) thick. The formation is 4,000 feet (1,220 m) thick in the Carbon Basin (Dobbin and others, 1929) and only 500 feet (152 m) thick in the southern Laramie Basin (Blackstone, 1983). The section is thin in the southern Laramie Basin because of truncation in late Paleocene time.

The source of the sediments for the Medicine Bow Formation at the type locality is not clear. Conglomeratic sandstones contain clasts of quartzite, quartz, and feldspar, as well as schist and volcanic rock, that suggest a western source. The fine-grained sediments were probably derived from recycled rocks removed from the crest of the incipient Sweetwater arch.

Knight (1953) and Houston and others (1968) described a lens of conglomerate in the Medicine Bow Formation in the Mill Creek syncline (section 29, T16N, R77W) and interpreted it to have been derived from the adjacent Medicine Bow Mountains. Blackstone (1970) reviewed the data on this conglomerate and concluded that the clasts were not derived from an immediate local source.

Positive areas were not greatly elevated (**Figure 5B**); therefore, the site of deposition was not a direct result of subsidence induced by loading but was due instead to broad crustal instability forming a sediment trap, possibly enhanced by the accumulating sediment.

Ferris Formation–lower part

The Ferris Formation of Cretaceous-Paleocene age (Gill and others, 1970) conformably overlies the Medicine Bow Formation at the type locality. The lower part of the formation is approximately 1,100 feet (335 m) thick and is characterized by conglomeratic sandstones (Bowen, 1918; Knight, 1953). The clasts in the conglomerates consist of black, red, and yellow chert; gray and red quartzite; and sparse clasts of rhyolite and quartz latite porphyry[1]. Some chert clasts contain Paleozoic invertebrate fossils. Bone fragments of *Triceratops* are common. The clasts suggest de-roofing of the Sweetwater arch to the west, but the source of the volcanic clasts is enigmatic. The lower part of the Ferris Formation up to the Dana No. 2 coal bed (Dobbin and others, 1929) is Cretaceous (Lancian) in age based on plant microfossils (Gill and others, 1970) and on dinosaur remains. **Figure 5C** illustrates the situation at the time of deposition of the lower Ferris Formation.

Ryan (1977) presented data indicating that the sandstones in the Ferris Formation were derived from a source to the northwest (probably the Sweetwater arch), but some material was also derived from the Medicine Bow-Sierra Madre complex to the south. Ryan (1977) also suggested that Simpson Ridge anticline was elevated at this time and affected the sediment distribution patterns from the south.

Ferris Formation–upper part

The upper part of the Ferris Formation is approximately 5,400 feet (1,646 m) thick, consisting of mudstones, sandstones, and persistent coal beds but lacking conglomerates and conglomeratic sandstones common to the lower part. The upper and lower Ferris are conformable but the lower Ferris is Late Cretaceous in age, based of plant microfossils (Gill and others, 1970).

The Hanna Basin subsided during the deposition of these strata, and the uplift of the Laramie Mountains to the east had begun (**Figure 5D**). The incipitent elevation of the Laramie Mountains blocked an eastward flowing river system and diverted it to the north, thereby cutting off any possibility of deposition of Paleocene rocks to the east of the present Laramie Mountains (Lilligraven and Ostresh, 1988). The localized subsidence was not caused by local thrusting but was the result of a general regional warping under regional compression.

Hanna Formation

The Hanna Formation occupies the deeper, central part of the Hanna Basin; is present in the Carbon Basin; underlies the Cooper Lake Basin in part; and occupies a syncline along the east flank of the Medicine Bow Mountains (**Figure 2**). The thickness may exceed 10,000 feet (3,048 m) as described by Gill and others (1970). The basal part of the formation along the basin perimeter is conglomeratic but the bulk of the formation is mudstone, sandstone, arkose, and numerous thick and persistent coal beds (Bowen, 1918; Dobbin and others, 1929; Knight, 1953; Glass and Roberts, 1980; Hansen, 1986).

The formation unconformably overlaps older strata toward the basin margins and in places overlaps down to the Precambrian basement. The unconformable relationship is particularly well exposed in the Carbon Basin; on the west flank of the Laramie Basin; near Wagonhound Creek (Hyden and McAndrews,

[1]The Precambrian basement exposed in the Seminoe Mountains near Bradley Peak (T25N, R.85W) contains banded iron formation of **very distinctive** lithology. Up to 1/2-inch thick bands of yellow-orange chert alternate with hematite-rich rock. No pebbles of this very distinctive lithology have been reported from either the Medicine Bow or Ferris Formations, suggesting that the Seminoe Mountain mass was not de-roofed to basement until a later date.

The name Seminoe Mountains apparently is derived from a mispronunciation of the name of an early trapper—Cimineaux.

1967); and in The Breaks (T24N, R80W). The formation laps high up onto the Medicine Bow Mountains in the vicinity of Kennaday Peak and Turpin Meadows as reported by Weichman (1988).

