Frontispiece. Aerial photograph with view to the northeast, emphasizing an asymmetric anticline (Beer Mug Anticline; cored by Pennsylvanian Tensleep Ss. and flanked by Permian Goose Egg Fm.) thrust atop a less obvious, synformal anticline (Ellis Ranch Anticline of Taylor, 1996; cored by Triassic Red Peak Fm. and stratigraphically overlain by the white, more clearly defined, Triassic Alcova Ls.). The steeply north-dipping thrust fault between the anticlines (Indian Spring Fault) is exposed only near the photo’s lower-left corner, and it strikes northeastward from there, hidden by the slopes of erosional debris. The camera is above the northern edge of the eastern Hanna Basin, and the general view is across southern parts of the adjacent Freezeout Hills. This image was selected for use as the Frontispiece jointly because of its clarity and for being emblematic of the extraordinary degree of Laramide structural complexity characteristic of the Hanna Basin area — and particularly so along the basin’s northern and southern margins. For structural details, see Taylor (1996, p. 31–50 and, especially, fig. 7). Photograph courtesy of Dan Hayward (©Copyright 2011; HaywardPhoto.com, image taken July 30, 2011).

Cover images:
Top photo—View is to northwest, looking across southeastern parts of ‘The Breaks’ at the northeastern corner of Wyoming’s Hanna Basin. Shirley Mountains dominate the left skyline. Camera is placed at dead center of the W ½ of sec. 10, T. 23 N., R. 80 W., featuring lower Paleocene strata of the >4.8 km-thick Hanna Formation. Photographer stands on steeply southwest-dipping lower parts of hanging wall of the out-of-the-basin Dragonfly (thrust) Fault. As per usual for thrusts around the eastern half of the Hanna Basin, the Dragonfly Fault puts younger strata onto older, leading to structurally thinned sections around basin margins. On opposite side of the ephemeral drainage in the photo’s center is the top of the Dragonfly’s footwall. The steeply northeast-dipping rusty sandstone at the ridge’s top is the southwestern edge of the fault’s footwall syncline (the ‘Great Tortilla’ of Lillegraven et al., 2004, fig. 4B, RMG, v. 39, no. 1).
Lower-left photo—Shown is a roughly 30 cm-wide band of tightly folded, alternating siltstone and coal found low in the hanging wall of the Dragonfly Fault (camera is directed northwest). This style of intense deformation is common at all scales adjacent to thrust faults around margins of the Hanna Basin, especially in hanging walls.
Lower-right photo—Shown are prosaic yet essential tools that greatly aided the field research included in the following article.
Late Laramide tectonic fragmentation of the eastern greater Green River Basin, Wyoming

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ABSTRACT

Today’s greater Green River Basin is limited to the southwestern quarter of Wyoming. From late in the Cretaceous into late Paleocene time, however, sedimentary accumulations within that basin continued uninterrupted much farther to the east, connecting areas now occupied by the isolated Hanna, Carbon, Pass Creek, and Laramie basins. Field-based research resulted in three contiguous geologic maps that focus on modern basin margins and boundaries among those eastern elements. Analyses of derived cross sections and restored stratigraphic columns suggest that active subsidence and rapid sedimentary accumulation persisted with only minor interruptions until very late in the Laramide Orogeny. That led to a generally symmetrical north–south cross-sectional configuration of the original Hanna Basin, with its true depositional axis set well south of its apparent position of today. The Hanna Basin’s present strong asymmetry developed only secondarily. That basin’s modern configuration reflects Paleogene influences of: (1) late Laramide (early Eocene and probably younger) basement-involved contractional tectonics and associated uplifts; (2) out-of-the-basin thrusting passively responding to stratigraphic crowding; (3) prodigious syntectonic erosion; and (4) resulting basin fragmentation. North–south dimension of the late Paleocene (i.e., pre-fragmentation) greater Hanna Basin sedimentary sequence was roughly twice that of today, and near-sea-level topographic conditions persisted until late Eocene time. As expected, remnants of basin margins universally show major thinning of stratigraphic sequences. Principal thinning was from tectonic causes, however, exhibiting erosional angular unconformities only rarely. Out-of-the-basin, younger-on-older faulting (in which fault planes cut down-section) accompanied by massive erosion was the rule at all basin margins. Uplift of Simpson Ridge Anticline postdated deposition of upper Paleocene strata in direct continuity between what is now the separated Hanna and Carbon basins. The basement-involved fault system responsible for westward relative tectonic transport (and ca. 8 km of elevation) by Simpson Ridge also led to raising the attached Carbon Basin. Original Hanna Formation of the Carbon Basin was beveled away by erosion and soon thereafter became replaced by shallow-slope sliding of a long-runout allochthon, the Carbon Basin Klippe. The klippe’s original site of deposition probably was to the northeast, above what later became Flat Top Anticline. Uplift of Flat Top and Simpson Ridge anticlines was essentially synchronous (latest Paleocene or, more probably, early Eocene), establishing a lengthy, faulted-synclinal separation of the Hanna/Carbon Basin from the Laramie Basin. That syncline also bifurcated Simpson Ridge Anticline into western and eastern segments. A second allochthon, the Dana Klippe, rests upon southern parts of the Hanna Syncline (of Hanna Basin). That klippe’s site of deposition probably was above the area that later became Elk Mountain, thus causing origin of Pass Creek Basin. Elk Mountain’s ca. 12 km uplift could not have occurred prior to the early Eocene, and that event contributed to tight folding of the Hanna Syncline. Coal Bank Basin is a giant foothill syncline ahead of the out-of-the-basin, thrust-faulted (with relative tectonic transport to the southwest) Dana Ridge Anticline. That fault–fold complex represents a common structural style seen at all scales across the Hanna Basin.


“Properly made geologic maps are the most quantitative data in geoscience. While we may debate the nature of a contact, the contact and dip-strike measurements, if properly located, should be there 100–200 years hence and are therefore both quantitative and reproducible, something that cannot be said of experiments in some of the other sciences.”

A. M. Celâl Şengör (2014, p. 45)

INTRODUCTION

Focus of Present Work

What we refer to today as the Hanna and Carbon basins represent two relatively small, eastern fragments of an originally enormous, Cretaceous and Paleocene greater Green River Basin (Lillegraven et al., 2004, figs. 15 and 19). The primary objective of this paper is to present hypotheses on how key steps in fragmentation of the original eastern end of that greater Green River Basin came to be. Through the course of this research it was necessary to gather a great deal of primary stratigraphic, attitudinal, and...
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structural-orientation data from the local rock units. Much information derived from that process is described and summarized.

Observations from original fieldwork also are linked wherever feasible to what I consider to approximate a ‘bibliography’ of geologically and geo-economically (i.e., coal reserves, other hydrocarbons, thermal energy, hydrology, etc.) oriented publications and theses/dissertations relevant to the area.

Early subdivision of the eastern greater Green River Basin occurred via shortening along basement-involved thrust faults allowing contractional Laramide deformation (Barlow, 1953b; Kraatz, 2002; Otteman, 2003; Lillegraven et al., 2004; Otteman and Snoke, 2005; and Clemens and Lillegraven, 2013). Several of those important thrust faults would be considered as ‘intrabasinal’ in the same sense applied to a more westerly part of the greater Green River Basin by Mederos et al. (2005). On opposite sides of these large, basement-involved thrusts developed much more numerous, but in most cases markedly smaller, thrust faults that usually exhibited opposite relative directions of transport. Almost certainly, these represent passive adjustments of the shallower, more centrally basal strata to influences of the basement-involved, principal faults (see Lillegraven et al., 2004, fig. 10). Some of the basic principles are discussed by Mount et al. (2011, figs. 1–6) using terminology of ‘wedge structure fault-related folds’ applied to 2-D regional seismic data gained in southern parts of the Hanna Basin. As shown in their figure 2, wedge structures can be basement-involved or they can be completely restricted to within the sedimentary column (i.e., basement-detached). In either case, these deep-wedge structures can have strong structural influences upon strata much higher in the overlying column (Mount et al., 2011, figs. 2, 5–7). Thus it is probable that some of the smaller, out-of-the-basin thrust faults mapped within the present study were influenced by more than simple flexural processes as the strata in the basins were transformed into synclinal folds. I have no hard data from the subsurface to contribute to such issues.

The Hanna and Carbon basins have been considered variously in terms of where they fit within North American physiographic and/or structural contexts. Example assignments include the: (1) ‘Wyoming Basin’ physiographic province (Fenneman, 1931, p. 133–149; Raisz, 1972); (2) ‘Southern Rocky Mountains, sensu lato’ (and more specifically the ‘crestal province of the Alvarado ridge’ or, alternatively, the ‘Southern Rocky Mountain epeirogen’; Eaton, 1986, 1987, 2008); and (3) ‘central Rocky Mountain orogenic plateau’ (sensu McMillan et al., 2006, fig. 1). The comparative fundamental natures of the Hanna/Carbon basin area also have been considered in attempts by Chapin and Cather (1983), Dickinson et al. (1988), and Cather and Chapin (1990) to fit within structural and/or depositional categories of Laramide basins within the Rocky Mountain region (briefly evaluated by Lillegraven et al., 2004, p. 51–52). A secondary focus of the present paper is to link newly gained geological information from the Hanna/Carbon basin area with these disparate and broader comparisons toward understanding Laramide and younger history of western North America.

But the essence of the present work involves interpretive use of field measurements taken principally from uppermost Cretaceous through Paleogene strata. Those collective data are applied to interpretation of paleogeographic evolution within the general vicinity of the greater Hanna Basin’s eastern half, including the Carbon Basin plus surrounding uplands and plains. My interpretations are expressed through original field studies that document: (1) the configurations of exposed strata bordering the basin; (2) the existence and physical nature of faults recognized for the first time within those strata; and (3) estimates of the oldest reasonable ages of folding, faulting, and erosion related to Laramide orogenesis that led to development of the local landscape. Complicating the picture is a pair of previously unrecognized, laterally extensive allochthonous masses (klippen) that entered the immediate study area late in the Laramide Orogeny.

It may seem odd to have limited this study to the ‘eastern half’ of the greater Hanna Basin area. Why not study the entire basin? The answer to that lies mostly in goals and statements expressed in the preceding paragraph. Intentional focus of the research deals with latest Cretaceous through Paleogene history, and the area mapped for this paper encompasses almost all of the strata within the greater Hanna Basin preserved from that interval. Excepting poorly exposed strata of Paleocene age that extend northward from the northern face of the Medicine Bow Mountains into the Pass Creek Basin (south of Elk Mountain), the nearest temporally relevant strata outside of the landscape specifically mapped in this study exist roughly 40 miles (ca. 64 km) to the west, well west of the city of Rawlins. Specifically, those relevant outcrops exist along the southeastern map curvature of the Great Divide Basin and eastern flanks of the Washakie Basin. From that eastern edge, the relevant strata extend westwardly with limited interruptions almost all the way to the far-western border of Wyoming (traversing roughly 210 mi; 338 km). And all of that expanse represents traditionally recognized components of today’s greater Green River Basin.

The next logical steps in research beyond the present paper would be to establish firm lithostratigraphic and biostratigraphic correlations along with structural interpretations of the gap between the above-mentioned sections in the eastern Great Divide/Washakie basins.
and those (referred to within the present paper) of the Hanna/Carbon basins. Fortunately, workers associated with the U.S. Geological Survey have developed geologic maps, measured sections, and diverse charts (based on drilling logs, geophysical logs, paleontological faunal/palynological lists, coal-based correlations, and diagrammatic geological cross sections) that extend from just south of U.S. Interstate Highway 80 (including and around Creston Junction) southward into northern Colorado (south of Baggs, Wyoming) along eastern extremes of the Upper Cretaceous into lower Eocene strata. Those detailed records document terminal regression of marine conditions upward through an extended history of locally fossil-rich nonmarine fluvial and lacustrine strata. The most relevant publications from that effort include: Hettinger and Honey (2005, 2006); Hettinger et al. (1991); Hettinger and Kirschbaum (1991); Honey (1990); Honey and Hettinger (1989a, 1992, 1994); Honey and Roberts (1994); Honey and Robertson Roberts (1989); and Sanders (1975).

Vertebrate-fossil collections gained from that eastern-most, greater Green River Basin landscape by my late colleagues Malcolm C. McKenna and James G. Honey (collections now at The American Museum of Natural History and University of Colorado Museum) are essential to the future of interbasinal correlation. Included mammalian fossils show a remarkably complete latest Cretaceous into early Eocene section, including species representative of Lancian, Puercan, Torrejonian, Tiffanian, and Wasatchian North American Land Mammal Ages.

Honey and I also discovered several examples of major intrabasinal faults within those sections that match the initially unexpected tectonic features observed in the Hanna Basin (discussed below). Full documentation of those uniquely informative faults will profoundly affect interpretations of Laramide stratigraphy and paleogeographic evolution, especially as they are seen north of Interstate Highway 80 along western flanks of the Rawlins Uplift. That worthy goal had to be put aside following Honey’s untimely death. In any case, I take this opportunity to propose that extraordinary thanks are due to the workers cited above for their contributions of fundamentally important information to the next generation of field-based researchers.

Essential Graphics and Appendices

Graphical representation of new field-based data support this paper’s essential foundation (see Table 1, which lists Figs. 1–12, and Table 2, which provides linkages to Appendices 1 and 2). I do not claim ‘truth’ for contents of any graphical interpretations presented in this paper; all geologic maps, cross sections, stratigraphic columns, and step-wise evolutionary sequences should be considered as interpretive hypotheses designed for further testing, improvement, and possible refutation. It is the case, however, that every such element presented here is constrained by field-measurement data developed during the research. All of that information has been conservatively presented and can be tested independently through reference to data contained in Appendices 1 and 2 accompanied by investigative return to relevant outcrops.

Specifically, the graphical elements include: (1) two digital-elevation representations of present landscapes (Fig. 1A–B) as reference maps to aid geographic orientation; (2) a composite stratigraphic column of Phanerozoic rock units showing generalized geologic ages and thicknesses typical for the study area (Fig. 2); (3) closeup digital-elevation representations of the study area (Fig. 3A–B) showing boundaries of included geologic maps and locations of geologic cross sections; (4) three geologic maps that encompass northern, eastern, and southern basinal margins (Figs. 4–6, respectively; 1:24,000 scale in addition to thumbnail versions placed for basic reference within the text); (5) 22 geologic cross sections (Fig. 7; scale 1:24,000 plus thumbnail), interpreted in the subsurface to uniform elevations of 4,500 ft (1,372 m) above mean sea level; (6) 36 stratigraphic columns of the remaining Phanerozoic section (scale 1:24,000 plus thumbnail; with thicknesses graphically gained from the cross sectional measurements) presented (upper parts of Fig. 8) as they would appear today if existing strata were returned to their nearly horizontal, depositional configurations and (lower parts of Fig. 8) with remaining rock components vertically rendered through estimations as though the strata locally cut out of those same cross sections by faulting and erosion were restored; and (7) three hypothetical, stepwise scenarios of structural evolution (Figs. 9–11, presented in cross-sectional format at scale of 1:100,000 plus thumbnail) interpreted to pre-deformational depths just below uppermost levels of Precambrian basement rocks. A composite geologic map of the eastern half of the Hanna/Carbon Basin that unites Figures 4–6 is presented as Figure 12 (thumbnail version only).

Supplementary to those graphical elements are two appendices, including: (1) Appendix 1, a tabular presentation of locality data for all new attitudinal measurements (searchable for quickly locating sites geographically along with finding stratigraphic and rock-attitudinal data; also includes occurrences of individual tepee rings, or clusters of rings, wherever they were incidentally recognized during fieldwork); and (2) Appendix 2, complete scanned copies of 11 books of my field notes (1992–2012) covering locations, lithologic natures, and stratigraphic orientations at all stations of observations.
Table 1. Principal data-bearing graphical elements and appendices underpinning this publication.

Notes: The scales designated below for Figures 4–11 apply to the full digital versions available for download and printing via the indicated URLs (duplicated following ‘REFERENCES CITED’). The ‘thumbnail’ versions, Figures 1–12, interspersed within this paper’s text are intended for online reference only, and they can be viewed at any desired scale.

Figure 1. Digital-elevation models as reference maps for general geographical orientation.

Figure 2. Stratigraphic sequences, abbreviations, and colors as used throughout this paper.

Figure 3. Digital elevation models of study area indicating topographic quadrangle names, geologic map boundaries, and alignments of cross sections (the ‘Breaks Map’ in part A is a reduced version of fig. 4B from Lillegraven et al., 2004).

Figure 4. Geologic map of northeastern Hanna Basin (scale 1:24,000; Fig. 4.PDF — geobookstore.uwyo.edu/sites/default/files/downloads/rmg/50.1/Lillegraven%20Fig.%204.pdf).

Figure 5. Geologic map of eastern Hanna Basin’s margin, Simpson Ridge Anticline, and Carbon Basin (scale 1:24,000; Fig. 5.PDF — geobookstore.uwyo.edu/sites/default/files/downloads/rmg/50.1/Lillegraven%20Fig.%205.pdf).

Figure 6. Geologic map of southern Hanna Basin (scale 1:24,000; Fig. 6.PDF — geobookstore.uwyo.edu/sites/default/files/downloads/rmg/50.1/Lillegraven%20Fig.%206.pdf).

Figure 7. Interpretive geologic cross sections (scale 1:24,000; Fig. 7.PDF — geobookstore.uwyo.edu/sites/default/files/downloads/rmg/50.1/Lillegraven%20Fig.%207.pdf).

Figure 8. Directly measured (above) and interpretively restored (below) stratigraphic columns along traces of cross sections (scale 1:24,000; Fig. 8.PDF — geobookstore.uwyo.edu/sites/default/files/downloads/rmg/50.1/Lillegraven%20Fig.%208.pdf).

Figure 9. Cross-sectional model of late Laramide evolution along transect 1–2–3, across eastern Hanna Basin (scale 1:100,000; Fig. 9 (trans 1–3).PDF — geobookstore.uwyo.edu/sites/default/files/downloads/rmg/50.1/Lillegraven%20Fig.%209.pdf).

Figure 10. Cross-sectional model of late Laramide origin of Carbon Basin Klippe along transect 4–5–6 across southeastern Hanna and Carbon basins (scale 1:100,000; Fig. 10 (trans 4–6).PDF — geobookstore.uwyo.edu/sites/default/files/downloads/rmg/50.1/Lillegraven%20Fig.%2010.pdf).

Figure 11. Cross-sectional model of late Laramide origin of Dana Klippe along transect 7–8–9 involving southernmost Hanna Basin and Elk Mountain (scale 1:100,000; Fig. 11 (trans 7–9).PDF — geobookstore.uwyo.edu/sites/default/files/downloads/rmg/50.1/Lillegraven%20Fig.%2011.pdf).

Figure 12. Composite geologic map of entire margin of eastern Hanna/Carbon Basin area, unifying Figures 4–6.

Appendix 1. Tabular presentation of locality data for all attitudinal measurements (also see Table 2). geobookstore.uwyo.edu/sites/default/files/downloads/rmg/50.1/Appendix%201.pdf.

Appendix 2. Digital copies of 11 books of field notes relevant to this research. Filenames indicate each book’s contents by range of included measurement numbers (also see Table 2).


Nevertheless, its area exhibits remarkable stratigraphic thicknesses. A CENTRAL CONCEPT FUNDAMENTAL TO THIS
research has been interpretation of paleogeographic evolution. Notice as well that virtually all of the above-listed studies intentionally
combined contributions from local paleontology (involving fossil vertebrates, invertebrates, macrofloras, and pollen) with
stratigraphy, paleoecology, and tectonic history. Admittedly, much refinement of chronological documentation of individual
sections has yet to be accomplished within the Hanna Basin. Nevertheless, the progress made to date has
benefitted through external funding dedicated to this project: Boyd and Lillegraven (2011); Burris (2001); Cifelli et al. (2004);
Clemens and Lillegraven (2013); Eberle (1996, 1999, 2003); Eberle and Lillegraven (1998a, b); Grimaldi et al. (2000);
Lillegraven and McKenna (2008); Lillegraven and Ostresh (1988, 1990); Lillegraven and Snoke (1996); Lillegraven et al.
(2004); Lofgren et al. (2004); McKenna and Lillegraven (2005, 2006); Secord (1996, 1998); Snoke (1993, 2005); Trujillo
(2003); Woodburne (2004); and Wroblewski (1997).

A consistent theme throughout that research has been development through exploration within structural traps. The following
quotations from Clemens and Lillegraven (2013, p. 164) contains a concept (highlighted here by addition of italics) that will be critically important to
understanding much of the present paper:

“The observed out-of-the-basin thrust faults, although having mostly bedding-parallel planes of relative displacement, regularly and preferentially cut stratigraphically down-section, thereby placing younger strata of the hanging walls onto older strata of the footwalls. The faulting thereby led to greatly thinned stratigraphic sections when juxtaposed against basin
margin, oppositely vergent [sic; intended meaning was ‘oppositely directed relative tectonic transport of’] mountainous uplifts. This ‘younger-on-old’ faulting is the general rule all around the eastern Hanna Basin. We suggest it to be a little recognized but common
phenomenon throughout the Rocky Mountain province. Several other occurrences distributed across
Wyoming may well have been long misinterpreted as erosional/depositional angular unconformities.

A CENTRAL CONCEPT FUNDAMENTAL TO THIS
RESEARCH

The Hanna Basin has relatively small geographic dimensions. Nevertheless, its area exhibits remarkable stratigraphic thicknesses
along with strong and complex deformation. Laramide uplift, highland erosion, basin sedimentary aggradation, subsidence,
and contractional basin-margin tectonism were prodigious. Without question, faults exhibiting the most lengthy individual
map traces and greatest stratigraphic separations are of the ‘thick-skinned,’ basement-involved variety. Among the most important
of examples around margins of the eastern Hanna Basin are the: (1) Shirley Fault (Clemens and Lillegraven, 2013, figs. 4, 6, and
7), seen directly external to the northern basin margin; and (2) Elk Mountain thrust complex (Figs. 7 and 11), just external to the
basin’s southern margin. Both thrusts have elevated Precambrian basement rocks at least 15 kilometers to form montane exposures
today that tower above even the stratigraphically highest outcrops of the basin’s youngest remaining Paleogene strata. Senses of
displacement exhibited by these kinds of faults ordinarily are into-the-basin. Brown (1988, 1993), Stone (1993), and McClay et al.
(2011) have provided useful, plate-tectonic-based and industry-oriented reviews of the diversity of basement-cored uplifts and
folds studied across Wyoming’s foreland and beyond.

Within present-day margins of the Hanna Basin itself, however, the dominant fault systems are ‘thin-skinned’ (i.e.,
ordinarily not basement-involved), contractional thrust faults that formed through passive responses to crowding from far
greater displacements along the deep-rooted, basement-involved faults. These thin-skinned thrusts generally have shorter map
traces and much lesser stratigraphic separations. Ordinarily, they exhibit out-of-the-basin senses of displacement, roughly
synchronous with, but antithetical in relative direction of transport to, the deeply rooted hanging wall. Matson (1984,
p. 504) may have been the first to recognize that the Hanna Basin would be a prime candidate for the development of basin-margin, “... out-of-the-basin thrusts terminating in
closed anticlines.” He visualized a bright future for petroleum
development through exploration within structural traps.

The following table from Clemens and Lillegraven (2013, p. 164) contains a concept (highlighted here by
addition of italics) that will be critically important to understanding much of the present paper:

<table>
<thead>
<tr>
<th>Measurement Stations</th>
<th>Field-book Numbers</th>
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<td>Book 1</td>
</tr>
<tr>
<td>1278 – 2341</td>
<td>Book 2</td>
</tr>
<tr>
<td>2342 – 3197</td>
<td>Book 3</td>
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<td>3198 – 3777</td>
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<td>8119 – 8168</td>
<td>Book 11</td>
</tr>
</tbody>
</table>

Table 2. Ranges of station numbers for measurements recorded in each of eleven field books (as finding-aids while using Appendices 1 and 2).
Wherever that has been the case, profound re-thinking of the areas’ geological histories would be required.”

Blackstone (1975, p. 254), for example, stated that: “Around the margins of the Hanna, Carbon, and Laramie basins, the Hanna Formation lies with marked unconformity upon older rocks.” The present paper, in contrast, presents evidence that the contact between the Hanna Formation and older strata, with but one exception in the northeastern Hanna Basin (northern edge of 'The Breaks'), is structural, not representing deposition upon an erosional surface. More specifically, except at bases of the two allochthonous masses introduced below (Figs. 5, 6, and 12), any structural contacts underlying the Hanna Formation exhibit out-of-the-basin thrusting, usually involving placement of younger strata onto older.

As seen in the northeastern Hanna Basin, Lillegraven et al. (2004, fig. 18) illustrated the concept and a mechanism of 'younger-on-older, out-of-the-basin-thrusting.' Lillegraven (2009, figs. 9–11, 29–30, table 1) later recognized the same phenomenon in northwestern flanks of Wyoming’s Bighorn Basin. Most recently, Clemens and Lillegraven (2013, fig. 5) also used that concept, applying a new form of graphical interpretation to illustrate the nature and magnitude of fault-induced loss of section along the Hanna Basin's northern margin. The phenomenon of younger-on-older thrusting also has been identified in Wyoming adjacent to the eastern extreme of the Wind River Basin (at the widely cited 'unconformity' between lower Eocene and Upper Cretaceous strata at Hell's Half Acre on the western extreme of the Casper Arch; see erroneous interpretation as an 'unconformity' by Lillegraven, 2004, fig. 5 and many other previous workers) and along the southeastern margin of the Great Divide Basin west of the Rawlins Uplift (unpublished documentation by the late James G. Honey and Lillegraven). Sterne (2006, p. 67–68 and fig. 3) quite independently developed parallel thought about younger-on-older displacements within much more complex tectonic settings along the eastern flank of Colorado's Front Range. As discussed by Lillegraven et al. (2004, p. 48 in relation to fig. 18), down-section-cutting thrust faults also can develop as long as the initial thrust ramp is oriented upward (relative to Earth’s surface) in the direction of transport.

Figure 8 of the present paper applies the concept of 'section-reduction due to faulting' to strata around the entirety of the eastern Hanna Basin's margin. Refer to the caption for Figure 8 for descriptions of how its correlations and estimations of magnitudes of 'missing section' (i.e., the narrow vertical blue bars in the lower half of the figure) were generated.

GUIDE TO STRUCTURAL FEATURES OF MAPPED AREA

Purposes of the following three major sections of this paper (dealing with geologic maps presented as Figs. 4–6) are to: (1) aid in grasping the nature and magnitude of individual structural elements that dominate this extraordinary basin-margin sequence; and (2) identify discoveries of previously unrecognized structural features resulting from this research. With exception of the largest mountainous, anticlinal, and synclinal features shown within the areas covered by Figures 4–6, most other elements of deformation are presented for the first time on these maps. For the most part, stratigraphic terminology applied within this study follows Cardinal and Parsons (1982) and Lovel et al. (1993).

I have designated a broad, arcuate transit for the guidance of descriptive introduction that begins at the western edge of Figure 4. The transit first extends eastward and then courses to the south through Figure 5, and finally it terminates at the western edge of Figure 6. Selected references are made to interpretive geologic cross sections (Fig. 7) encountered through the transit and to the paired versions of the directly measured versus palinspastically restored stratigraphic columns (Fig. 8).

Subheadings within the 'Northern Map,' 'Eastern Map,' and 'Southern Map' sections of the following text are intended to aid in circumscribing a systematically ordered descriptive guide to geographic components within each map. Many individual structural features are laterally extensive, however, continuing across two or more of these artificially limited descriptive areas. In such cases, the feature’s description begins at its first appearance along the sequenced transit and continues onward to the point at which it is no longer traceable or has coursed beyond limits of the map.

The following three sections of this paper (involving the northern, eastern, and southern maps) are principally descriptive. Thereafter, I present three case studies (Figs. 9–11) of stepwise interpretive tectonic-evolutionary sequences across especially informative parts of the eastern Hanna/Carbon basin area. These case studies are intended to supplement a similar effort focused on the northern margin of the Hanna Basin as conducted by Clemens and Lillegraven (2013, figs. 6 and 7).

NORTHERN MAP (FIG. 4)

General Features

The principal source of interest in Figure 4 is tectonic interplay between: (1) the Archean plus Phanerozoic mountainous terrains of the Shirley Mountains (see Bergh and Snoke, 1992; and Houston et al., 1993, p. 138–140) and adjacent Freezeout Hills (Fig. 1B); versus (2) the...
northeastern margin of the Hanna Basin (Weitz and Love, 1952). The southern part of the Shirley Mountains is a highly asymmetric anticline having a north–south-oriented hinge line (see Lillegraven and Snoke, 1996, figs. 4 and 26). Configuration of the anticline is controlled by an east-dipping, basement-involved thrust fault along the structure’s western flank (southern part along western edge of NW ¼ of sec. 5, T. 24 N., R. 82 W.). That same fault trace in map view makes a hard eastward turn at the southern edge of the Shirley Mountains Anticline, where it is better known as the Shirley Fault (or Thrust; Dominic and McConnell, 1994, fig. 2). It sharply truncates the southern end of the basement-cored Shirley Mountains Anticline.

The Shirley Fault along the southern border of the Shirley Mountains Anticline is a north-dipping, basement-involved thrust plane that precisely defines today’s northern margin of the northeastern Hanna Basin (Clemens and Lillegraven, 2013, figs. 4–7). LeFebre et al. (1986) estimated approximately 43,000 ft (ca. 13.1 km) of ‘basement offset’ (presumably meaning vertical separation) along the Shirley Fault. That fault’s eastern surface expression terminates within the Frontier Formation (Fig. 4) in the SE ¼ of sec. 1, T. 24 N., R. 82 W.

Although I question its defensibility on the basis of contradictory field evidence (discussed below) and absence of well-control data, Rocky Mountain Map Co. (1992a) suggested in its structure-contour map of the Hanna Basin (based on the top of the Cloverly Formation) that the Shirley Fault continues much farther to the southeast, terminating in sec. 12 of T. 23 N., R. 80 W. Bekkar (1973, pl. 2), using a similar approach unassociated with well control, plotted a similar eastern termination of the Shirley Fault, in sec. 13 of T. 23 N., R. 80 W. Mitchell (1968, fig. 2), in his Cloverly-based structure-contour map of the Laramie and Hanna basins, presented no indication of extension of the Shirley Fault to the east beyond the southeastern corner of the Shirley Mountains. Unless I am misunderstanding the intention of the map, the continuous fault trace shown by Mount et al. (2011, fig. 3) as coursing eastwardly atop the Seminole and Shirley Mountains and continuing across the

Figure 2. Stratigraphic sequence as recognized within Figures 4–12, including formational/group names, their geochronologic designations, maximum thicknesses observed within mapped boundaries (note qualification, below, for Ferris Fm.), and stratigraphic symbols/colors used. Undulating lines represent erosionally unconformable stratigraphic contacts. Sidebar column provides relative thicknesses of individual rock units* comprising this over 14 km- (roughly 9 mi)- thick Hanna/Carbon Basin composite sequence. Note overwhelming dominance of strata deposited during Late Cretaceous into early Eocene time, capped by two geographically separated, late Laramide, gravity-emplaced klippen from outside immediate study area. Lowry et al. (1973, sheet 1), considering basins under discussion here, simplified discussion of groundwater (its occurrence, quality, potential for development, and relation to surface water) in context of geology by dividing the local stratigraphic column into eight hydrographic ‘Units.’ Applied to presently used mapping (exclusive of Unit 8), the equivalents are:

<table>
<thead>
<tr>
<th>Unit</th>
<th>Stratigraphic Base</th>
<th>Stratigraphic Top</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Pleistocene deposits</td>
<td>Holocene deposits</td>
</tr>
<tr>
<td>7</td>
<td>middle Eocene rocks</td>
<td>Pliocene rocks</td>
</tr>
<tr>
<td>6</td>
<td>Mesaverde Group</td>
<td>Hanna Formation</td>
</tr>
<tr>
<td>5</td>
<td>Thermopolis Shale</td>
<td>Steele Shale</td>
</tr>
<tr>
<td>4</td>
<td>Sundance Formation</td>
<td>Cloverly Formation</td>
</tr>
<tr>
<td>3</td>
<td>Goose Egg Formation</td>
<td>Chugwater Group</td>
</tr>
<tr>
<td>2</td>
<td>Madison Limestone</td>
<td>Tensleep Sandstone</td>
</tr>
<tr>
<td>1</td>
<td>Precambrian rocks</td>
<td>Precambrian rocks</td>
</tr>
</tbody>
</table>

*Qualification on thickness of Ferris Formation — The roughly 2.5 km (1.6 mi) thickness shown here is a typical observable value within the mapped area, which reflects the usual condition of consequential loss of section along the basin margins due to effects of younger-on-older thrust faulting. But in the southern Hanna Basin, on both flanks of the Hanna Syncline (see Figs. 6, 7 [cross section F–G], and 8 [column F–G]), the relatively unfaulted Ferris Formation (there uniquely measuring from central parts of the basin) measures closer to 5 km (3.1 mi) in thickness.
Freezeout Hills is placed roughly 8 kilometers (5 mi) too far north.

Clemens and Lillegraven’s (2013, figs. 6 and 7) interpretation of the Shirley Fault’s plane employed the concept of a deeply rooted, into-the-basin blind thrust, divergent as a north-dipping splay from deep parts of the more-shallowly dipping Shirley Fault proper. Such an interpretation, although in this case admittedly lacking in supporting evidence from the subsurface, is characteristic of Ersliev’s (1991) mountain-front, trishear fault-propagation model (Bump, 2003; and Lillegraven et al., 2004, fig. 10).

A remarkably intact Phanerozoic stratigraphic sequence supporting evidence from the subsurface, is characteristic of the Shirley Mountains Anticline. The mesa is in the NE ¼ of sec. 11, T. 24 N., R. 81W., even though confirmatory rock almost certainly continues southward into the SW ¼ of sec. 17, T. 24 N., R. 81W., even though confirmatory rock exposures in this well-vegetated grazing land are absent. Generally overturned and shattered strata of the Hanna Formation tectonically override the Lewis Shale northward at the presumed southernmost recognizable position of the syncline.

The most striking structural features in southwestern parts of the Freezeout Hills (Fig. 4) are the topographically dramatic Bald Mountain and Troublesome Creek anticlines. Hinge lines of both folds are formed by Paleozoic and Mesozoic strata that uninterrupted course southward to become tectonically overridden by strata of the Hanna Formation. Because the Shirley Fault lacks surface expression this far to the east, there exists only an arbitrarily defined, topographic boundary between uplands of the Freezeout Hills and the relative lowlands of the Hanna Basin.

The southeast-flowing Troublesome Creek (W ½ of sec. 5, T. 24 N., R. 81 W.) roughly marks the boundary between the Shirley Mountains Anticline and Bald Mountain Anticline (see Koenig, 1952, pl. III). The Bald Mountain Anticline is transitional between the Shirley Mountains and the Freezeout Hills to the east (Fig. 12). A syncline cut by a thrust fault having west-directed relative tectonic transport exists between the relatively shallow-dipping eastern flanks of the Shirley Mountains Anticline and the overturned western edge of the Bald Mountain Anticline. That syncline almost certainly continues southward into the SW ¼ of sec. 17, T. 24 N., R. 81W., even though confirmatory rock exposures in this well-vegetated grazing land are absent. Generally overturned and shattered strata of the Hanna Formation tectonically override the Lewis Shale northward at the presumed southernmost recognizable position of the syncline.

The most striking structural features in southwestern parts of the Freezeout Hills (Fig. 4) are the topographically dramatic Bald Mountain and Troublesome Creek anticlines. Hinge lines of both folds are formed by Paleozoic and Mesozoic strata that uninterrupted course southward to become tectonically overridden by strata of the Hanna Formation. Because the Shirley Fault lacks surface expression this far to the east, there exists only an arbitrarily defined, topographic boundary between uplands of the Freezeout Hills and the relative lowlands of the Hanna Basin.

The youngest Tertiary rocks shown on Figure 4 exist on a shallowly southeast-dipping, small mesa known as Chalk Bluff (Lillegraven and Snoke, 1996, fig. 27). It is situated roughly a half kilometer southeast of Archean basement rocks of the southeastern extreme of the Shirley Mountains Anticline. The mesa is in the NE ¼ of sec. 11, T. 24 N., R. 82 W. Its depositional origin traditionally has been
presumed to be post-orogenic, and it is composed of welded rhyolitic ash-flows along with relatively minor thicknesses of reworked volcanic sediments from those ash flows and locally derived Precambrian and Phanerozoic pebbles and cobbles. Radiocarbon ages of the ash flows are under study by K. R. Chamberlain, M. T. Heizler, J. M. Cottle, C. Smith, and Lillegraven. Dips of strata on southern parts of Chalk Bluff reach as high as 24° to the southeast.

Clemens and Lillegraven (2013, figs. 4–6) published the cross sections and stratigraphic columns for transsects R′–S′ and T′–U′ (to the west and east of Chalk Bluff, respectively) as shown in this paper’s Figure 4. We pointed out for cross section R′–S′ (fig. 5) “...that steep to overturned southward dips in basinal strata exist as much as six kilometers southward from the exposed Shirley Fault.” Cross sections R′–S′ and T′–U′ have both been cut by multiple out-of-the-basin, younger-on-older thrust faults having relative tectonic transports to the north. That faulting led to major thinning of the tectonically affected section as compared to their probable depositional and subsequently compacted thicknesses. That observation demands a laterally more extensive Hanna Basin during the early Paleogene.

Transect L′–M′ of Figure 4 is presented as cross section L′–M′ in Figure 7, but it does not appear as a stratigraphic column in Figure 8. No reliable measurements of stratigraphic thicknesses of specific rock units exist along that transect of generally unexposed strata.

The Paleocene–early Eocene Hanna Formation dominates the southern half of the map area as shown in Figure 4. Notice that the Hanna Formation carries a variety of lengthy W–E- or NW–SE-oriented anticlinal/synclinal folded and/or faulted features. Some of these elements are not obvious within a field setting, but they can be clearly validated through detailed mapping. Specific structures are discussed below within successive subheadings.

**Horseshoe and Schneider Ridges and Farther South**

Alternating units of Upper Cretaceous, shallow-water marine shale and lowland clastic, mainly fluvial strata dominate the northwestern quarter of the map area shown in Figure 4. It is a remarkable section in that most of the strata dip very steeply to the south or are overturned. Stratigraphic boundaries in close proximity to the Shirley Mountains are almost universally covered by erosional debris and vegetation, but lithologic boundaries become more distinct to the south. Early petroleum-drilling experience in this area (e.g., Hollis and Potter, 1984, Horseshoe Ridge, p. 78–79) speaks to the structural complexity of this area.

Two lengthy ridges dominate that area’s local topography. The more northerly is called Horseshoe Ridge, constructed principally of the dominantly fluvial Allen Ridge Formation of the Mesaverde Group (sensu Gill et al., 1970, table 1, Gill and Cobb, 1973, fig. 12, and Martinson et al., 1993, fig. 3). The more southerly is Schneider Ridge, dominated by the much younger fluvial and shallow marine Medicine Bow Formation. Between those two ridges, restricted to the far western parts of the map, is a less extensive ridge composed of an overturned anticlinal feature known as the Austin Creek Anticline. The western crest of that anticline is eroded deeply enough that the Allen Ridge Formation is exposed in a window cut through the overlying Lewis Shale.

Strata between the Austin Creek Anticline and northern Horseshoe Ridge are cut by bedding-parallel and lengthy, out-of-the-basin thrusts having relative tectonic transport originally to the north. A complexly deformed and pervasively fractured, faulted, and overturned syncline (‘Card-tricks Hill’ of Lillegraven and Snoke, 1996, fig. 29) exists across adjacent parts of secs. 8–9 in T. 24 N., R. 82 W. Very probably, the structure at Card-tricks Hill represents a supremely deformed footwall syncline of the overturned and thrust-faulted (with relative tectonic transport to the north) Austin Creek Anticline, seen directly to the south.