The age of the Hanna Formation is Paleocene, ranging from Torrejonian to at least Tiffanian (North American Land Mammal provincial age) based on palynomorphs and vertebrate fossils. Weichman (1988) prepared a summary of published data concerning microfossils from the Hanna Formation. J.A. Lillegraven (University of Wyoming, oral communication, 1991) has recently collected vertebrate fossils of Paleocene (Tiffanian) age from the Hanna Formation in the northeastern corner of the basin (T24N, R80W). In the same area, he has demonstrated the existence of a lacustrine environment during the Paleocene.

The existence of lacustrine beds indicates that the strata were deposited in near-horizontal position as shown on **Figure 5E**, and that these strata overlapped older rocks along the basin margin. There was no strong localized deformation at this time along the north flank of the basin and subsidence continued.

Wind River Formation

Strata of Eocene age exist in the area and the formation names are given in **Table 1**. Harshman (1968) reported the existence of the Eocene Wind River Formation in the Shirley Basin and along the west flank of the Laramie Mountains. Eocene age rocks in the Cooper Lake Basin have been designated Wind River Formation (perhaps erroneously) and dated as Lower Eocene (Wasatchian) by Nace (1936), Princhinello (1971), and Davidson (1987). Rocks of Eocene age that have not been given a formational designation are present in both the northern and southern synclines of the Hanna Basin (shown as "Te" on **Figure 2**). The Eocene age of these unnamed rocks is in part based on microfossils (Blackstone, 1973; Weichman, 1988). The boundary between the Paleocene Hanna Formation and the overlying unnamed Eocene rocks in the small syncline near Hanna, Wyoming, lies between the Hanna No. 1 coal bed and the 83-A coal bed of Dobbin and others (1929) (Blackstone, 1973).

Knight (1951) mapped a sequence of rocks near the northern margin of the Hanna Basin (Ts23-24N, Rs80-81) that he considered to be Eocene in age but did not name the unit. The age of this unit is Eocene as discussed above.

Overall, the Eocene rocks in this area of Wyoming are only slightly folded and show no signs of major deformation.

Late Cenozoic depositional history

The late Cenozoic history of southeastern Wyoming was reviewed in detail by Blackstone (1975) and need not be repeated here. The landscape in post-Wind River time (Wasatchian) was one of strong mature relief. During Oligocene time the region was inundated by airborne volcanic debris derived from the Great Basin region. These deposits backfilled the canyons that existed in the earlier cycle of erosion (Evanoff, 1990). The Oligocene deposits were in turn overlain by Miocene and Pliocene(?) deposits until only the higher parts of the uplifts stood above the aggraded surface. (Love and others, 1963; Blackstone, 1975).

Normal faulting under an extensional regime developed after the Pliocene(?) or at least in post-Miocene time. In the Hanna Basin region, displacement on the normal faults was of small magnitude, and has no bearing on the development of the basin proper.

Time of major deformation

The major, climactic episode of deformation that developed the synclinal complex described in this paper occurred in post-Tiffanian, pre-Late Greybullian time (**Figures 5E** and **5F**). The Late Paleocene Hanna Formation on the north margin of the Hanna Basin is folded and dips from 60° south to 60° overturned to the north and is overridden by the upper plate of the Shirley thrust fault. The synclinal basin deepened and the surrounding highlands (Sweetwater arch, Shirley Mountains-Freezeout Mountains) reached maximum elevation. Along the south margin of the Hanna Basin near Kennaday Peak, Paleocene strata overlap onto the Precambrian basement of the Medicine Bow Mountains (Weichman, 1988). In the southern part of the Cooper Lake Basin, strata of very late Paleocene age overlap older rocks and are in turn deformed by the Arlington-Corner Mountain complex (Blackstone, 1983).

Rocks of early Eocene age, as mapped by Knight (1951) and dated by J.A. Lillegraven (University of Wyoming, oral communication, 1991), unconformably overlie the trace of the Shirley thrust fault, and are in turn slightly folded. The Wind River Formation is slightly folded into broad synclines in both the Shirley Basin (to the northwest) and the Cooper Lake Basin. Conglomerates in the basal unit of the Wind River Formation contain clasts derived from the immediately adjacent highlands.

During Middle Eocene time, erosion accelerated, and a mature topography developed with extensive canyons along the basin margins. Deposition occurred in the low lying central parts of the basins contemporaneously with degradation along the basin margins.

Models for geometry and development

Models depicting the geometry of the Hanna Basin are based on several types of data. Dobbin and others (1929) described the basin as a simple, broad syncline with local structural variation on the western margin; however, the cross sections in this early report are too shallow and do not reach basement. Blackstone (1983) in a short discussion placed the basin in the regional framework. Prucha and others (1965) investigated several Rocky Mountain foreland structures, some marginal to the Hanna Basin. Prucha and others (1965) considered all faults to be vertical at depth, with dominant vertical motion. Shelton (1968) considered the Hanna Basin to have developed contemporaneously with high angle bounding faults. Blackstone (1983) discussed the Shirley thrust fault on the north flank of the basin as a low angle thrust fault.