Lillegraven and Snoke (1996, fig. 28) undertook initial mapping of this ridge-and-valley complex along with attempts at constructing three interpretive cross sections (fig. 30) oriented normal to bedding planes. It becomes obvious, both in the field and in study of Figure 4, that when following this ridge system from west to east, there exists progressive and major loss of the Cretaceous section as Chalk Bluff is approached. Almost certainly, the loss in section resulted both from: (1) having been overridden by basement-involved thrusting with south-directed relative tectonic transport along the Shirley Fault; and (2) thin-skinned, down-section cutting along north-directed out-of-the-basin thrusts. The relative magnitudes of those diachronically opposed components involving loss of section are illustrated in the absence of vertical exaggeration by Clemens and Lillegraven’s figure 6 (2013).

Although neither precision nor close accuracy can be claimed for the procedures used to develop the paired

**Figure 3.** Digital-elevation models of eastern half of Hanna Basin, Carbon Basin, and adjacent areas. A. Indicated are names of U.S. Geological Survey 7.5-minute topographic quadrangle maps (used as bases for geologic mapping throughout this study) and outlines of boundaries for three geologic maps (Figs. 4–6, combined in Fig. 12). Small inset ‘Breaks Map’ is part of Figure 5. B. Reference locations for interpretive geological cross sections plotted as map transects on Figures 4–6 and fully rendered in Figure 7. For convenience in use, all information presented in Parts A and B also is duplicated on each geologic map (Figs. 4–6) along with with cross sections (Fig. 7) and derived stratigraphic columns (Fig. 8). Principal contents of Figures 4–8 all employ 1:24,000 scale. Figures 9–11, developed using 1:100,000 scale, employ different placements of cross-sectional transects and numbering systems (see diversity of inset maps).
stratigraphic columns (i.e., before and after thrusting) along cross sections R–S' and T–U' (Clemens and Lillegraven, 2013, fig. 5) or N–O' (fig. 8), the approximately estimated losses of correlative section thickness following faulting are 50, 75, and 38 percent, respectively. Landon (2001), Hajek (2009), Hajek et al. (2010, 2012), and Wang et al. (2011) recently pursued various forms of sedimentological and stratigraphic analyses of the upper Ferris and lower Hanna formations in this area.

Boyd and Lillegraven (2011, p. 46–48) considered the history of nomenclature relevant to original designations of the Ferris and Hanna formations. A formal type section for neither formation was ever specified. Nevertheless, the area originally intended to stand as the formational contact is known to be near the western edge of sec. 28, T. 23 N., R. 83 W. (Dobbin et al., 1929, p. 27). That is almost ten kilometers to the southwest of the southwestern corner of Figure 4. Clemens and Lillegraven (2013, p. 162–163) traced the original stratigraphic level presented in the Dobbin et al. 1929 map to the stratigraphic level at which the Ferris–Hanna formational contact is shown along the western parts of Figure 4.

Notice that through the most westerly three miles (4.8 km) of Figure 4 the Ferris–Hanna contact is shown to be conformable. Beginning within sec. 17, T. 24 N., R. 82 W., however, and continuing eastward for the total length of the remainder of Figure 4, the contact is shown to be transformed into an out-of-the-basin thrust having relative tectonic transport to the north that locally cuts down-section as deeply as the Niobrara Formation. Minimally, that represents roughly eight kilometers of tectonically omitted section, including complete loss of the Ferris Formation downward through Steele Shale. And, with two geographically short exceptions, all of the remainder of the basal contact of the Hanna Formation with underlying strata all around the circumference of the eastern Hanna Basin (Figs. 4–6 and 12) is interpreted here as structural, not depositional.

Well south of the Hanna–Ferris formational contact in the western part of Figure 4 is a relatively short out-of-the-basin thrust having relative tectonic transport to the northeast. Minimally, it can be traced to the east from the eastern margin of sec. 24, T. 24 N., R. 83 W. to the N-central part of sec. 29 in T. 24 N., R. 82 W., and the thrust marks a roughly 50° decrease in dip of the hanging wall’s section from underlying (i.e., more northerly) strata. What appears to be a different fault makes its first appearance in the northwestern corner of sec. 29, T. 24 N., R. 82 W. and courses generally NNE to the southwestern quarter of sec. 24 and then bends abruptly to continue into the southeastern corner of sec. 30 of T. 24 N., R. 81 W. At that point it seems to lose its faulted nature and becomes fully converted into a subtly expressed anticlinal structure that undulates broadly in map view to an apparent termination at the eastern extreme of Figure 4. It is probable, however, that this lengthy anticline actually continues southeastward, without visible expression across a part of the floodplain of the Medicine Bow River to connect with a minor anticline/syncline pair in the southern adjacent parts of sections 31 and 32 of T. 24 N., R. 80 W. That anticlinal/synclinal pair is within the hanging wall of the Owl Ridge Fault (Fig. 5; see Lillegraven et al., 2004, fig. 4B).

Southeastern Extreme of Shirley Mountains and Farther South

Dipping to the east, off the southeastern extreme of the Shirley Mountains Anticline, is a 1,274 m- (4,180 ft-) thick, generally well-exposed sequence of Paleozoic through Lower Cretaceous strata (Fig. 7, cross section J–K’). Ferren (1935) pioneered study of the area, although Lee (1927, p. 70–71) raised questions significantly earlier about correlations of nearby stratigraphic units. This thin veneer of dominantly pre-Laramide strata is typical within the vicinity of the Hanna Basin. The section has not been subjected to consequential internal faulting (Fig. 8). The remainder of the minimally 14 km-thick sedimentary sequence of the basin is composed of Upper Cretaceous into lower Eocene strata capped by a thin, locally developed volcaniclastic deposit, the age of which is under investigation. The Shirley Fault (Fig. 4) truncates the entire southern exposures of the J–K’ stratigraphic column (Fig. 8) with exception of the Upper Cretaceous Frontier Formation; it contains the fault’s most easterly surface expression. Clarey (1984) attempted limited applications of seismic refraction and electromagnetic surveys, along with remote sensing of linear features, to trace a concealed fault eastward. He considered existence of a low-angle, north-dipping thrust fault.

At the extreme southeastern exposures of the Archean basement rocks of the Shirley Mountains Anticline (SW ¼ sec. 2, T. 24 N., R. 82 W.), note that the trace of the Shirley Fault on Figure 4 is indicated by (opposite) oriented teeth...
Although it was recognized even at that time as a lengthy named the 'defining syncline of northeastern Hanna Basin.' (here presented as the northwestern-most insert to Fig. 5), stratigraphy, structure, and paleontology of 'The Breaks' N., R. 82 W., courses SSW for half a mile and then turns to fold that commences in the N-central part of sec. 13, T. 24 W. It may well have been initiated by the tightly anticlinal influence can be traced from the W-central part of sec. 13, represents another thrust within the Hanna Formation and paralleling it, exists a cryptic structure that probably (Clemens and Lillegraven, 2013, figs. 3 and 4). Bases of both underlying formations exhibit fault traces having directions of relative tectonic transport to the north and northeast. About 300 m (984 ft) directly west of Chalk Bluff is a strong, asymmetrically deformed synclinal fold that is expressed both in the Ferris Formation and overlying thrust plate of the Hanna Formation. The hinge line of that syncline initially courses to the SSW, but in the NW ¼ of sec. 14, T. 24 N., R. 82 W. it turns to the SE and appears to terminate in the western part of sec. 29, T. 24 N., R. 81 W. Throughout the syncline's total crossing of sec. 24 in T. 24 N., R. 82 W., its axial surface becomes a thrust with relative tectonic transport both to the north and to the south. The opposed toothed symbols, however, are intended to show the apposition of uplift of the Shirley Mountains (by basement-involved faulting) directly against upturned thin-skinned deformation that expressed opposite directions of relative tectonic transport. Quite in contrast, Shelton (1968, figs. 3 and 4) interpreted all major Laramide faults of the Hanna Basin as vertically oriented, normal faults.

As mentioned above, Chalk Bluff is a small, erosional-remnant mesa located mostly in the NE ¼ of sec. 11, T. 24 N., R. 82 W. It is composed of rhyolitic welded tuffs and their eroded detritus. Lithologically identical, volcanic-derived sediments also occur two miles to the north-northwest, plastered onto Precambrian basement rocks high on the Shirley Mountains (N-central sec. 35, T. 25 N., R. 82 W.; see Lillegraven and Snoke, 1996, fig. 4). Love (1963, fig. 1) mapped those rocks as 'Pliocene (?),' but he did not actually discuss them in his open-file report.

Chalk Bluff itself was deposited on both fossil-wood-bearing Medicine Bow Formation and dinosaur- and mammal-bearing, latest Cretaceous Ferris Formation (Clemens and Lillegraven, 2013, figs. 3 and 4). Bases of both underlying formations exhibit fault traces having directions of relative tectonic transport to the north and northeast. About 300 m (984 ft) directly west of Chalk Bluff is a strong, asymmetrically deformed synclinal fold that is expressed both in the Ferris Formation and overlying thrust plate of the Hanna Formation. The hinge line of that syncline initially courses to the SSW, but in the NW ¼ of sec. 14, T. 24 N., R. 82 W. it turns to the SE and appears to terminate in the western part of sec. 29, T. 24 N., R. 81 W. Throughout the syncline's total crossing of sec. 24 in T. 24 N., R. 82 W., its axial surface becomes a thrust with relative tectonic transport to the southwest. Strata parallel to the thrust's trace both in its footwall and hanging wall exhibit chaotically deformed bedding (indicated by pink pattern in Fig. 4).

Less than 300 m to the northeast of that faulted syncline, and paralleling it, exists a cryptic structure that probably represents another thrust within the Hanna Formation having relative tectonic transport to the southwest. Its influence can be traced from the W-central part of sec. 13, T. 24 N., R. 82 W. into the SW ¼ of sec. 19, T. 24 N., R. 81 W. It may well have been initiated by the tightly anticlinal fold that commences in the N-central part of sec. 13, T. 24 N., R. 82 W., courses SSW for half a mile and then turns to the southeast, crossing a tributary to Dry Creek, to terminate by plunging into the NW ¼ of sec. 19, T. 24 N., R. 81 W.

Lillegraven et al. (2004, fig. 4), while studying the stratigraphy, structure, and paleontology of 'The Breaks' (here presented as the northwestern-most insert to Fig. 5), named the 'defining syncline of northeastern Hanna Basin.' Although it was recognized even at that time as a lengthy structural feature, it now can be said to be an inter-basinal syncline that is the most extensive structural element known from the Hanna Basin. The surface expression of this syncline minimally involves the: (1) Hanna and Ferris formations of the Hanna Basin; and (2) Hanna (of the Carbon Basin Klippe), Ferris, and Medicine Bow formations of the Carbon Basin. The syncline then extends into the northeast beyond the area mapped during this research. Much deeper parts of the stratigraphic column also are affected by this syncline across grazing lands east of the present map.

The western termination of the 'defining syncline of northeastern Hanna Basin' as seen in surface strata is in the center of sec. 25, T. 24 N., R. 82 W. The structure-contour geologic map of the Hanna Basin developed by Rocky Mountain Map Company ['RMMC'] (1992a), however, shows the syncline's minimal northwesterly continuation at depth of the Lower Cretaceous Cloverly Formation (i.e., a 'Dakota equivalent') to the NW corner of sec. 5, T. 24 N., R. 82 W. At that point, the syncline is shown as having been overridden by basement rocks of the Shirley Mountains. Tectonic transport by the Shirley Fault was directed to the south. RMMC does continue to show the feature in question as a clearly defined syncline, however, whereas Hinckley and Heasler (1984, pl. III) had portrayed its axial surface as a major fault in which the Cloverly Formation was differentially uplifted by roughly two miles along the structure's northeastern flank. As considered below, it is certain that this extensive syncline does become profoundly

Figure 5. Geologic map of entire eastern margin of Hanna Basin and all but southern extremes of Carbon Basin. Map is bounded to east by western parts of Flat Top and Big Medicine Bow anticlines, to north by course of Medicine Bow River, and to south by U.S. Interstate Highway 80 at southern extreme of Simpson Ridge Anticline. Colored map at full 1:24,000 scale is presented in digital form suitable for printing as 'Fig. 5.PDF.' A thumbnail version for quick reference, however, exists unscaled on following page. Indicated geographic cross sections are presented using 1:24,000 scale in Figure 7 (note that transects D–L and J–K continue westward onto Fig. 6). Unless otherwise indicated, strike/dip measurements are by the author, and associated station numbers (e.g., '5745') allow access to additional geographic and geologic information listed under those numbers in Appendices 1 and 2 (Table 2). Exceptions on this map include attitudinal measurements shown: (1) without station numbers in the map's northeastern corner (from Elevens, 1984); (2) as 'Taylor' in northern part of inset (from Taylor, 1996); (3) with initials 'DBH' (from Dobbin et al., 1929) in western parts of Como West quadrangle; and (4) without station numbers on core and eastern flanks of Simpson Ridge Anticline (from Kraatz, 2002). Inset of 'The Breaks' at northern edge of map is rescaled (original 1:12,000) from figure 4B of Lillegraven et al. (2004), with cross section P’–Q’ re-labelled here from the original as A–A'.
faulted as it courses across the broad hinge of Simpson Ridge Anticline farther to the southeast. In any case, this extensive syncline stands as a shining example for the importance of combined surface mapping and searching for constraints on structural relationships at depth.

From its western termination as observed on the surface, the defining syncline of northeastern Hanna Basin courses: (1) ESE (onto Fig. 5) to the SW corner of sec. 6, T. 23 N., R. 80 W.; (2) then SEward to the NW corner of sec. 17, T. 23 N., R. 80 W.; (3) SE to the NW corner of sec. 22, T. 23 N., R. 80 W.; (4) turning there to an extended SSE course into the N-central part of sec. 13, T. 22 N., R. 80 W.; (5) continuing across the Carbon Basin to the SE as far as the southern part of Halfway Hill in SW ¼ of sec. 2, T. 21 N., R. 79 W.; and (6) then turning sharply to the NE, extending beyond the eastern edge of Figure 5. The easternmost transit of this syncline deserves serious study. It certainly continues northeasterward beyond the edge of Figure 5 across grasslands with poorly exposed rocks. Indeed, it probably is continuous with the Bone Creek Syncline (see Dunbar, 1944, p. 1208) that is south of Flat Top Anticline and borders to the north of the tectonically northwest-directed Como Bluff Anticline’s thrust-fault. The latter basement-involved fault complex continues unabated through more than three townships toward the ENE, finally to become obscured within western flanks of the Laramie Mountains (in T. 24 N., R. 73 W.).

Following this new recognition of the basin-into-mountain continuity of the ‘defining syncline of northeastern Hanna Basin,’ its name as designated by Lillegraven et al. (2004) has become inappropriate. Also, notice that through more than a three-mile-long stretch, that syncline crosses the broad hinge of Simpson Ridge Anticline (i.e., from the NE corner of sec. 34, T. 23 N., R. 80 W. to the N-central part of sec. 13, T. 22 N., R. 80 W.), across which it becomes profoundly thrust-faulted. I suggest here that minor eastward relative tectonic transport exists, combined with an apparent right-lateral strike-slip component as seen in map view.

**Bald Mountain Anticline, Troublesome Creek Anticline, and Farther South**

Soft, shale-rich Upper Cretaceous strata with occasional resistant, outcrop-forming sandstone interbeds dominate the broadly open landscape constituting much of the northeastern quarter of Figure 4. Specifically, that refers to the area north of the faulted edge of the Hanna Formation, east of the Shirley Mountains Anticline, south of the dramatic topographic expression of Bald Mountain Anticline (see Prucha et al., 1965, p. 974–975 and fig. 13), and west of the edge of Difficulty Quadrangle. Nevertheless, the entire area is represented (listed in order of west-to-east occurrences) by the: (1) strata of the Mowry through Steele Shale as stratigraphic caps of the southeastern Shirley Mountains Anticline; (2) N–S-oriented, faulted syncline defining the western edge of the Bald Mountain Anticline (see ‘General Features of Northern Map (Fig. 4)’ above); (3) N–S-oriented hinge line of the Bald Mountain Anticline (parallel to cross section H’–I’ of Figs. 4, 7, and 8); (4) SW–NE-oriented hinge line of a faulted syncline that in part defines the southeastern border of the Bald Mountain Anticline; and (5) profoundly faulted and asymmetrically folded Troublesome Creek Anticline, with its SSW-plunging, tightly folded axial surface.

Notice that across the entire traverse of features (numbered 1–5) in the preceding paragraph, there exists no sign of any part of the Mesaverde Group. It apparently has been completely overridden by north-directed, out-of-the-basin thrust faulting of the younger Lewis Shale, Medicine Bow Formation, and even part of the Ferris Formation. That is, the area under discussion is a somewhat less complex, structural parallel to the style of faulting described above as seen to the west of Chalk Bluff, especially as has resulted along the entire extent of Horseshoe Ridge.

As only partially covered in Figure 4, the hinge line of the Bald Mountain Anticline begins in the S-central margin of sec. 33, T. 25 N., R. 81 W. and extends essentially due south to its termination in the NW ¼ of sec. 21, T. 24 N., R. 81 W. Notice that most of the anticlinal strata of the Medicine Bow Formation in adjacent parts of sections 20 and 21 are overturned (contra Knight, 1951, fig. 4), representing a marked increase in the degree of plunge of the Bald Mountain anticlinal hinge line compared to its more northerly parts. The overturned outcrops thereby constitute a synformal anticline. The pink pattern on both sides of Figure 6.

**Figure 6. Geologic map of southern parts of Hanna Basin.** Map is approximately bounded to north by U.S. Highway 30/287, to south by northern topographic base of Elk Mountain, to west by northern end of Dana (Pass Creek) Ridge, and to east by western edge of southern half of Figure 5. Colored map at 1:24,000 scale is presented in digital form suitable for printing as ‘Fig. 6.PDF’. A thumbnail version for quick reference, however, exists unscaled on following page. Indicated geological cross sections are presented in Figure 7 (note that transects D–L and J–K continue onto Fig. 5). Unless otherwise indicated, strike/dip measurements are by the author, and associated station numbers (e.g., ‘7812’) allow access to additional geographic and geologic information listed under those numbers in Appendices 1 and 2 (Table 2). Exceptions on this map include attitudinal measurements shown as: (1) ‘BH’ (from Hitchens, 1999) on Dana Ridge and Coal Bank Basin; and (2) ‘RHB’ (from Beckwith, 1941) along southern edges of map. Dotted, east–west straight-line contacts between underlying strata and Hanna Formation of Dana Klippe on its northern edge and along northeastern flanks of Dana Ridge reflect prohibition of author’s access by landowner for purposes of this research.
the synformal anticline’s hinge line at the fault trace on Figure 4 between the Hanna and Medicine Bow formations represents chaotically deformed strata. Quite possibly, several levels of out-of-the-basin thrusts converge all along the northern mapped boundary of the Hanna Formation where it makes contact with southern ends of the Bald Mountain and Troublesome Creek anticlines.

The syncline forming the eastern margin of the Bald Mountain Anticline is faulted along much of its northern length. As shown on Figure 4, its hinge line courses from the SE corner of sec. 35, T. 25 N., R. 81 W. southwestward across Cretaceous strata onto heavily deformed rocks of the Hanna Formation at the adjacent midlines of sections 16 and 21. At that point, the synclinal hinge line makes a hard
turn to the SE and then undulates generally eastward at least through sec. 24. In map view, the general configuration of this southern part of the syncline behaves similarly to the one described above, beginning just west of Chalk Bluff.

The southernmost parts of Troublesome Creek Anticline on the eastern extreme of the T.E. Ranch Quadrangle are most unusual in the east–west narrowness of its hinge. Observation of map relationships between the thrust fault having relative tectonic transport to the northwest and the overridden, mostly Upper Cretaceous strata suggest considerable structural separation along the total length of the fault. Small, isolated ‘islands’ of Hanna Formation persisting on Upper Cretaceous rocks in the NE corner of sec. 21 and northern parts of sec. 22 of T. 24 N., R. 81 W. demand greater complexity of faulting than can be interpreted from the simple map pattern rendered in Figure 4. The actual nature of those complexities, however, remains quite unknown.

Early in the above discussion of the ‘Northern Map (Fig. 4)’ ‘General Features’ section, I stated that surface expression of the eastern termination of the Shirley Fault is near the stratigraphic base of the Frontier Formation in the SE ¼ of sec. 1, T. 24 N., R. 82 W., south of eastern parts of the Smith Creek Anticline. In contrast, several of my predecessors have indicated on maps that the Shirley Fault extends as much as 15 miles (24 km) southeast of that point. I think information presented above can be brought to bear on this controversy.

The source of the controversy begins on Figure 4, directly northeast of Chalk Bluff at Nelson Spring (at the boundary of sections 2 and 11 of T. 24 N., R. 82 W.). Under the interpretation applied in the present paper, the Shirley Fault continues eastward from Nelson Spring to terminate within the south-central part of the SE ¼ of sec. 1, T. 24 N., R. 82 W. (see photo in outside, front cover of v. 48, no. 2 of Rocky Mountain Geology, 2013). In error, I contend, many other authors show the ‘Shirley Fault’ as extending southeastward from Nelson Spring, undulating into the NE ¼ of sec. 21, T. 24 N., R. 81 W., then coursing generally eastward into sec. 19 of T. 24 N., R. 80 W.—and then beyond the present map coverage. I consider the trace described in the preceding sentence as representing out-of-the-basin relative tectonic transport, first to the northeast and then to directly north, of parts of the Medicine Bow, Ferris, and Hanna formations. That faulting represents younger-on-older displacements as indicated in cross sections T’–U’ and H’–I’ in Figures 4 and 7. Thus, the structural history presented here for the northeastern margin of the Hanna Basin differs in a fundamental fashion from that of previous researchers.

Adding to the concept of a greatly curtailed eastward extent of the Shirley Fault, one can directly observe a marked southerly shift in the structural boundary between the southern edge of the Freezout Hills and northermost Hanna Basin. Notice in Figure 4 that (1) the north–south-aligned, faulted syncline between the Shirley Mountains and Bald Mountain, (2) the Bald Mountain Anticline, (3) the Troublesome Creek Anticline, and (4 — seen in Fig. 5) the Freezout Mountain Anticline (see sections 27, 34, and 33, T. 24 N., R. 80 W.) all plunge southward or southwestward in uninterrupted fashion, from the main bulk of the Freezout Hills into the northeastern margin of the Hanna Basin. To that list could be added the synformal Ellis Ranch Anticline (Taylor, 1996, pl. 1; Frontispiece of present paper), which is mostly north of coverage by Figure 5, dominating sections 19, 20, 29, and 30 of T. 24 N., R. 80 W.

The Paleocene and early Eocene Hanna Formation universally overlies the southern extremes of all five of the fold-structures mentioned in the preceding paragraph. If the Shirley Fault were in reality to extend so far east from the Shirley Mountains, why do those folds not reveal evidence?

Figure 7. Geologic cross sections following transects shown in Figures 4–6. Illustrated is surface topography (scale 1:24,000 with no vertical exaggeration), with geologic features interpreted consistently to depth of 4500 feet (1372 m) above mean sea level. Sheet of colored sections at 1:24,000 scale is presented in digital form suitable for printing as ‘Fig. 7.PDF’. A thumbnail version for quick reference, however, exists unscaled on following page. Dips of strata, or their apparent dips (‘ap.’) as appropriate, are specified in degrees from horizontal, and each is: (1) graphically represented by a short black line projecting downward from surface at the relevant angle from its point of measurement; and (2) identified by a black station number (e.g., 6052). Additional geographic and lithologic information is provided for rocks at each point of measurement in Appendices 1 and 2, readily accessed by sequentially ordered station number (Table 2). Quadrangle, township, and section boundaries are indicated along baselines of all transects. Vertical, thin red lines serve to subdivide each cross section into natural units by which cumulative thicknesses can be measured along surface transects with progressively varying dips. Between each pair of red vertical lines are sets of red numbers, which represent individual components of measured thicknesses. Measurements are numbered sequentially and ordered stratigraphically up-section (see corresponding numbers on matching stratigraphic columns in Fig. 8). Thickness (in meters) of each individual stratigraphic unit was digitally measured (from screen-enlarged cross sections) normal to field-recognizable features such as dips of strata, fault planes, or formational contacts. Cross section F’–G’ (which traverses Elk Mountain) is unique within this paper in being only in part restricted to landscape mapped here (attitudinal measurements identified as ‘RHB’ are from Beckwith, 1941). Cross section P’–Q’ is duplicated (and reduced in scale from 1:12,000 to 1:24,000) from figure 4C in Lillegraven et al. (2004), where it was identified as cross section A–A’. Cross sections R’–S’ and T’–U’ are duplicated from Clemens and Lillegraven, 2013 (there as fig. 5). Notice that almost all faulting on this sheet is interpreted to have been in the nature of out-of-the-basin, décollement-type thrust faults. [See ‘Qualification on thickness of Ferris Formation’ in caption to Fig. 2.]
Figure 7. Interpretive Geologic Cross Sections Along Eastern Margins of Hanna Basin and Carbon Basin, Carbon County, Wyoming

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for structural offsets from an underlying thrust fault? The Troublesome Creek and Ellis Ranch anticlines respectively expose rocks as old as the Permian and Triassic. Thus those anticlines would seem to be especially vulnerable to distortions from having been cut by any significant transverse fault. If valid evidence exists for extended eastward continuity of the Shirley Fault, I have been unable to determine what it is.

A revised interpretation of the eastern extent of the Shirley Fault has many practical implications of human import. As an example, a graduate thesis developed by Johnson (1994) deals with the nature of structural compartmentalization of groundwater related to drainage basins of Troublesome and Difficulty Creeks. Those drainages are located east of the Shirley Mountains and involve, respectively, eastern flanks of the Shirley Mountains and western parts of the Freezefout Hills (Johnson, 1994, fig. 1). The area covered in his research includes roughly 167 square miles (433 km²), draining watersheds that exhibit strong compartmentalization (i.e., isolation) of water masses among the three areas. Johnson (1994, p. 65) concluded:

"The groundwater system in the Troublesome–Difficulty Creek drainage basins has been isolated from the circulation system in the northern Hanna Basin as a result of hydraulic severing of the Paleozoic rocks along the mountain-basin margin by the Shirley thrust fault. Geochemical and potentiometric data indicate the Troublesome Creek and Paradise [outside of the present map areas in sections 20, 17, 8, 5, and 6, W and NNW of the Beer Mug and Ellis Ranch anticlines; Frontispiece] faults structurally divide the hanging wall block of the thrust fault into three hydraulically independent groundwater compartments: the Troublesome Creek, Hay Slough, and Difficulty Creek groundwater compartments."

Although I believe Johnson's (1994, pls. 1–V) evidence to be sound in favor of existence of three groundwater compartments north of the Hanna Basin, I challenge involvement of the Shirley Fault itself as the barrier to southward water flow into the basin. Rather, I suggest alternatives akin to what is shown in cross sections T’–U’ and H’–I’ of Figure 7. Both cross sections suggest barriers involving undersurfaces and bulk composition originally having north-directed relative tectonic transport. But now they are steeply dipping to overturned barriers composed of faulted strata of the Hanna Basin that are composed principally of low-permeability barriers (also see Clemens and Lillegraven, 2013, fig. 5).

**Western Extreme of Indian Spring Fault and Farther South**

The Indian Spring Fault (sec. 19, T. 24 N., R. 80 W.), which had south-directed relative tectonic transport, near the northeastern corner of Figure 4 sharply truncated Lower and Upper Cretaceous strata and thrust them onto significantly younger rocks of the Steele Shale. The Indian Spring (thrust) Fault tectonically defines the southern boundary of the spectacular Beer Mug Anticline (see Brown, 1939, pl. 1; Stone, 1993, fig. 31; and Lillegraven and Snoke, 1996, fig. 18), composed of Pennsylvanian Tensleep Sandstone through Upper Cretaceous Frontier Formation (Hamilton, 2003b; and occurrence of ‘78 coal,’ as mapped by Dobbin et al., 1929).

**Figure 8.** Geologic columns (36 total, each column with two representations—one above and another below the red dotted, mostly horizontal line), constructed from field data presented in cross sections of Figure 7. Sheet of colored columns at 1:24,000 scale is presented in digital form suitable for printing as ‘Fig. 8.PDF’. A thumbnail version for quick reference, however, exists unscaled on following page. Individual columns are variously correlated stratigraphically by use of four, broadly relevant markers (specifically: approximate base of Lewis Sh., using maps in this paper; Ferris–Medicine Bow formational contact, using maps in this paper; approximate boundary of Torrejonian–Tiffanian land-mammal ages, of Higgins, 2003b; and occurrence of ‘78 coal,’ as mapped by Dobbin et al., 1929). Columns above red dotted line are presented as they would be measured during field encounters today (i.e., faults and unconformities might be recognized on outcrops, but they would not affect reporting of measurable thicknesses). Columns below red dotted line, in contrast, provide reasonable estimates (i.e., conservatively expressed interpretations based upon geographically nearby, more complete sections) of reductions in thickness of stratified rocks (indicated by narrow blue vertical lines) resulting from a combination of Laramide faulting and erosion (see Figs. 9–11; such gaps are not considered here in strata older than Steele Sh.). Stratigraphically ordered red numbers (to left of columns) represent corresponding, individually measured increments of rock as shown and explained in Figure 7, with their total thicknesses (in meters). Purpose of this figure is to graphically provide comparisons between estimates of original depositional thicknesses (upper columns) and today’s thicknesses following faulting and erosion (lower columns). [See ‘Qualification on thickness of Ferris Formation’ in caption to Fig. 2.]
To the east of the present map, and north of Figure 5, the Indian Spring Fault (carrying the Beer Mug Anticline) overrides a deeply eroded, synformal anticline known as the Ellis Ranch Anticline (Taylor, 1996, pl. I; Frontispiece of present paper). Those structurally overlapping folds help greatly in grasping the levels of complexity of tectonism that characterize southwestern flanks of the Freezeout Hills.

Notice within the expanse of the Hanna Formation (Fig. 4) north of the Medicine Bow River in sections 23–25 of T. 24 N., R. 81 W., there exist blue traces showing ‘Leg 18,’ ‘Leg 19,’ and ‘Leg 20.’ These refer to the uppermost three components of the composite measured section of the Hanna Formation as seen in the northeastern corner of the Hanna Basin (Lillegraven et al., 2004, figs. 11–13). Because of space constraints on the map (fig. 4) prepared for the 2004 publication, the positions of those three legs within uppermost parts of the measured section could not be included.

The knob at the northern termination of Leg 20 (just east of the center of sec. 23) is stratigraphically the highest level of the Hanna Formation remaining today across the entire Hanna Basin. The stratigraphic level at that point is at least 11,600 ft (ca. 3.54 km) above the base of the formation (Lillegraven et al., 2004, fig. 11). The total thickness of the Hanna Formation would be still greater if it were possible to reliably quantify the amount of section lost through effects of four younger-on-older faults recognized within the lowest ten legs of the measured section. Lillegraven (1994) reported discovery, near the top of Leg 19, of *Hyracotherium grangeri*, a ‘dawn horse’ characteristic of the early ‘Wasatchian’ North American Land Mammal Age, now considered as an early part of the Eocene Epoch.

The information provided in the preceding two paragraphs becomes important when one recognizes on Figure 4 the minor difference in elevation (and represented stratigraphic thickness) between the top of Leg 20 and the poorly exposed bounding fault trace for the Hanna Formation seen just to the north. What is labeled in sections 19 (Fig. 4) and 30 (Fig. 5) of T. 24 N., R. 80 W. as the ‘Owl Ridge Fault’ should more appropriately be considered as the superposition, or probably even confluence, of at least two, quite distinct out-of-the-basin thrust faults. Those relationships were considered in detail through figures 17 and 18 and associated text by Lillegraven et al. (2004). Beginning along the southern juxtaposition of sections 29 and 30 of T. 24 N., R. 80 W., the stratigraphically higher Owl Ridge Fault has overridden the Dragonfly Fault.

The Dragonfly Fault, along with its highly irregularly paralleling footwall syncline, have been traced several miles to the southeast, extending at least to South Pine Draw in the SW corner of sec. 14, T. 23 N., R. 80 W. (Fig. 5). Near that point, at least three out-of-the-basin thrusts have overridden one another. The relevant point of all this is that the simplicity of map representation of the nature of
the fault at the base of the Hanna Formation all along the northeastern margin of the Hanna Basin is an illusion. The reality is that two to perhaps several superimposed faults probably are involved along any given tract of that single mapped thrust symbol. Indeed, the complexly imbricated faulting documented along the boundary between the SW ¼ of sec. 14 and the NW ¼ of sec. 23, T. 23 N., R. 80 W. would seem to be a valid model for much of the length of the Hanna Formation’s faulted contact with older strata.

**EASTERN MAP (FIG. 5)**

**General Features**

Figure 5 is the most complex of the three geologic maps presented in this paper. The complexity results from the combination of contractional structures and crowding of strata from several surrounding late Laramide uplifts. Each uplift has deep-seated faults rising to, or nearly to, the modern surface. Directly north of the map are southerly flanks of the Freezouit Hills, defined by the Sledge Creek and Freezouit Mountain anticlines (see Maravich, 1941, fig. 2; Gist, 1957, pls. II and III; and Taylor, 1996). The latter anticline exhibits a relative tectonic transport to the northwest by a basement-involved thrust fault along its northwestern flank (Lillegraven and Snoke, 1996, figs. 4 and 7).

At the northeastern corner of the map are western parts of the Oil Springs (Blackstone, 1994, fig. 4; Lillegraven and Snoke, 1996, fig. 34) and Flat Top (Blevens, 1984) anticlines, separated by the west-plunging Flat Top Syncline. The broad, north–south-elongated, dome-like Big Medicine Bow Anticline dominates the southeastern quarter of the map (Blackstone, 1983, fig. 24 and 1993a, fig. 2, pl. 2; Rocky Mountain Map Co., 1992b) to as far as the northern end of the Carbon Basin. The southern extreme of the Carbon Basin is not included within this mapping project. Finally, the Hanna Syncline has its northern termination in E-central parts of sec. 12, T. 23 N., R. 81 W. in the northwestern part of Figure 5; it is described below in primary context of Figure 6.

Pre-eminent features in central parts of Figure 5 are Simpson Ridge Anticline (Kraatz, 2002; Veronda, 1951; Saddleback Hills Anticline of older literature) and the Carbon Basin (Dobbins et al., 1929, pl. 27). Simpson Ridge Anticline in the western half of the map is remarkably symmetrical when viewed in cross section at right angles to its axial surface trace (Fig. 7 D–L, M–O, and P–Q). Its western component is a north–northeast- to north–south-aligned structural and topographic feature. Toward its northern end, however, the anticline’s hinge line effects a hard turn to the northeast, seemingly only to vanish upon confluence with the faulted trace of the ill-named ‘defining syncline of northeastern Hanna Basin’ (see previous discussion) in the SE ¼ of sec. 2, T. 22 N., R. 80 W. Notice, however, that the Simpson Ridge Anticline appears once again in the NW ¼ of sec. 13 of that same township, over two kilometers to the southeast, but now linked to the eastern side of the ‘defining syncline.’

Eastern parts of the hinge line of Simpson Ridge Anticline in the eastern half of Figure 5 course northeastward up to the NE ¼ of sec. 32, T. 23 N., R. 79 W. At that point, the hinge line effects a grand arc through the southern extremes of sections 28 and 27. and then is directed southeastward, trending beyond the eastern edge of the map onto the Medicine Bow Quadrangle near the southeastern corner of sec. 35 in T. 23 N., R. 79 W. The core of the anticlinal fold as seen within adjacent parts of sections 32, 33, and 28 is overturned to the north within the plastically deformed Steele Shale.

The hinge line of Simpson Ridge Anticline, at least in the western half of Figure 5, by tradition defines the structural boundary between the eastern Hanna Basin and the Carbon Basin. As will be considered in more detail below, all structural evidence presented within this paper supports the concept that Simpson Ridge Anticline developed after deposition of the greater Hanna Basin’s Hanna Formation. That differs fundamentally from the interpretation provided on the basis of inferred trends in paleocurrent directions as presented by Ryan (1977). Following tradition firmly established by Dobin et al. (1929), the youngest major rock unit in both basins has been mapped as Hanna Formation, and in both basins the Hanna is coal bearing.

As first recognized through mapping by Dobin et al. (1929, pl. 27), many of the numerically identified coal beds within the Hanna Basin proper can be traced in outcrop for miles (Lillegraven et al., 2004, fig. 5). Dobin’s team utilized a simple and practical system of coal-bed enumeration for the Hanna Basin (revised by Blanchard and Comstock, 1980; Flores et al., 1999a, fig. HS-3 and Hettinger, 1978, fig. 1 and table 1 devised alternative systems of enumeration for use in the Carbon Basin), summarized township-by-township in a regularized, orderly fashion. But in the Carbon Basin, which is a broadly synclinal structure, Dobin et al. (1929) developed a totally separate scheme of coal-bed enumeration for its version of Hanna Formation; they ventured no attempt at correlations of individual coal-beds or identifiably related groups of coal-bearing strata between the two basins.

Teereman (1983) focused on petrographic study of local coals from the Hanna Formation in both basins, noting higher ash and total sulfur contents in many Carbon Basin samples than in those from the Hanna Basin. Maceral contents from the Carbon Basin could only be estimated (Teereman et al., 1985, p. 6–7). As directly stated by Teereman et al. (1987, p. 318), “Hanna Basin coals have not been correlated with coals in the Carbon Basin.” Texas Instruments Incorporated (1978a, p. 10), however, did propose ‘probable equivalents’ between three Carbon Basin
Figure 9. Interpretive cross-sectional model of late Laramide tectonic and erosional evolution across eastern Hanna Basin, following transect 1–2–3 on geologic reference map (which conjoins Figs. 4–6). A sheet of evolutionary cross sections and reference map at scale of 1:100,000 is presented in digital form suitable for printing as 'Fig. 9 (trans 1–3).PDF'. A thumbnail version for quick reference, however, exists unscaled on following page. **Cross section A** postdates early deformation of Ferris Formation and deposition of Hanna Formation but predates principal deformation of the latter. An earlier stage would show deposition of Hanna Formation extended to southwest of marker-point ‘1’ into Saratoga Basin, where any correlative remnants today, if they existed, would be designated as Coalmont Formation (such designation by Montagne, 1991, pls. I and III is questionable — see text). Solid colors in **A** indicate strata remaining today, whereas partially transparent colors represent strata lost through erosion or faulting prior to completion of **B**. According to this interpretation, as suggested by Lillegraven et al. (2004, fig. 15), deposition of Hanna Formation originally overtopped and buried the Freezout Hills (see northeastern end of cross section **A**). **Cross section B** depicts configuration of today’s Hanna Basin. Also notice in cross sections **A** and **B** that, contrary to palynostratigraphic expectation, Paleocene pollen assemblage ‘P5’ sensu Nichols and Ott (1978, 2006) and Nichols (2009) underlies pollen assemblage ‘P3’ (see Lillegraven and McKenna, 2008) and mammalian assemblages (Higgins, 2003b) of Torrejonian (early Paleocene) age. Representation of basement origin for out-of-the-basin thrust faulting across the gap between Saint Marys Hill and Dana Ridge anticlines seems clear (see Mount et al., 2011, fig. 5), but the actual situation this far south remains quite unknown. [See ‘Qualification on thickness of Ferris Formation’ in caption to Fig. 2.]