On the basis of regional gravity data, Malahoff and Moberly (1968) presented a profile through the Hanna Basin that is smooth and regular with no major faulting. Oliver (1970) measured the value of gravity at 300 stations in the basin and interpreted the basin to be essentially circular but bounded on the north flank by a thrust fault dipping approximately 30°NE. Sacrison (1978) presented a series of seismic reflection profiles for the western part of the basin in which high angle reverse faults were the controlling factor. Kaplan and Skeen (1985) presented a seismic profile in the western part of the basin but the profile does not agree well with data from drilling.

Dickinson and Snyder (1978) discussed Rocky Mountain foreland structure in terms of plate tectonics, and suggested a very flat subduction slab beneath the region. Bird (1984) proposed that from approximately 70 to 40 million years before present, the region was underlain by a horizontally-subducting slab of Farallon lithosphere moving northeast.

LeFebre (1988) discussed the general stratigraphy of the Hanna Basin and the rate of subsidence. His basic cross section is derived from other sources. LeFebre (1988) proposed large scale block rotation to explain the origin of the basin. Bergh and Snoke (1992) conducted detailed studies of deformation in the Shirley Mountains and recognized polyphase deformation.

Data obtained from the COCORP reflection seismic line across the Wind River thrust fault and the southeastern Wind River Range provides a model for foreland thrust faulting. Smithson and others (1979) interpreted the Wind River thrust fault to be an essentially planar feature dipping approximately 35°NE. A subparallel plane close to and below the major thrust was noted. Complex structure exists in the Precambrian basement in the footwall of the fault. The fault plane was traced to a depth of 30 kilometers (18.6 miles) and appeared to flatten into a ductile zone in the crust.

The Wind River thrust is a well documented case history of foreland thrusting and probably is representative of other Rocky Mountain foreland thrust faults. The writer considers the Shirley, Arlington, and Corner Mountain thrust faults to be similar in geometry and character to the Wind River thrust fault.

The major point from the restored cross sections (**Figure 5**) is that there was no local, intense crustal deformation until post-Tiffanian time, near the end of most of the deposition of the Hanna Formation. The Rocky Mountain foreland up to that time was not strongly deformed (Lillegraven and Ostresh, 1988), but was affected by a regional compressional stress field oriented approximately N60°E. The crustal response to this stress field was the formation of broad uplifts and basins with sediment accumulating in the low areas. The events took place above sea level since all the sediment that was deposited at this time is continental in character. By latest Paleocene time, the major structural units were well defined.

Deformation in the northwest trending trough now occupied by the Hanna, Carbon, and Cooper Lake Basins accelerated during and after the deposition of the upper part of the Ferris Formation (early Paleocene). These strata and the underlying units were broadly warped before deposition of the basal Hanna Formation (**Figure 5D**). There is no evidence for any major thrusting at this time.

The Paleocene Hanna Formation in the northeastern Hanna Basin ranges in age from Torrejonian to post-Tiffanian (J.A. Lillegraven, University of Wyoming, oral communication, 1991) and accrued to a thickness in excess of 9,000 feet (2,743 m). The angular unconformity at the base of the formation as exposed on the northeast flank of the Hanna Basin was rotated by faulting to the position shown on **Figure 5F**.

Structural observations

As mentioned previously, the N70°W trending synclinal depression of the Hanna-Carbon-Cooper Lake Basin complex has been interpreted to develop in several ways. The following comments are pertinent to the interpretation: (1) The basin complex was not at a continental margin undergoing subduction. (2) It is unlikely that the Rocky Mountain foreland is underlain by a flat subduction slab in view of the seismic data obtained in the COCORP investigation of the Wind River thrust fault. (3) There is no hard evidence to indicate that the basin complex developed by contemporaneous faulting as suggested by Shelton (1968). (4) The basin complex did not develop by an overriding thrust plate with a foreland basin. (5) The basin complex did not develop because of sediment loading but rather by regional subsidence providing a sediment trap. (6) There is limited evidence for Laramide strike slip movement upon either the Cheyenne line or the Wyoming lineament.

Summary and conclusions

1. The early history of the basin complex up to the time of withdrawal of marine waters (Maastrichtian age) was one of broad regional subsidence probably with normal crustal thickness.

2. Subsidence was localized in two troughs that extended across Wyoming through the Late Cretaceous (Lancian) but there was little evidence of local uplift in southeastern Wyoming.

3. Subsidence accelerated in Late Cretaceous through Paleocene (Tiffanian). Uplifts were broad, and there is no evidence of well defined thrust faulting. Most of the Medicine Bow, Ferris, and Hanna Formations were deposited during this time.

4. Strong deformation with large scale overthrust faulting began in post-Tiffanian time. Adjacent highlands were well defined and shed clastic waste into the basins. Major faulting occurred on the Emigrant Trail, Shirley, and Arlington-Corner Mountain thrust faults.

5. Individual basins in the complex were separated by differential uplift across the Wyoming lineament.

6. Erosion and canyon cutting occurred during Middle Eocene and developed a mature topography.

7. Widespread deposition of air-borne volcaniclastic debris occurred during Oligocene, Miocene, and Pliocene. High level erosion surfaces developed.

8. Epeirogenic uplift initiated a new cycle of erosion and extensional tectonics modified some structures.

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