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*Figure 9.* Interpretive cross-sectional model of late Laramide tectonic and erosional evolution across eastern Hanna Basin, following transect 1–2–3 on geologic reference map (which conjoins Figs. 4–6). A sheet of evolutionary cross sections and reference map at scale of 1:100,000 is presented in digital form suitable for printing as ‘Fig. 9 (trans 1–3).PDF’. A thumbnail version for quick reference, however, exists unscaled on following page. **Cross section A** postdates early deformation of Ferris Formation and deposition of Hanna Formation but predates principal deformation of the latter. An earlier stage would show deposition of Hanna Formation extended to southwest of marker-point ‘1’ into Saratoga Basin, where any correlative remnants today, if they existed, would be designated as Coalmont Formation (such designation by Montagne, 1991, pls. I and III is questionable — see text). Solid colors in **A** indicate strata remaining today, whereas partially transparent colors represent strata lost through erosion or faulting prior to completion of **B**. According to this interpretation, as suggested by Lillegraven et al. (2004, fig. 15), deposition of Hanna Formation originally overtopped and buried the Freezout Hills (see northeastern end of cross section **A**). **Cross section B** depicts configuration of today’s Hanna Basin. Also notice in cross sections **A** and **B** that, contrary to palynostratigraphic expectation, Paleocene pollen assemblage ‘P5’ sensu Nichols and Ott (1978, 2006) and Nichols (2009) underlies pollen assemblage ‘P3’ (see Lillegraven and McKenna, 2008) and mammalian assemblages (Higgins, 2003b) of Torrejonian (early Paleocene) age. Representation of basement origin for out-of-the-basin thrust faulting across the gap between Saint Marys Hill and Dana Ridge anticlines seems clear (see Mount et al., 2011, fig. 5), but the actual situation this far south remains quite unknown. [See ‘Qualification on thickness of Ferris Formation’ in caption to Fig. 2.]
coal beds (Johnson, Finch, and Carbon 6) and Hanna Basin coal beds, unaccompanied by stated evidence.

Certain stratigraphic relationships are clarified in the present paper by combining densely spaced measurements of rock attitudes linked (using thin white map-lines) with detailed outcrop-to-outcrop correlations. Figure 5 shows that all exposed rock units from the Pine Ridge Formation (Mesaverde Gp.) upward through the Ferris Formation exhibit individual beds that are continuous between the Hanna and Carbon basins across the hinge line on the northern nose of Simpson Ridge Anticline. It is certain, therefore, that individual strata from as high as the Ferris Formation do wrap directly across the structural divide between the Hanna and Carbon basins.

Quite in contrast to the situation described in the preceding paragraph, however, no direct lithologic connections exist between what is mapped as the Hanna Formation in the Hanna Basin and what is so identified in the Carbon Basin. Teerman (1983, p. 140) related the observed petrographic differences in coals from the Hanna Formation between the Hanna and Carbon basins to quite disparate fluvial settings. Additionally, along the modern erosional margins of the Hanna Formation of the Carbon Basin, at essentially any well-exposed contact between the Hanna and underlying older rock units, one can observe evidence for a tectonic—not a depositional—contact. A significant conclusion of this paper, the evidence for which will be presented below, is that the Hanna Formation of the Carbon Basin was not deposited in its present position. Rather, it represents one of two large elements of mass transport of allochthons into the eastern area of the greater Hanna Basin, from a more distant site of deposition. I dub this one the Carbon Basin Klippe. The other allochthon (the Dana Klippe) is restricted to the southern map (Fig. 6), placed well to the west of Simpson Ridge Anticline and atop the southern main body of the Hanna Syncline.

Northwestern Quarter of Eastern Map South to Northern Flanks of Simpson Ridge Anticline

Most of the northwestern quarter of the eastern map (Fig. 5) is vegetated rangeland with only widely scattered rock outcrops. Also, the Sevenmile Hill Wind-Energy Project presently occupies a good part of the area in which clear rock exposures once existed, now replete with many new roads, widely bulldozed topography, and highly restricted access. The principal items of interest include the: (1) transit, as described above, of the ‘defining syncline of northeastern Hanna Basin’; and (2) nature of the eastern margin of the Hanna Formation along its complexly faulted contacts with the underlying Ferris Formation. The greatest clarity of representation of those faults extends from north of the main Pine Draw (at N-central edge of sec. 15, T. 23 N., R. 80 W.) southeastward to the western flanks of Sevenmile Hill (at adjacent boundaries of sections 22 and 23 of that same township). As interpreted here, the northern half of that more southerly swarm of younger-on-older fault traces represents the southern end of the

Figure 10. Interpretive cross-sectional model of late Laramide origin of Carbon Basin Klippe, following transect 4–5–6 on geologic reference map. A sheet of evolutionary cross sections and reference map at scale of 1:100,000 is presented in digital form suitable for printing as ‘Fig. 10 (trans 4–6).PDF’. A thumbnail version for quick reference, however, exists unscaled on following page. Note 77° change in vector of transect at reference point 5 (in southwestern part of Carbon Basin). Solid colors in cross section A indicate strata remaining today in section D, whereas partially transparent colors represent strata lost through erosion or faulting prior to completed development of section D. Cross section A is intended to represent initial conditions during Paleocene time, through which most of Hanna Formation had been deposited. A normal basinal east–west stratigraphic sequence then ran generally uninterrupted (contra Ryan, 1977) across a flat landscape that later became deformed into Simpson Ridge Anticline. A progressively thinning section presumably ran eastward into what is now Laramie Basin. Cross section B indicates origin of a basement-involved thrust complex having relative tectonic transport to west that led to early uplift of Simpson Ridge Anticline (see Kraatz, 2002), eventually resulting in physical separation of Hanna Basin from Carbon Basin. Basement rocks below developing Simpson Ridge Anticline were elevated by about six kilometers. That led both to incipient stages of out-of-the-basin thrusting against steepening anticlinal flanks along southeastern margin of Hanna Basin and to erosion of originally present Hanna Formation from markedly uplifting area of newly developing Carbon Basin. Cross section C, in addition to continuing definition of Simpson Ridge Anticline, reflects origin of genuinely spectacular anticlinal folding of landscape (‘area of northeast-trending folds’; Fig. 1B) between Carbon Basin and Laramie Mountains (see Blackstone, 1983 and 1993a plus Lillegraven and Snoke, 1996). These were post-Paleocene events, because lower Eocene strata in Hanna Basin were profoundly deformed, both as related to uplift of Simpson Ridge and to northern elements in area of northeast-trending folds. This also would have been probable time of dumptruck-style, southwest-directed, overland sliding of Carbon Basin Klippe (composed of Hanna Fm. as deposited in originally more expansive formation within area that is now atop northern parts of Flat Top Anticline) along an irregular detachment surface to its present abutment against eastern flanks of Simpson Ridge. Thick red line (shown crossing multiple stratigraphic units) indicates then-future position of today’s land surface. Cross section D shows fully modern development of Simpson Ridge Anticline, eastern Hanna Basin, Carbon Basin, and Carbon Basin Klippe. Configuration of basement-involved faulting within Simpson Ridge Anticline is simplified here from Kraatz (2002, figs. 12–15) for diagrammatic purposes.
Dragonfly Fault, first seen in northern parts of The Breaks (Lillegraven et al., 2004, fig. 4B).

Cross section D’–E’ (Figs. 5 and 7) extends from west of the hinge line of the defining syncline of northeastern Hanna Basin across the imbricated marginal thrust faults and then down-section ENE toward the western nose of Flat Top Anticline. Stratigraphic relationships, as interpreted in Figure 8 (between upper and lower representations of column D’–E’), suggest that today’s strata remaining in the Hanna Formation between the syncline and the formational contact with the Ferris Formation represent major loss of the original thickness through out-of-the-basin, younger-on-older thrust faulting.

Beginning in S-central parts of sec. 22, T. 23 N., R. 80 W. (west of southern end of Sevenmile Hill) and continuing southward through sections 27–28 and in the area of wind-configured sandy deposits characteristic of ‘The Lakes’ (usually dry) in sections 33 and 34, any observable rock exposures become rare. Nevertheless, enough exist to indicate clearly that this is a structurally complex area exhibiting traces of many individual faults, interrupted by modern aeolian transport and entrapment of sand. As portrayed on Figure 5, the multiple faults radiate outward to
the northeast like ribs in a fan from their area of convergence along the southern boundary of section 33. The many dashed trend lines, however, indicate that much uncertainty exists about the true distribution of any given individual fault.

**Beer Mug Ranch Through 'The Breaks'**

The small, vertically elongated rectangular map segment extending out of the northwestern top of Figure 5 is a duplication of the geologic map (originally scaled 1:12,000) covering an area near the northeastern corner of the Hanna Basin known as 'The Breaks,' Lillegraven et al. (2004, fig. 4B) constructed the original map. Their paper focused on the stratigraphy, paleontology, structural features, and paleogeographic implications derived from study of that small area's evolution through late parts of the Laramide Orogeny. Cross section P'–Q' of Figure 5 (= A–A' of Lillegraven et al., 2004, fig. 4C) is shown reduced in Figure 7 of the present paper and as a derived stratigraphic column in Figure 8. Stratigraphic relationships, as interpreted in column P’–Q’ (lower part) of Figure 8, suggest that today’s strata remaining in the Hanna Formation between the defining syncline of northeastern Hanna Basin and the formational contact with the Steele Shale represent a significant loss of section.

Additional information of special importance in the 2004 paper, not duplicated here, includes: (1) a measured section and description of the most complete representation of the Hanna Formation from all of the Hanna/Carbon Basin area (figs. 11–13 and appendix 1); (2) evolutionary tectonic steps in relationships between the Freezout Mountain Anticline and The Breaks (fig. 14) and in more detail within The Breaks itself (figs. 17 and 18); and (3) paleogeographic maps of the eastern component (fig. 15) and entire original configuration of the greater Green River Basin (fig. 19) as hypothesized for late Paleocene time.

It is important to recognize that the only known depositional contacts between the Hanna Formation and any older rock unit across the entirety of the eastern Hanna Basin occur from the E-central part of sec. 32 in T. 24 N., R. 80 W., then coursing southeastward to the extreme SW corner of sec. 3 in T. 23 N., R. 80 W. That short length of depositional contact is especially important in showing that the southwestern extreme of the Freezout Mountain Anticline was in existence and deeply beveled by erosion prior to deposition of oldest components of the Hanna Formation (Lillegraven et al., 2004, fig. 14B–C). The remaining evolutionary history of that depositional contact onto the beveled southern edge of the Freezout Mountain Anticline—along with secondary tectonic over-riding by

**Figure 11.** Interpretive cross-sectional model of late Laramide tectonic and erosional evolution of Elk Mountain and Dana Klippe, following transect 7–8–9 on geologic reference map. A sheet of evolutionary cross sections and reference map at scale of 1:100,000 is presented in digital form suitable for printing as ‘Fig. 11 (trans 7–9).’ PDF. A thumbnail version for quick reference, however, exists unscaled on following page. Cross sections A–C (which contain reference points 7–9) derive from sections H–I combined with F’–G’ of Figure 7. Reference point 8 represents a spatial jump between two discrete places on laterally correlative strata along crest of Halleck Ridge (which is the northwestern limb of Bloody Lake Anticline). A 1:24,000-scaled cross section of existing geologic relationships (components from Fig. 7, secs. H–I + F’–G’) is at top right of figure. Cross section C is part of that same (i.e., present-day) transect but interpreted to greater crustal depth. Solid colors in cross sections A and B indicate rocks remaining today, whereas partially transparent colors represent rocks lost through erosion or faulting prior to completed development of cross section C. Cross section A is intended to represent initial conditions, in which Medicine Bow Mountains (well south of transect shown) already had commenced uplift and Hanna Formation was deposited but had not yet undergone consequential deformation. Presumptive positions of then-future thrusts are indicated. Thin dashed lines (to left) in Steele Shale and Mesaverde Group–Ferris Formation indicate approximate then-future positions of vertical left edge of cross section C following deep-centered fault motions that led to rotations (indicated by broad yellow arrows). Yellow star indicates approximate then-future position of eastern summit of Elk Mountain. Thick red line indicates then-future approximate stratigraphic position of (today’s) land surface following emplacement of Dana Klippe. Cross section B is a hypothesized intermediate stage in which basement-involved thrusting having relative tectonic transport to the southeast had initiated early uplift of Elk Mountain (thus separating what is now Pass Creek Basin from an originally contiguous and southerly more-extensive Hanna Basin) in addition to out-of-the-basin thrusting along Elk Mountain’s northern and southern flanks. Also indicated is earliest initiation (within strata directly above then-future Elk Mountain) of gravitational effects upon lower components of Hanna Formation to form Dana Klippe. This step predated its miles-long northwesterly slide across a shallowly dipping detachment surface to its modern position atop Hanna Syncline in southern Hanna Basin. Two thick red lines (shown crossing multiple stratigraphic units) indicate then-future position of today’s land surface following emplacement of Dana Klippe. Cross section C requires at least five kilometers vertical uplift of basement rocks that form Elk Mountain and floor of Pass Creek Basin above conditions seen in cross section 11B (and at least 12 km above condition seen in cross section 11A). Lower right-hand digital-elevation reference map illustrates distribution of remaining strata mapped as Hanna Formation on high flanks of Medicine Bow Mountains.
Dragonfly and Owl Ridge Faults—is diagrammed in four key steps in figure 17A–D by Lillegraven et al. (2004).

Along most of that length of its deposition, the Hanna Formation was laid down with angular unconformity upon the Upper Cretaceous Steele Shale. In the E-central part of sec. 4 in T. 24 N., R. 80 W., however, the Hanna encounters a pervasively faulted hillside (Lillegraven et al., 2004, fig. 6A) of younger strata. From that point southeastward, the Hanna Formation rests unconformably upon the Haystack Mountains Formation and then progressively (and predictably) up-section to lower parts of the Lewis Shale. Notice on Figure 5 that at three separate places along that hillside there exist in situ outcrops of Hanna Formation that were overridden by thrust-faulted hanging walls (having relative tectonic transports to the southwest) of readily identifiable Upper Cretaceous strata exhibiting (in map view) left-lateral, strike-slip components. As discussed below, that complexity of faulting probably derived from influences of structural completion of the highly asymmetric Flat Top Anticline and associated basement-involved fault system along the northeastern corner of Figure 5.
R. 79 W., along with sections 12 and 13 in R. 80 W., are in the following adjacent sections of 7 and 18 in T. 23 N., of the Steele Shale in their figures 4–6. Preserved strata al. (2011) emphasized the structurally incompetent nature of the more rigid Mesaverde Group. Mount et al. (2011) modified several of the formational contacts, attitudinal data expressed, footwall syncline. Its strata also appear to have behaved as though utterly detached from stratigraphically higher layers within the same formation. Notice, too, that the syncline itself was cut by a transversely oriented small thrust fault (in the SE ¼ of sec. 29). Because of complications issuing from these kinds of observations, confidence becomes challenged in almost any attempted thickness measurement of the Steele Shale within vicinity of the Hanna Basin.

Complicating the local stratigraphy even further, the superbly documented dissertation completed by Davis (1966, fig. 3) dealing with upper parts of ‘Mesaverde’ strata emphasizes existence through most of the Hanna Basin of an ‘upper tongue of Steele Shale.’ It is a marine unit, usually poorly exposed, that pinches out westwardly between upper parts of the Allen Ridge Formation and the base of the Pine Ridge Sandstone (two nonmarine units, both of the Mesaverde Gp.). Soon thereafter, Gill et al. (1970, p. 26–27) referred to Davis’s ‘upper tongue of Steele Shale’ as an ‘unnamed marine tongue’ of the Allen Ridge Formation (see Grimaldi et al., 2000, figs. 4 and 5, measured section A–A’ upper). I consider the 1970 change in nomenclature to be unfortunate, because it detracts from the conceptual clarity of stratigraphically intertonguing relationships between the Steele Shale of the Western Interior Seaway to the east with the lower Mesaverde Group of its western shoreline (see section on ‘diachronic units’ as covered by North American Commission on Stratigraphic Nomenclature, 2005, p. 1584–1585).

Western Parts of Simpson Ridge Anticline and Southeastern Margin of Hanna Basin

Kraatz (2002) provided the most recent description and the most comprehensive structural interpretation of Simpson Ridge Anticline (Saddleback Hills Anticline of older terminology). The present map (Fig. 5) uses Kraatz’ work as the basis for the anticline’s representation, but I have modified several of the formational contacts, attitudinal data are liberally supplemented on both limbs of the primary fold as well as across its northern and eastern (i.e., within R. 79 W.) components, and several structural details are added.

The faulted hinge line of the southwestern extreme of Simpson Ridge Anticline (having relative tectonic transport
to the southeast) rises abruptly from the ill-exposed Steele Shale within the NE ¼ of sec. 2, T. 20 N., R. 81 W. The greatest depth of modern erosion along the anticlinal axial surface trace probably is to the Haystack Mountains Formation (of the Mesaverde Gp.), questionably represented on the strongly vegetated surface from sections 30 to 9 of T. 21 N., R. 80 W. Thus most of the highland map area of the anticline exposes Allen Ridge Formation (of the Mesaverde Gp.).

The Halleck Creek Syncline delimits the western side of Simpson Ridge Anticline parallel to its southernmost elements. The syncline’s markedly contorted southern extreme is near the southeastern corner of sec. 3 in T. 20 N., R. 81W., first visible at the northern edge of the Rattlesnake Pass Road (south of U.S. Interstate Highway 80). The syncline’s axial surface is faulted, with relative tectonic transport to the east as it crosses most of the Allen Ridge Formation. Most indications of synclinal hinge-line
faulting vanish before the axial surface trace climbs to the Pine Ridge Formation (of the Mesaverde Gp.). The Halleck Creek Syncline loses surface expression north of the NE ¼ of sec. 24 in T. 21 N., R. 81 W. Laterally restricted, out-of-the-syncline thrusting with relative tectonic transport to the southeast onto the western flank of Simpson Ridge Anticline exists just south of the center of sec. 36, T. 21 N., R. 81 W.

The southwestern extreme of Simpson Ridge Anticline is composed of the full expression of the Mesaverde Group with exception of the Haystack Mountains Formation, which is noted locally for highly variable presence and lengths of disappearance. On the western flank of Halleck Creek Syncline, however, the Haystack Mountains Formation appears as a prominent rock unit. Along with local strongly developed ridges of sandstone near the top of the Steele Shale (near the NW corner of sec. 35, T. 21 N., R. 81 W.), the Mesaverde Group forms the topographically striking base of Bloody Lake Anticline.

The deepest-exposed core of the Bloody Lake Anticline is seen within the Upper Cretaceous Steele Shale south of Interstate Highway 80, within the SE ¼ of sec. 34 in T. 21 N., R. 81 W. (Figs. 5, 6, and 12). From there its hinge line plunges to the northeast, with exposures climbing up-section through the entirety of the Mesaverde Group and remaining traceable through the (usually dry) complex of Soda Lakes almost into the NW ¼ of sec. 24 within upper levels of the Lewis Shale. In the SW ¼ of sec. 13, upper parts of the Lewis Shale exhibit a clear series of imbricated, younger-on-older thrust faults that probably are on the northwestern flank of the northern surficial terminus of the Bloody Lake Anticline. In the southern half of sec. 23 of T. 21 N., R. 81 W., radiating across the broad hinge of the anticline within the Lewis Shale exists a series of five small faults that consistently show apparent right-lateral strike-slip components of stratigraphic separation. The hinge line of the Bloody Lake Anticline converges northward toward its eastern neighbor, the Halleck Creek Syncline.

As best appreciated through examination of Figure 12, the hinge line of the Bloody Lake Anticline, as it continues to the southwest from Interstate Highway 80, parallels the prominent Halleck Ridge (Fig. 6). That ridge is composed principally of the Mesaverde Group, which in reality is the northwestern flank of Bloody Lake Anticline. In turn, the Halleck Ridge section continues to the southwest as the southeastern border of the Hanna Syncline of the Hanna Basin. The axial surface trace of Bloody Lake Anticline remains erosionally unroofed down to poor exposures of the Steele and Niobrara shales, and at Rattlesnake Pass (N-central edge of sec. 23 in T. 20 N., R. 82 W.) the hinge line was overidden by the northern extreme of the Elk Mountain Thrust complex (discussed below), having relative tectonic transport to the east. Covering the adjacent margins of sections 8, 9, 16, and 17 of T. 20 N., R. 81 W. (in Fig. 6) is a small erosional remnant (the Fort Halleck Syncline, composed of Allen Ridge Fm. of Mesaverde Gp.) of the southeastern flank of Bloody Lake Anticline.

The north–south-oriented cross section M–N (Figs. 5, 7, and 8) suggests a generally intact, more or less uniformly north- to northwest-dipping stratigraphic sequence from the Steele Shale up-section through the lower half of the Ferris Formation. A poorly exposed yet laterally extensive, younger-on-older thrust fault having relative tectonic transport to the south is encountered within the Ferris Formation near the W-central edge of sec. 2 of T. 21 N., R. 81 W. In turn, an estimated more than three kilometers of upper Ferris plus lower Hanna formations has been lost at the fault contact between those two formations just south of the north end of transect M–N.

Cross section P–Q (Fig. 7) suggests a remarkably symmetrical Simpson Ridge Anticline near its southwestern end, showing no consequential faulting on either side of its axial surface trace from the Steele Shale (not quite exposed by erosion) upward through the Lewis Shale. The stratigraphic column on the eastern flank of the anticline presented in Figure 8, however, shows the profound stratigraphic gap (involving ca. 7.4 km of section) between the Hanna Formation (of the Carbon Basin Klippe) and the Lewis Shale, caused by deep erosion prior to emplacement of the klippe and gravity-driven tectonism.

Farther north, along the western flank of the main body of Simpson Ridge Anticline (specifically surrounding the transit of cross section M–O; Figs. 5 and 7), thrusts within the Medicine Bow, Ferris, and Hanna formations having relative tectonic transports to the southeast bring those overlying units closer to and partially onto the Lewis Shale. In essence, those younger-on-older thrust faults came out of the Hanna Syncline (a focus of Fig. 6) onto lateral flanks of the Simpson Ridge Anticline. As shown on Figure 5, that series of thrusts begins in earnest within the Medicine Bow Formation just to the north of influence of the northeast-plunging Bloody Lake Anticline. On the southeastern flank of Simpson Ridge at this latitude, the stratigraphic column in Figure 8 suggest that over seven kilometers of section are missing due to pre-klippe erosion along cross section M–O below the faulted edge of the Carbon Basin Klippe.

Still farther north along the western flanks of Simpson Ridge Anticline (at cross sections J–K and D–L), the Hanna Basin’s thrust systems having relative tectonic transports to the southeast in the Medicine Bow, Ferris, and Hanna formations are even more prominently developed as they impinged onto the anticlinal flank from the Hanna Syncline. Along those latitudes, the anticline itself also had begun its northward plunge, such that the Lewis Shale forms the entire outcrop of the anticlinal crest. Simpson Ridge Anticline’s hinge line trends almost due north. Figures 5, 7, and 8 suggest that the combined effect of the out-of-the-basin thrusts on the western flank of Simpson Ridge Anticline has been considerable tectonic thinning through.
loss of section. That is especially the case within the Ferris and Hanna formations west and northwest of the entire length of Hi Allen Ridge (sections 31–7 of T. 22 N., R. 80 W.). The present thickness of relevant parts of stratigraphic column J–K (measured from Fig. 8 column J–K) represents a loss of approximately half of that section's original thickness through younger-on-older thrusting. Although greater density of fault traces has been recognized in the Medicine Bow Formation, greater stratigraphic separations occurred via individual faults within the overlying Ferris and Hanna formations along cross sections J–K and D–L (Figs. 7 and 8).

Cross sections J–K and D–L also traverse the flanks of Simpson Ridge Anticline east of its structural hinge line (Fig. 5). Figures 7 and 8 suggest that the tectonic plus erosional loss of section below the Carbon Basin Klippe along cross section J–K is just over seven kilometers; along comparable parts of section D–L the loss is estimated at 6.7 kilometers.

Near the north-central part of sec. 16 of T. 22 N., R. 80 W., the hinge line of Simpson Ridge Anticline begins a turn to the northeast. Also, in that latitude strata of the Medicine Bow Formation cover the entire highlands of the now northeast-plunging anticline. Within the west-central half of section 10, however, it appears that the anticlinal axial surface trace itself, through means of two thrust faults having relative tectonic transports to the southwest, becomes displaced southeastwardly in two discrete steps. Then, from dead center of section 10, the hinge line of Simpson Ridge Anticline courses northeastwardly to the center of the SE ¼ of sec. 2, T. 22 N., R. 80 W. At that point, the anticlinal hinge line encounters the faulted 'defining syncline of northeastern Hanna Basin' (as discussed above) and appears to vanish from more easterly landscapes. As interpreted here, however, the axial surface trace of Simpson Ridge Anticline was tectonically displaced southeastwardly (but now on the eastern side of the faulted syncline) by well over a mile to reappear into the north-central part of sec. 13 of the same township.

Observe closely the densely measured arrays of stratigraphic attitudes in adjacent parts of the central halves of sections 11 and 14 along with western halves of sections 12 and 13 of T. 22 N., R. 80 W. as they occur on opposing sides of the faulted 'defining syncline of northeastern Hanna Basin.' Notice too the opposite directions of attitudinal fanning on either side of the faulted syncline and the clear loss of section northward as starting from the northern edge of the Carbon Basin Klippe. My interpretation (based on the general pattern of local younger-onto-older deformation) is that relative tectonic transport along that fault was northeastward, having put younger strata of the more westerly Ferris Formation onto its more easterly older levels (see cross section B–C' in Figs. 5 and 7).

Returning now to the northwestern margin of the main body of Simpson Ridge Anticline, cross section A'–Z (Figs. 5 and 7) suggests especially strong out-of-the-basin thrust development within upper parts of the Ferris and lower parts of the Hanna formations northwest of the crest of Hi Allen Ridge. Measurements of relevant components of the Ferris and Hanna formations from Figure 8 suggest younger-on-older, thrust-related loss of at least 80 percent of the original thickness beyond their remaining strata. Faulting within the Medicine Bow Formation also was consequential, estimated to be nearly 30 percent fault-related reduction from its original thickness.

As is obvious following a glance at the northern half of T. 22 N., R. 80 W. in Figure 5, the marked bend of the hinge line of Simpson Ridge Anticline to the northeast was made possible by an abundance of thrust faults, most of which cut diagonally out of surrounding basins toward the anticlinal hinge line. In the southeastern quarter of section 9, the axial surface trace itself becomes a thrust having relative tectonic transport to the southeast. The great bulk of recognized deformation within that northeasterly bend is centered throughout the entire thickness of the Medicine Bow Formation and upper Lewis Shale. Some of the faulting observable within the NE ¼ of section 9 approaches sheer chaos, although it does seem to be related somehow to segmentation of the anticlinal hinge line recognized just west of the center of section 10. Many of the Medicine Bow faults show imbrication, with one overriding another. Surprisingly, there are no recognized faults within the Ferris Formation in sections 2 or 11–14 other than the faulted 'defining syncline of northeastern Hanna Basin' (see Fig. 7, cross section B–C').

Although based on minimal data, Hinckley and Heasler (1984, pl. IV) show unusually high, near-surface groundwater temperatures (up to 175° F) in the northwestern quadrant of the Carbon Basin, just south of the structural complexities exhibited within the hinge-line bending to the northeast of the Simpson Ridge Anticline. An un-quantified, general observation of possible relevance might be permitted here. Across sections 2, 11, 12, and 14 of T. 22 N., R. 80 W., most sandstones of the Ferris Formation (which underlie the Hanna Fm. of the Carbon Basin Klippe) exhibit an unusual rusty-red coloration (siderite-rich) and roughened texture that provide a 'cooked' appearance. The color and texture differs markedly from most of the remaining Ferris Formation of surrounding outcrop areas, and the strata may exhibit effects of moderate but prolonged heating and hydrothermal alteration.

**Eastern Parts of Simpson Ridge Anticline, Calvin Bend, and Southeast-trending Cretaceous Strata**

This is the first study to seriously pursue the location and nature of the northern end of Simpson Ridge Anticline. Most workers (e.g., Blackstone, 1983, fig. 2; Ryan, 1977, figs. 9–12; and Mount et al., 2011, fig. 3) have suggested that its main expression continues straight north, crossing U.S. Highway 30/287, then plunging into the eastern margin...
of the Hanna Basin west of Sevenmile Hill. Indeed, Perry and Flores (1997, fig. 3) show on their map of the Hanna Basin a single continuous thrust fault having relative tectonic transport to the west. They propose that the fault courses northward along the west flank of Simpson Ridge from the northern base of Elk Mountain all the way to the ‘Shirley Fault’ bordering the northern length of the eastern basin. But as described above, the traditionally recognized Simpson Ridge anticlinal hinge line appears to terminate abruptly at the faulted ‘defining syncline of northeastern Hanna Basin’ in the SE ¼ of sec. 2, T. 22 N., R. 80 W.

The hinge line of Simpson Ridge Anticline, however, regains existence in N-central parts of sec. 13. From there it extends northeasterly, becoming well defined as it traverses along the northwestern flank of Pynchin Lake (usually dry) in sec. 7 of T. 22 N., R. 79 W. (see King and Van Ingen, 1977, map in pocket). Within the Steele Shale in the NE ¼ of sec. 32 of T. 23 N., R. 79 W., the directly northeastern course becomes ENE, and for at least 1,500 m (4,921 ft) the anticlinal axial surface trace is overturned to the north. Within what is ordinarily a dry lake in the SE ¼ of sec. 28, the anticlinal hinge line attains its most northerly extent. Thereafter, the axial surface trace is exposed within the Niobrara Formation, and it turns directly southeast to exit Figure 5 near the southeastern corner of section 35, there entering the Medicine Bow quadrangle. Notice that this southeastern extreme of the anticline is significantly east of the course shown for the same structure, identified by Bekkar (1973, pls. 1 and 2) as the ‘Allen Lake Anticline.’ The anticline in question encounters neither Allen Lake (north of U.S. Highway 30/287) nor East Allen Lake (south of the highway).

Recognition of that full extent of Simpson Ridge Anticline comes as a surprise. In normal map view (see Fig. 12), the full length of the anticline is basically a deformed, inverted letter ‘U.’ But cutting through the northwestern curvature of the inverted ‘U’ is a NNW–SSE-oriented, faulted syncline that exhibits over 1.5 miles (ca. 2.5 km) of apparent right-lateral stratigraphic separation. And, as discussed earlier, that syncline (inappropriately named the ‘defining syncline of northeastern Hanna Basin’) actually separates both the Hanna and Carbon basins from southwestern flanks of Flat Top Anticline. As shown on Figure 5, that syncline continues southeastward from the displaced anticlinal hinge line for yet another 11 kilometers (6.8 mi) to Halfway Hill (in SW ¼ of sec. 2 of T. 21 N., R. 79 W.). At that point, the sporadically faulted syncline makes a hard turn first to the east and then northeast to course north of the Como Bluff Anticline and its controlling North Como Fault (see Blackstone, 1983, figs. 31 and 33, the latter simplified from Dunbar, 1944; Blackstone, 1993a) and all the way into the western flank of the Laramie Mountains.

South of the hinge line of the eastern segment of Simpson Ridge Anticline, the eroded and imposingly thick (> 6 km; 3.7 mi) Upper Cretaceous section (of Niobrara Formation through lower Ferris Formation; shown in E-central part of Fig. 5), with but one marked exception, strikes monotonously southeastward with 30º–50º dips to the southwest. The exception is just south of an area known as Calvin Bend. That name applies to a natural eastward passage of First Sand Creek (just downstream from confluence with Carbon Creek) through a natural water-gap carved into lower strata of the Mesaverde Group along the southwestern margin of sec. 10 in T. 22 N., R. 79 W. That water gap also served as the original path of the Union Pacific Railroad before development of massive cuts and fills farther to the north that allowed construction of the much more direct, current main line.

Directly south of Calvin Bend are prominent sandstone-dominated uplands composed of the entirety of the Mesaverde Group. As shown on Figure 5, in sections 15 and 16 of T. 22 N., R. 79 W., a previously unrecognized thrust fault having relative tectonic transport to the southeast (here named the ‘Calvin Bend Thrust’) cuts transversely across the very top of the Steele Shale through the Mesaverde Group and across at least the lower half of the Lewis Shale. Stratigraphic separation seems to be minor. There also is a roughly 250-m (820 ft), apparent right-lateral strike-slip component to the faulting as seen in map view. Notice, however, that along the S-central parts of section 10 the strata, even in upper parts (but not uppermost parts) of the Steele Shale, can be traced uninterruptedly across landscape into which the Calvin Bend Thrust might have been expected to extend. The thrust seems to terminate at the northeastern end of cross section R–S (Figs. 5 and 7) by turning sharply northwestward to become lost between bedding planes of the Steele Shale. Thrust faults transverse to bedding are uncommon but not rare in the eastern Hanna Basin. Most of them are minor, and the most obvious of other examples are at various stratigraphic levels around the margins of Simpson Ridge Anticline. Flowing springs are usually associated with the transverse faults, as is the case south of Calvin Bend.

**Big Medicine Bow Anticline**

The long-time oil/gas-producing Big Medicine Bow Anticline occupies the southeastern corner of Figure 5. It is a topographically broad, north–south elongated, dome-like structure (see Blackstone, 1983, fig. 24) that less obviously plunges both to the northwest and south. Irregularly deformed strata of the Mesaverde Group rim exposures of Upper Cretaceous marine shales of the fold’s core. The Big Medicine Bow Anticline is moderately asymmetric in cross section, with more steeply dipping to locally overturned beds on its eastern flank. As pointed out by Blackstone (1983, p. 20 and fig. 18), this anticline is the most northerly of an en echelon series of NNW-aligned anticlinal structures.
paralleling northeastern flanks of the Medicine Bow Mountains (Crawford, 1953, fig. 1; Nyberg, 2001, pl. 1).

Although not well documented at depth, the Big Medicine Bow Anticline probably resulted from a basement involved thrust fault having relative tectonic transport to the east. Stone (1966) provided a generalized structural and stratigraphic summary of the area extending from the eastern Hanna/Carbon/Pass Creek Basin into the Laramie Basin. Despite the characteristically subdued, modern-day surface topography of the Laramie Basin, its highly faulted, Laramide anticlinal complexity in subsurface is best described as bewildering. Mount et al. (2011, fig. 3) show a thrust fault having relative tectonic transport to the northeast that cuts through the northeastern corner of the Medicine Bow Mountains and continues to the northwest all the way to the fault system forming Simpson Ridge Anticline. I know of no evidence, however, for existence of the westernmost 15 kilometers (9.3 mi) of that proposed fault.

Notice on Figure 5 that the hinge line of Big Medicine Bow Anticline continues northwestwardly beyond its topographically obvious dome-like structure as seen within the western half of sec. 10 of T. 21 N., R. 79 W. (Fig. 7, cross section O–Y). The hinge line continues beyond that point to the northwest for another six kilometers (3.7 mi). Although that extension is not prominent topographically, it parallels the Halfway Hill Syncline that dominates the northeastern Carbon Basin and extends southeastward to its namesake (in sec. 2 of the same township). The extended hinge line of Big Medicine Bow Anticline crosses a small patch of elevated Lewis Shale exposed within a window eroded through the Medicine Bow Formation in S-central sec. 4 of T. 21 N., R. 79 W. (Fig. 7, cross section Q–X). Beginning near the northeastern corner of sec. 31 of T. 22 N., R. 79 W. (Fig. 7, cross section R–S), the anticlinal hinge line is diverted and then wanders generally northward to be lost against the southeastern flank of Simpson Ridge Anticline near the center of sec. 13 of T. 22 N., R. 80 W. It appears that northern parts of the Big Medicine Bow Anticline’s hinge line both affected, and was affected by, existence of the Carbon Basin Klippe (discussed below).

Carbon Basin, Hanna Formation of Carbon Basin, and Carbon Basin Klippe

Definition of Limits of Carbon Basin

Before launching into discussion of this complex part of Figure 5, a reasonable definition of the ‘Carbon Basin’ should be provided. As the most straightforward component, I concur with common wisdom that the hinge line of Simpson Ridge Anticline should serve as the western defining boundary of the Carbon Basin. Only slightly less objectively, I suggest that the faulted syncline seen in the center of the W-central edge of sec. 12 of T. 22 N., R. 80 W. (i.e., the southeastern extension of the ‘defining syncline of northeastern Hanna Basin’ of Lillegraven et al., 2004, fig. 4B) that continues southeastward to Halfway Hill (in center of SW ¼ of sec. 2 of T. 21 N., R. 79 W.) should serve as the eastern boundary of Carbon Basin. Even though anticlinally deformed (as the eastern components of Simpson Ridge Anticline plus other relatively minor anticlinal ridges, synclinal valleys, and small domes), all of the vast tract of Cretaceous strata covering Figure 5 northeast of that ‘defining syncline’ (including Halfway Hill Syncline) belong structurally to the southwestern flank of Flat Top Anticline (Barlow, 1953a; Rocky Mountain Map Co., 1992b).

Ambiguities in definition of the Carbon Basin, however, come into play with the large topographic bulk of the Big Medicine Bow Anticline. Probably its central broad hinge should form the southeastern boundary. But the topographically cryptic northern extension of the hinge line that inserts itself to the northwest (extending nearly to the northern end of territory otherwise considered to be within the Carbon Basin) should not be involved. Thus a short, arbitrarily chosen connection to the north would be needed to connect the main northern bulk of the Big Medicine Bow Anticline to Halfway Hill.

Finally, although not actually included within Figure 5, I suggest that the entire southern boundary of the Carbon Basin should be designated at the also arbitrarily chosen, upturned formational contact between the top of the Steele Shale and base of the Mesaverde Group. That contact directly parallels the northern lanes of Interstate Highway 80.

The boundaries suggested in the preceding three paragraphs are based principally upon influences of the locally most important tectonic and topographic features resulting from late phases of the Laramide Orogeny. Prior to tectonic development and subsequent erosion of the defining features for all sides of the Carbon Basin, the distribution of the Ferris and Hanna formations would have been dramatically more expansive than today’s. First, both formations almost certainly were continuous across landscape that now is occupied by Simpson Ridge Anticline (contra Ryan, 1977). Secondly, as shown in Figure 5, even the modern-day erosional edges of those two rock units persist on both sides of the eastern syncline (i.e., the Hanna and Ferris formations exist both within the Carbon Basin proper as defined here and on edges of the southwestern flanks of Flat Top Anticline).

Prior to development of the ‘defining syncline’ (including Halfway Hill Syncline) and Flat Top Anticline, both the Ferris and Hanna formations almost certainly extended much farther to the east. Specifically, they probably were continuous to the southeast into all of the Laramie Basin as well as to the east, northeast, and north (see Lillegraven et al., 2004, figs. 15 and 19), covering landscapes that subsequently...
became folded into the present forms of Freezeout Mountain, Flat Top, Como Bluff, Boswell Spring, Gillespie, and McGill Anticlines (see Blackstone, 1983, fig. 31 for geographic relationships of those folds). Prodigious erosion during and following Laramide orogenesis led to today’s paucity of remnant correlatives of the Ferris and Hanna formations north and east of the Carbon Basin. Cather et al. (2012) pursued the Cenozoic timing and magnitudes of erosion across most of Wyoming and southward through much of Mexico (to 22° N latitude).

**Nature of Hanna Formation Within Carbon Basin**

Research in mammalian paleontology of the Hanna Formation as it occurs in the northern Carbon Basin has provided valuable information about the age of that basin’s youngest strata. Secord (1996, 1998) has shown that only Paleocene species (possibly latest Torrejonian plus very definite Tiffanian taxa; Lofgren et al., 2004, fig. 3.2 and table 3.1) characterize the local Hanna Formation of the Carbon Basin. Contrary to assumptions in many publications (e.g., Ryan, 1977, table 1), the modern erosional surface in the Carbon Basin closely overlies late Paleocene mammalian assemblages, thus precluding preservation of any sedimentary deposition during Eocene time.

Brooks (1977) provided much descriptive information about general lithologic aspects of the Hanna Formation across the Carbon Basin. His observations were made on diverse isolated outcrops, development of five surface-based measured sections (Brooks’ pocket-map 3) along the basin’s southern border, interpretation of four well cores (Brooks’ pocket-map 2) widely spaced across the interior of the plate, and sandstone thin-section petrography (37 samples). Brooks’ well core #4 came from directly north of the hinge line of the Carbon Basin Syncline. A series of 21 open-file reports (Brooks’ pocket-map 3) along the basin’s southern border, interpretation of four well cores (Brooks’ pocket-map 2) widely spaced across the interior of the plate, and sandstone thin-section petrography (37 samples). Brooks’ well core #4 came from directly north of the hinge line of the Carbon Basin Syncline. Texas Instruments Incorporated (1978a–d) provided the most authoritative public access to detailed information on the Carbon Basin’s coal resources and their general geological relationships. Nevertheless, those summaries make no mention of out-of-the-basin thrusting. Instead, they relate many of the recognized displacements within and along the edges of the Hanna Formation to results of normal faults. A series of 21 open-file reports for the U.S. Geological Survey also was released by Texas Instruments, Inc. in 1978 for coalfields in the Hanna Basin. Their complete bibliographic listing can be found within the ‘References’ section of Glass and Roberts (1979, p. 77–79). However, “... contract requirements forbid calculation of any coal resources or reserves for any lands other than unleased Federal mineral lands” (Glass and Roberts, 1979, p. 55). Utility of these reports for purposes of meaningful research is thus greatly limited.

Notice too in Figure 5 that, tracing from north to south along eastern edges of the Hanna Formation, the contact between the Hanna and underlying formations involves progressively older Cretaceous strata. The Hanna Formation at the north end of the Carbon Basin rests upon Ferris Formation separated by evidence of faulting. But with southward excursion, one then sees Hanna contacts along
the eastern edge with progressively older strata—first on the Medicine Bow Formation and then on the still older Lewis Shale. South of Figure 5, the base of the Hanna Formation almost reaches as low stratigraphically as uppermost strata of the Mesaverde Group (Brooks, 1977, pocket-map 1). Stone (1984, figs. 2–6) documented stratigraphic relationships of the entire Phanerozoic column between the northern Pass Creek Basin and southern end of the Carbon Basin. The progressively older substrate from north to south on which the Hanna Formation is set suggests that a significant interval of erosion had cut progressively more deeply into southerly parts of the Carbon Basin area prior to emplacement of strata of the local Hanna Formation. Furthermore, emplacement of the Hanna Formation upon that erosional surface was tectonic, not depositional. These observations are expanded below in relation to discussion of Figure 10.

As indicated across the surface of the Hanna Formation, the Carbon Basin is a broad and topographically shallow syncline (Figs. 5 and 7). Rather than coursing straight north–south, the synclinal hinge line of the Carbon Basin in map view is a markedly convex-westward bow, with the hinge line's northern half more-or-less paralleling the northeastward bend of Simpson Ridge Anticline. The northern end of the Carbon Basin Syncline's hinge line terminates almost by direct abutment against the northern extension of the Big Medicine Bow Anticline in the E-central part of sec. 24 of T. 22 N., R. 80 W. The detailed course of the synclinal hinge line south of the southwestern corner of sec. 18 of T. 21 N., R. 79 W. has yet to be traced in the field.

The following cross sections (Fig. 7), ordered from north to south, approximate or intersect the Carbon Basin's synclinal hinge line: D–L, J–K, R–S, Q–X, and O–Y. As interpreted from Figures 7 and 8, approximations of remaining thicknesses of the Hanna Formation (in feet; meters) increase progressively southward, as listed within the parentheses for each cross section: D–L (750 ft; 229 m), J–K (1,400 ft; 427 m), R–S (2,700 ft; 823 m), Q–X (2,800 ft; 853 m), and O–Y (2,800 ft; 853 m). Although not confirmed from well logs, none of those cross sections suggests existence of remnant strata of the Ferris Formation below the Hanna Formation. Except near the northern end of the Carbon Basin, all basal Hanna contacts are interpreted as being upon the Medicine Bow Formation or Lewis Shale. Note that cross-section T–U, at the southeastern flank of the Carbon Basin, is only a short distance north of the point at which the Hanna Formation has overridden the Lewis Shale. The greatest magnitude of erosion near the center of the Carbon Basin prior to emplacement of the Hanna Formation would have exceeded four kilometers (2.5 mi). And along the eastern margins of Simpson Ridge and the western flanks of Big Medicine Bow Anticlinal, the magnitudes of pre-Hanna erosion probably ranged from five to over seven kilometers (3.1–4.4 mi).

Referring to sequences of shale and coal in the Hanna Formation of the Carbon Basin, Brooks (1977, p. 55) stated: “They are generally thickest in the central parts of the basin, and thin toward the basin edges interfingering with braided alluvial plain deposits.” Such relationships might, indeed, be expected within a small isolated basin that represented sedimentary deposition in place. It remains the case, however, that neither the well cores (Brooks’ pocket-map 2) nor the measured sections (Brooks’ pocket-map 3) that Brooks presented actually show those trends in coal or shale thicknesses. Much more probable is that he was being misled by the cryptic and then-unanticipated existence of out-of-the-basin, younger-on-older thrust faults scattered around the Carbon Basin’s margins. The existing relationships would physically appear almost the same following either developmental interpretation. It is my interpretation that the Hanna Formation of the Carbon Basin, as an allochthonous klippe, represents a relatively small fragment of an originally much broader extent of strata, most of which subsequently has been eroded away.

**Carbon Basin Klippe**

As stated above, the strata mapped as Hanna Formation throughout the Carbon Basin do not exhibit a depositional base upon older strata. Rather, all naturally clean or excavated exposures suggest a tectonic contact. To characterize that situation, I employ the first sense of definition of the term ‘klippe’ as given by Neuendorf et al. (2005): “(a) An erosional remnant of a thrust sheet that is completely surrounded by exposure of the footwall.” In short, I view the Hanna Formation as mapped in the Carbon Basin as an allochthonous slide mass that slid toward the southwest very late in the Laramide Orogeny.

The vast majority of that Hanna-upon-older-rock contact around the Carbon Basin remains poorly exposed or completely covered by Quaternary alluvium, soil, and vegetation (implied by dominance of dashed lines in Fig. 5). Nevertheless, many places have been pinpointed in Appendices 1 and 2 (commonly with GPS coordinates) that adequately show the nature of the contact between the Hanna Formation and older strata.

More generally, the following information (arranged by township and section) indicates prime areas in which specific localized features of the contact can be examined, particularly when aided by digging and extensive brushing (see recommendations by Lillegren, 2009, p. 40). Especially fruitful encounters start at the northwestern side of the Carbon Basin and, as sequentially encountered by section, clockwise follow the edge of the Hanna Formation around the basin: (1) T. 22 N., R. 80 W. (NW ¼ of sec. 27; E ½ of sec. 22; SE corner of sec. 15; and S ½ of sec. 14); (2) T. 22 N., R. 79 W. (NE ¼ of sec. 31); (3) T. 21 N., R. 79 W. (W ½ of sec. 9; entirety of sec. 16; W ½ of sec. 21; SE corner of sec. 20; W ½ of sec. 29; and NW corner of sec. 32); and (4) T. 21 N., R. 80 W. (NW corner of sec. 28; E ½ of sec. 21; SE corner of sec. 16; and W ½ of sec. 3).
The following is a listing of the variety of features seen along these specific contacts of interest that ordinarily would be expected within a tectonic setting. The deformation can be observed either in the hanging wall or the footwall, or in both, and I have yet to recognize any perceptibly predictable pattern of occurrence. Similarly, the deformation in some cases is strictly limited to immediate vicinity of the contact itself, and in other cases it is distributed extensively (sometimes for tens of meters) upward into the hanging wall or (less commonly) downward from the contact. Shattered rocks, comminuted bits of shale within churned soft strata (especially in the footwall), linear faults (with or without obvious gouge layers), slickensides, chatter-marks, localized wholly chaotic bedding at/near the contact, broad-scale deformation including undulations of strata, tight kinking, step faults, roll-over folds, and fault-imbricated stratigraphy are almost ubiquitous. Faults most commonly occur along coaly or carbonaceous, soft-sediment bedding, but they also developed between well-indurated strata of hanging walls and footwalls. Commonly, bedding at the top of the footwall is frictionally upturned or overturned relative to underlying strata, with its undersurface in limited but direct contact with the undersurface of the hanging wall (i.e., stratigraphically ‘belly-to-belly,’ in what I commonly refer to in the field notes as a ‘great-wall’ effect). Fluid-flow-derived Liesegang staining within massive sandstone units nearby the contact is common, and might be expected to be related to ground-water adjustments following major structural dislocations. Equally important is the absence of clear evidence for gradational depositional contacts between the Hanna and underlying formations.

Although observationally less direct, Weichman (1988, p. 75–80) inadvertently has provided yet another reason to consider the relatively thin plate of Hanna Formation of the Carbon Basin as an allochthonous mass. Nearly all of the northern wall of the Medicine Bow Mountains and the so-called Pass Creek Basin directly north (see Fig. 1B and inset digital-elevation models in lower-right quadrant of Fig. 11) are covered by Paleocene age, generally very coarse-grained facies of the Hanna Formation (Houston et al., 1968, pl. 1). Although the Pass Creek Basin is south of the Hanna and Carbon basins as defined today, during the Paleocene it was the original, not-yet-separated southern end of the paleo-greater Hanna Basin. As recognized by Ashley (1948), Knight (1953), Gries (1964), Barton (1974), Ryan (1977), and Weichman (1988), the northern Medicine Bow Mountains served as an important sediment source for the evolving basin complex just to the north. Additionally, Ryan (1977) and Weichman (1988) independently recognized that the Hanna Basin received prodigious amounts of sedimentary input during the Paleocene from the north (i.e., from the Sweetwater Arch/Granite Mountains area of Love, 1970). Citing conclusions made by Ryan, however, Weichman (1988, p. 76–77) wrote: “Ryan (1977) concluded that the Hanna Formation in the Carbon Basin was derived from a dominantly sedimentary terrane to the north and northeast. He states that cross-bed dip azimuths and feldspar frequency in the southern Carbon Basin indicate a minor southern source, but that the frequency distribution of lithic and epidote grains in sandstone, median grain size of sandstone, and maximum pebble size of conglomeratic sandstone refute any sediment contribution to the Hanna Formation from the south.”

In light of the fact that the coarse materials flowing northward through the Pass Creek Basin during the Paleocene were only a few kilometers away and in direct alignment with the southern Carbon Basin, Weichman (1988) sought to test the concept of no substantial sedimentological input from the south into the Carbon Basin’s Hanna Formation. He thus developed sandstone thin-section petrographic samples (comparing compositions of quartz, feldspar, and lithic fragments) from vicinity of the Pass Creek Basin and compared them in a ternary diagram (his fig. 32) with data gathered by Brooks (1977) from eight locations in the Carbon Basin. Weichmann found that samples from the Pass Creek area define a compositionally fully distinct petrologic field from samples collected in the Carbon Basin. The lithic fragments, in particular, indicate that materials in the Carbon Basin, indeed, did not arrive there by way of the Pass Creek Basin.

The obvious question then becomes, just why was sediment input to the Carbon Basin from proximate sources in the south so very limited? Weichman (1988, p. 79) postulated a depositional barrier in the form of “...the river system flowing from Pass Creek Basin. Since it did not flow into the Hanna or Carbon basins, the only remaining possibility is that it flowed northeast, between Shepherd Hill [located just northeast of Pass Creek Basin] and southeast Carbon Basin, into the Laramie Basin.” That interpretation, although intuitively reasonable, is not accompanied by actual evidence in its support. And the possibility that the present Hanna Formation of the Carbon Basin slid as a gravitationally driven landslide mass into its present position after the basin’s original strata of the Hanna Formation had been eroded away raises a whole new realm of reasonable considerations about local geologic history.

Notice from rock attitudes plotted in Figure 5 that the putative klippe itself exhibits post-emplacement deformation. Underlying strata showing uplift or folding after transport of the klippe clearly affected margins of the slide mass. Specifically, that involves combined effects of late-Laramide deformation of the eastern flank of Simpson Ridge Anticline, the southeastern extension of the ‘defining syncline of northeastern Hanna Basin,’ and the western flank of Big Medicine Bow Anticline. Probably the combined...
effects of surrounding deformation also were responsible for development of the Carbon Basin Syncline itself (as seen on the surface) along with the various irregularly occurring, generally minor thrust faults mapped (Fig. 5) within the klippe’s more central mass.

A hypothesis for the origin of this previously unanticipated ‘Carbon Basin Klippe’ is presented below, illustrated with graphics in Figure 10. Minimally, the pre-erosional dimensions of this allochthonous plate would have been in excess of 55 square miles (ca. 143 km²). The preserved components presented in Figure 5 total about 41 square miles (ca. 106 km²). A second probable allochthonous feature exists east of the Dana (= Pass Creek) Ridge. It is described in relation to Figures 6 and 11.

SOUTHERN MAP (FIG. 6)

General Features

Principal Structural Elements

Three major structures dominate the area of the southern Hanna Basin specifically covered within Figure 6. By far the largest of those features is the Hanna Syncline, which (as alluded to above) grades to the southeast into the northwestern flanks of Bloody Lake (as Halleck Ridge) and Simpson Ridge Anticlines. Strata involved at the syncline’s modern surface include the Steele Shale and Mesaverde Group upward through most of the Hanna Formation. Much of the area covered in Figure 6 is covered by what I consider to be a second allochthonous mass, here dubbed the Dana Klippe.

The second principal structural element is Walcott Syncline, which contains the axial surface trace of what is known locally as the Coal Bank Basin. The Walcott Syncline extends to the northwest (see Chadeayne, 1966) far beyond the limits of Figure 6. The Coal Bank Basin’s northeastern flank is tectonically apposed against the southwestern edge of the Hanna Syncline (along with the more southerly Sheephead Mountain Anticline) to form the topographically prominent and importantly thrust-faulted Dana Ridge Anticline (= Pass Creek Anticline and Mead Hills of older literature). In essence, the Coal Bank Basin is a giant form of footwall syncline ahead of the thrust-faulted (with relative tectonic transport to the southwest) of the Hanna Syncline (see Figs. 6–9 and 12).

Finally, the Dana Klippe, rests as a remarkably thin sedimentary veneer (Fig. 7, cross section B–D) upon a deeply eroded surface cut into the Hanna Syncline. As discussed below, my decision to identify the mappable rock unit comprising the allochthon as ‘Hanna Formation of Dana Klippe’ (Tₕ₍₋₉) assuredly is open to challenge. That decision was made, however, following reflection upon the lithologic composition of its lower elements plus the interpretation of the gross structure’s origin.

Boundaries Between Ferris and Hanna Formations

When one compares geographic distributions of the Hanna and underlying Ferris formations as seen in this paper’s Figures 4 and 5 with original placements by Dobbin et al. (1929, p. 27), the agreements are generally close. Most differences can be explained by availability of the more detailed, global-positioning devices independently employed in most of the present work. The plotted boundary between those two formations proposed within Figure 6, in contrast, differs markedly from the 1929 original. Specifically, the current interpretation puts the boundary several kilometers farther to the north, such that the definitive, coal-rich Hanna Formation makes no contact with present northeastern erosional limits of the Dana Klippe. The original mapping exhibited a major overlap of the definitive Hanna Formation by what Dobbin et al. (1929) identified as North Park Formation (here labelled ‘Hanna Formation of Dana Klippe’). The discrepancies are approached in the following discussion.

For practical reasons, it is important for readers to recognize three procedural elements of the present research. First, unless indicated otherwise (as restricted to specific borderlands along the northern and southern edges of the Hanna Basin), all mapping presented here was intentionally conducted independently from that done by prior workers. The resulting general agreement among formational distributions between present and original efforts, therefore, would seem to enhance confidence in verifiability of the observational criteria employed. Secondly, my own pattern of mapping efforts was initiated within the Hanna Formation near the northeastern corner of the Hanna Basin (i.e., area of ‘The Breaks’; Lillegraven et al., 2004, fig. 4B). It then extended systematically east-to-west and north-to-south, progressing along the basin margins. Landscape encompassed by the northeastern half of Figure 6 (principally involving the Hanna and Ferris Fms.) was investigated last during my research. Finally, my field efforts strongly emphasized an outcrop-by-outcrop systematic recording of lateral stratigraphic equivalents combined with identifications of previously unrecognized out-of-the-basin thrust faults.

Those systematized procedures led naturally to a dramatically revised interpretation of the Hanna/Ferris formational boundary as seen in the westernmost part of Figure 5 and the northeastern corner of Figure 6. Future workers should find a way to test the present interpretation by conducting a detailed tracing of stratigraphic levels northward, across the roughly 11 miles (17.7 km) to the presumed ‘type’ Hanna/Ferris contact near the western margin of sec. 28 in T. 23 N., R. 83 W. (see Boyd and Lillegraven, 2011, fig. 2A; with added focus by Clemens and Lillegraven, 2013, p. 162). I was unsuccessful in gaining permission from the controlling corporate entity for research access to that extensively mining-disturbed and partially reclaimed landscape.
One surprising result of the revision in mapping is recognition that, in the southern Hanna Basin, the Ferris Formation is considerably thicker than has been recognized heretofore. It measures about 4.9 km (ca. 3 mi) in thickness along cross section F–G (Figs. 6–8) on the southeastern flank of the Hanna Syncline. In reasonable agreement, thickness of the Ferris Formation measures roughly 5.6 km (ca. 3.5 mi) on the opposing flank of the syncline (along a line from the western edge of sec. 6, T. 21 N., R. 82 W. to the western edge of sec. 31, T. 22 N., R. 81 W.).

As considered both above and below within this paper, because of younger-on-older thrusting of the Hanna onto the Ferris Formation along the western flank of Simpson Ridge Anticline, surface exposures of the Ferris Formation appear markedly thinned (see sections J–K and A'–Z in Figs. 5, 7, and 8). The northeast–southwest cross-sectional asymmetry observable across the Hanna Basin as seen in Figure 9B, therefore, clearly represents late Laramide differential subsidence (LeFebre et al., 1986; Biree, 1987; and LeFebre, 1988) as well as contractional tectonism. Prior to Eocene time (i.e., late into deposition of the Hanna Formation), that cross section would have been much more symmetrical. McQueen and Beaumont (1989, p. 69), viewing the Hanna Basin as a tilted and 'downdropped block,' possibly were thinking of it only in its present-day configuration.

Stratigraphic relationships between the Ferris and Hanna formations have suffered a painful amount of confusion from the very beginning of their distinction. Veatch (1907a, p. 249–250), working above the Lewis Shale (then termed Lewis Fm.), coined the terms ‘Lower Laramie’ beds and ‘Upper Laramie’ beds for combined strata now termed the Medicine Bow (‘Lower Laramie’) and Ferris plus Hanna (‘Upper Laramie’) formations. Veatch (1907b) attempted to relate that sequence to strata (locally and elsewhere within the Rocky Mountains and Great Plains) as then recognized by other workers (e.g., Hague and Emmons, 1877; King, 1878). In both 1907 papers, Veatch claimed that a major unconformity (quantified to representation of “. . . over 20,000 feet of [missing] strata” in 1907b, p. 527) exists between his ‘Lower’ and ‘Upper Laramie’ beds. The present study provides no evidence whatever for such an unconformity (i.e., between what is now the Medicine Bow Fm. and Ferris + Hanna Fms.). Indeed, data presented in Figure 8 show that the Ferris/Medicine Bow formational contact is among the most consistently developed of uniformly conformable stratigraphic markers as exists across the entire eastern Hanna Basin. Nevertheless, Veatch’s (1907a, pl. XIV) geologic map of the Hanna and Carbon basins, constructed under primitive conditions, remains a pioneering effort of remarkably high quality.

Bo wen (1918, p. 230), without actually employing Veatch’s highly useful geologic map, proposed the name Medicine Bow Formation as replacement for the ‘Lower Laramie’ beds. He also argued that Veatch’s great unconformity, originally stated to separate the Upper and Lower Laramie beds, in reality is higher in the section, wholly within Veatch’s Upper Laramie beds. That ostensibly real unconformity was used by Bowen to separate two newly named rock units (originally unified, comprising the Upper Laramie beds), now called the Hanna Formation above the presumed ‘unconformity’ and the Ferris Formation below it. As to magnitude of the alternatively placed ‘unconformity,’ Bowen (1918, p. 232) stated: “It represents the removal of more rather than less than the 20,000 feet assigned by Veatch.”

In justification for existence of that unconformity, Bowen (1918, p. 232) stated:

“The existence of this unconformity is demonstrated by the following field relations: (1) There is a marked angular discordance between the underlying and overlying formations; (2) the Hanna formation transgresses all the underlying formations at least down to the Cloverly and possibly down to the granite; (3) the Hanna formation has been less intensely deformed than the underlying formations; . . . .”

In the present paper, all of those relationships are interpreted as results of out-of-the-basin thrust faulting, and no generalized unconformity of consequence exists between the Ferris and Hanna formations other than what is mentioned in the next paragraph. Brown (1962, p. 21) accepted Bowen’s concept of a major unconformity in his invaluable treatise on the Paleocene floras of the Rocky Mountains and Great Plains.

Bowen (1918, p. 231) also stated: “All the rocks up to and including the Ferris formation seem to have been equally deformed and were folded, faulted, and deeply eroded before the deposition of the Hanna Formation.” Lillegraven et al. (2004, figs. 4B, 14, and 16B–18) documented that instead to have been the case at the boundary between the northeastern corner of the Hanna Basin and southern flanks of the Freezeout Hills. Elsewhere around margins of the eastern Hanna/Carbon basins, however, little evidence exists for any significant deformation by folding until very late in the history of deposition of the Hanna Formation. And all of the items of Bowen’s justification for existence of a major erosional unconformity between the Hanna and Ferris formations are better explained by a single, late-Laramide (i.e., almost post-Hanna deposition) episode of intense deformation that minimally involved the entire eastern half of the Hanna Basin plus Carbon Basin. I re-emphasize that this late Laramide pulse of deformation long post-dated any traditionally mapped Hanna/Ferris formational boundary. Additional information on relative timing of principal diastrophism is presented in the next section.

Age Relationships of Ferris and Hanna Formations

It has long been known that deposition of the Ferris Formation in the Hanna Basin transgressed the Cretaceous–
Tertiary boundary (Veatch, 1907a, p. 230–231). Its age relationships today are best known from studies in sections 21, 27, and 28 of T. 23 N., R. 84 W., as documented through systematic study of diverse forms of fossil vertebrates. The North American Land Mammal Ages of the latest Cretaceous (Lancian, sensu Cifelli et al., 2004) and earliest Paleocene (Puercan, sensu Lofgren et al., 2004) are represented there. Salient literature includes: Eberle (1996, 1999, 2003); Eberle and Lillegren (1998a, b); Lillegren and Eberle (1999); and Wrblewski (1997).

A thin sequence of marine strata exists in uppermost Puercan strata further up-section at Pats Bottom along the southeastern shore of Seminoe Reservoir in sec. 26, T. 23 N., R. 84 W. Boyd and Lillegren (2011) described that locality, and it is closely associated with an early Paleocene leaf locality described by Dunn (2002, 2003). Another Lancian (latest Cretaceous) mammal-bearing locality (Clemens and Lillegren, 2013) is known from sec. 12 of T. 24 N., R. 82 W., well to the northeast of the previously cited, better-known sites. As recorded throughout Appendices 1 and 2 of the present paper, the Ferris Formation has yielded shows of fossil bone at many additional stratigraphic levels, but none has yet been thoroughly investigated.

Age relationships (following principles discussed by: Flynn et al., 1984; and Woodburne, 1987, 2004, and 2006) of the Hanna Formation are best documented from the badlands area of the northeastern Hanna Basin known as The Breaks (inset map in NW part of Fig. 5). Within that area, reworked marine Upper Cretaceous shark and ray teeth (Burris, 2001) are mixed with locally abundant dental remains of genuine Paleocene mammals (representing Torrejonian and Tiffanian North American Land Mammal Ages sensu Archibald et al., 1987 and Lofgren et al., 2004) in fluvial deposits. Key literature relevant to local mammal-based chronostratigraphy includes: Higgins (2000, 2003a, 2003b, 2012); Lillegren (1993); and Lillegren et al. (2004).

Trace fossils of great variety (see Hasiotis, 2002; Appendices 1 and 2; and Boyd and Lillegren, 2011) abound within the Laramide sequence of marine and terrestrial deposits of the Hanna Basin. The Hanna Formation in vicinity of The Breaks exhibits especially dramatic banks of freshwater crayfish burrows (Hasiotis and Honey, 1995 and 2000, fig. 9).

Dunn (2003), sampling near the base of the Hanna Formation in The Breaks, described palynological species of biostratigraphic interest. Pertinent discourse related to controversy resulting from Dunn's investigation include: Lillegren et al. (2004); Lillegren and McKenna (2008); McKenna and Lillegren (2005, 2006); and Nichols (1999, 2003, and 2009). Flores et al. (1999b, p. HF-2 and figs. HF-2 and 3) and Flores (2003, fig. 6 and p. 77) claimed that the Hanna Basin presents a complete series of expected Paleocene palynozones P1–P6. That assertion, however, was based upon statements in an abstract by Cavaroc et al. (1992) and represents a conclusion that has yet to be documented in a verifiable fashion.

Fossilized freshwater molluscs (Kirschner, 1984), of potential biostratigraphic utility, also locally abound in association with unstudied remains of fishes (Lillegren et al., 2004, appendix 1) within stromatolite-bearing (Davis, 2006), lacustrine sequences (Kaplan, 1977) high in the Paleocene and lower Eocene section in and near The Breaks.

The highly irregularly exposed uppermost surfaces of the Hanna Formation are universally deeply eroded, both in the Hanna and Carbon basins. Except possibly within the Dana Klippe as discussed in a subsequent section of this paper, nowhere does there exist a conformable upper surface involving a younger rock unit. As considered above in the brief section entitled ‘Western Extreme of Indian Spring Fault and Farther South,’ the stratigraphically highest level of the Hanna Formation seen anywhere within the Hanna Basin is in its northeastern corner (shown on Fig. 4 at the northern end of Leg 19 of the measured section developed by Lillegren et al., 2004). That spot has yielded fossils of Hyracotherium grangeri, representing an early part (Wasatchian North American Land Mammal Age; Lillegren, 1994) of the Eocene Epoch. See Lillegren et al. (2004, fig. 11 and appendix 1) for a composite measured section of the Hanna Formation in vicinity of The Breaks.

Paleocene mammalian assemblages also occur in northern parts of the Carbon Basin as described by Secord (1996, 1998). They exist in two main collecting areas, representing three demonstrably distinct faunas. Two of the faunas represent antiquity close to the Torrejonian–Tiffanian boundary, and the third is somewhat younger, assigned a middle or late Tiffanian age.

As also true for the Ferris Formation, Appendices 1 and 2 provide leads to as-yet-undisturbed, bone-bearing sites within multiple stratigraphic levels of the Hanna Formation.

Comments on Utility of a Distinction Between Ferris and Hanna Formations

As recognized in the above discussions, Bowen’s (1918) basic justification for subdivision of Veatch’s (1907a, b) original ‘Upper Laramie’ beds into the Ferris Formation overlain by the Hanna Formation was the assumed existence of an intervening, major erosional unconformity. Bowen (1918, p. 232) proposed that the putative unconformity represented over 20,000 feet of eroded pre-Hanna strata. Field-based observations in the present study, however, provide evidence in support of a consequential unconformity only along the northeastern margin of the Hanna Basin against southern flanks of the Freezeout Hills (see Lillegren et al., 2004, fig. 14). But along the entire eastern border of the Hanna Basin, an out-of-the-basin thrust fault system having relative tectonic transport to the east is here recognized as defining the Hanna/Ferris
contact. Except for minor variations, that is essentially the mapped contact recognized by Dobbin et al. (1929, pl. 27), but then interpreted as a major unconformity. Building on unconformity-based concepts that he initiated in 1983, Hansen (1986, p. 483) said of that contact: “Except in the Carbon Basin and along the eastern margin of the Hanna Basin, the unconformable Ferris–Hanna contact mapped by Dobbin et al. (1929) does not exist.”

That same fault system has now been traced, first to the south, and then westward across the southern Hanna Basin (Figs. 5 and 6) to a point northwest of the hinge line of the Hanna Syncline (W-central edge of sec. 31, T. 22 N., R. 81 W.). Beginning just east of the boundary between Figures 5 and 6 and extending westward, however, the structurally defined boundary between the Hanna and Ferris formations as considered in the present paper diverges markedly from mapping by Dobbin et al. (1929).

Presumed lithologic distinctions between the Hanna and Ferris formations as recognized by Bowen (1918, unnumbered table on p. 228 and text on p. 230–231) emphasize local derivation of coarse-clastic and feldspathic elements in the Hanna Formation. Bowen contrasted that to dominance of more distantly derived, non-feldspathic clastic elements in the Ferris Formation. Those lithologic criteria have proven not to be reliable, however, as becomes pervasively obvious from site-based information provided in Appendices 1 and 2.

Fieldwork for the present project provided nearly basin-wide opportunity to test the generalized information summarized from the preceding pair of paragraphs. My experience has been that attempting to deal with historical lithologic distinctions between named ‘Hanna’ and ‘Ferris’ formations is a consequential hindrance to objective mapping and communication of its results to the geological community. Straight-forward mapping of structurally significant anomalies would have been greatly eased had it been possible to cope with but one named, very thick, dominantly nonmarine rock unit (i.e., strata combining what had previously been broken out as Hanna vs. Ferris Fms.). This viewpoint also appears to have been favored by Knight (1951), and McElhaney (1988) pursued it in detail. In short, I suggest that status of Hanna and Ferris formations perhaps best involves the retention of early-Twentieth Century versions of ‘legacy formations’ in the sense of Raymond et al. (2012).

Boyd and Lillegraven (2011, p. 46–48), followed by Clemens and Lillegraven (2013, p. 162), attempted to determine Bowen’s (1918) intended geographic position for the equivalent of a ‘type’ boundary between the Ferris and overlying Hanna Formation. We concluded it probable that Bowen intended the contact to be placed in strata near the western edge of sec. 28, T. 23 N., R. 83 W. That is in agreement with the open-file mapping by Blanchard and Comstock (1980), who nevertheless stated: “The contacts mapped by Dobbin, Bowen, and Hoots (1929) between the Medicine Bow–Ferris and Ferris–Hanna formations could not be retraced in the field.” But in respect to the existence of a major unconformity between those rock units, Blanchard and Comstock wrote:

“Gill, Merewether, and Cobban (1970, p. 46) and the authors of this report found no evidence for an unconformity in the [Pats Bottom] quadrangle, as the upper part of the Ferris Formation grades into the lower part of the Hanna Formation in many places. In addition, no evidence of a persistent, thick, conglomeratic sandstone and local conglomerate was found at the base of the Hanna Formation.” . . .

“The upper part of the Ferris and Hanna Formations becomes increasingly more conglomeratic in a northerly direction.”

Despite all best efforts here, I predict that controversies about the Hanna vs. Ferris nomenclature as applied to specific packages of strata within the greater Hanna Basin may actually hamstring future research progress. What would be much more important goals, in my opinion, would simply be focused pursuit of biostratigraphic and additional sources of geochronologic evidence that would allow recognition of additional sites yielding reliably detailed age determinations.

Hanna Syncline

The Hanna Syncline plus Simpson Ridge Anticline constitute the paramount structural features of the southeastern Hanna Basin. Indeed, the Hanna Syncline, broadly considered, defines the fundamental structure of the Hanna Basin proper (see Glass and Roberts, 1980a, fig. 8; 1980b, fig. 14). Thus it includes the bulk of coal resources that have been mined in the area exclusive of the Carbon Basin. Glass (1975) and Glass and Roberts (1984) contributed representative information on stratigraphy and chemistry of each subunit of the Hanna Coal Field. Berryhill et al. (1950, 1951) reported early data on stratigraphic coal occurrences and estimated reserves. Hackley and Anderson (1986) studied the origin of organic sulfur from a single section of coal in the upper Hanna Formation of the northern Hanna Basin, suggesting some degree of bacterial reduction of sulfate in a partially closed drainage system.

The south end of the Hanna Syncline’s axial surface trace originates (under a different name) within poorly differentiated elements of the Benton Group (i.e., equivalents of Lower Cretaceous Thermopolis Sh. to base of Upper Cretaceous Niobrara Sh.; see Weitz and Love, 1952 and Espenschied, 1957) near the center of sec. 15, T. 19 N., R. 82 W. This is well south of landscape covered by Figure 6. The equivalent of the Hanna Syncline in that area has long been known under the name of Rattlesnake Creek Syncline (see Beckwith, 1941, pl. 1; and Fig. 11, lower-right inset map).
The Rattlesnake Creek Syncline starts as a recognizable feature in the valley between the southeastern corner of Bear Butte and the southwestern border of Elk Mountain. The hinge line of that syncline then courses just slightly west of north, climbing up-section across surface exposures into the Steele Shale.

The Rattlesnake Creek Syncline enters the southern edge of Figure 6 (with name-change to the Hanna Syncline) at the S-central edge of the SW ¼ of sec. 22 in T. 20 N., R. 82 W. It then continues directly up-section through the Mesaverde Group, Lewis Shale, and onto the much younger Dana Klippe. Following a northward traverse across the Dana Klippe, the hinge line of the Hanna Syncline can be traced in a NNE direction for about 10 km (6.2 mi) into the S-central part of sec. 12 of T. 21 N., R. 82 W. At that point the synclinal hinge line makes a broad turn to the northeast, then exits the klippe onto what is mapped here as the Ferris Formation. Closely thereafter it encounters the profoundly folded main body of the Hanna Formation. In map view, the synclinal hinge line undulates in a generally northeastern direction, continuing the climb up-section within the thick Hanna Formation to its effective disappearance (in SE ¼ of sec. 12, T. 23 N., R. 81 W.; Fig. 5) just south of the defining syncline of northeastern Hanna Basin.

As exhibited stratigraphically at the surface through almost all of the Hanna Syncline's length, its axial surface trace progressively encounters older strata southward. At the syncline's northern end in the Como West Quadrangle (Fig. 5; elevation 6,800 ft = 2,073 m), the landscape surface represents roughly the middle of the local Hanna Formation's thickness. At the syncline's southern end in the Rattlesnake Pass Quadrangle (south of Fig. 6; elevation ca. 8,100 ft = 2,469 m), however, the modern surface represents undivided Thermopolis Shale and Muddy Sandstone. Thus, even though the northern end of the Hanna Syncline's hinge line at the ground surface is topographically some 390 m (1,280 ft) lower than its southern end, stratigraphically its northern exposure is roughly 11.8 km (7.3 mi) higher in the section. The overall trend of the Hanna Syncline as observed on outcrops, therefore, rather consistently cuts topographically shallowly to the north but exposes stratigraphically deeper levels to the south.

Two exceptions to those otherwise consistent trends exist. The more northerly exception is a stretch of about 7 km (4.4 mi), centered east of the town of Hanna (see Lillegraven et al., 2004, fig. 5), in which the synclinal hinge line progresses essentially horizontally, both stratigraphically and topographically. The other exception is a few kilometers to the southwest, where the Hanna Syncline's hinge line encounters the Dana Klippe. As readily visualized on Figures 6 and 7 (cross sections B–D and F–G), the comparatively flat-lying, Tertiary klippe overlies deeply dipping, mostly Cretaceous strata including the Lewis Shale–Ferris Formation. The klippe itself distinctly reflects distortion of the syncline, suggesting that its transport predated completion of structural folding of the Hanna Syncline.

The area mentioned in the preceding paragraph exhibiting an essentially horizontal stretch of the Hanna Syncline's hinge line is of special interest related to the Hanna Formation of the central Hanna Basin. Through detailed study of well logs and cores from sections 29–30 in T. 22 N., R. 81 W. (directly west of the hinge line of the Hanna Syncline; Fig. 6 and Fig. 7, cross section B–D), Craig (1982, p. 18–115) provided the most detailed lithologic description and depositional interpretation of the Hanna Formation done from any part of the Hanna Basin. That work also was associated with a federally sponsored underground coal gasification (UCG) experiment inducing extreme heating of bedded coal to initiate release of methane gas to the surface for capture and potential commercial use. Of particular interest are the experimental results of heat-related diagenesis of overburden above the site of combustion. That heating led to extremes of pyrometamorphism in which sandstone layers were melted to a mobile state. Similar but lesser diagenetically altered strata (‘paralava’ rocks; Craig, 1982, p. 115–135; Craig et al., 1982) have been recognized as resulting from natural processes within the Ferris and Hanna formations of the Carbon Basin.

Another general observation about the Hanna Syncline is that, along most of its length, folding along its eastern limb is more acutely angled toward the synclinal hinge line than is its western limb. Although that generalized distinction does vary, the asymmetrically tighter folding of the syncline’s eastern limb clearly reflects combined influences of the Bloody Lake and Simpson Ridge anticlines (in Fig. 7, compare cross sections A–D and D–L).

Traces of out-of-the-syncline thrust faulting within the Ferris Formation close to the eastern border of Figure 6 (especially in sections 3, 9–10, and 16–17 of T. 21 N., R. 81 W.) are especially numerous, unexpectedly complex, and quite different in nature from what has been represented through prior mapping. For example, in the geologic map by Dobbin et al. (1929, pl. 27), a normal fault (down to the west) is shown to extend from the SE ¼ of sec. 3 of T. 21 N., R. 81 W. to near the SW corner of sec. 13 of that same township. Detailed mapping now shows, however, that three quite separate thrust faults having relative tectonic transports to the southeast and east converge within the SE ¼ of sec. 3, providing only the topographic illusion of a normal fault. Additionally, as traced southeastward across sections 11, 14, and 13 (on Fig. 5), one recognizes laterally extensive stratigraphic continuities that preclude existence of normal faulting within that area. Similarly, Dobbin et al. (1929, pl. 27) indicate four additional normal faults placed en echelon along nearby outcrops to the northeast. Although Weitz and Love (1952), Love and Christiansen (1985), Secord (1998), and Kraatz (2002, fig. 4) and many other workers have reiterated those putative normal faults within
that during latest Cretaceous and earliest Paleocene generally steeply dipping), and as discussed above it reveals section F–G is relatively undeformed (aside from being the northwestern flank of the rising Bloody Lake Anticline. compression of the Hanna Syncline's eastern flank against the probably represent contractional adjustments resulting from the more westerly of these faults is quite unexpected. Both apparently emanate from the thrust fault that courses through poorly exposed strata in sec. 20 and probably into sec. 17 to finally become unrecognizable in outcrop south of that section. As judged by stratigraphic relationships observable both in its hanging wall and footwall in sec. 17, however, the Elephant Rock Thrust probably continues southward through poorly exposed strata in sec. 20 and probably into sec. 30. The trace hypothesized in the preceding sentence is not symbolized as a discrete feature on Figure 6. The surface trace of the Elephant Rock Thrust first courses southward parallel to the eastern margin of the SE ¼ of sec. 3 in T. 21 N., R. 81 W. and then turns sharply to the southwest, continuing across the NW ¼ of sec. 10, the S ½ of sec. 9, and into the SE corner of sec. 8. From that point, the fault basically courses southward across Percy Creek and through the entire, strongly deformed eastern half of sec. 17. In map view, the Coal Bank Basin's rounded eastern terminus resembles the end of an old-fashioned bathtub. The Upper Cretaceous Medicine Bow Formation and most of the underlying Lewis Shale form the basin's floor. Basal sands within the Lewis Shale plus the top three formations of the Mesaverde Group form the basin's usually sharply defined northeastern rim. Generally poorly exposed erosional remnants of Tertiary volcaniclastic strata of the Browns Park Formation rest unconformably on Cretaceous sequences within topographically lower parts of the basin, mainly south of the Walcott Syncline's hinge line. Despite the superficially simple appearance of the Coal Bank Basin, its degree of deformation is strong northeast of the hinge line of Walcott Syncline and across Dana Ridge. Notice in Figure 6 that much of the basin's northeastern lower rim contains Cretaceous strata that are steeply dipping to the southwest, vertical, or actually overturned. Also, beginning in sec. 34, T. 21 N., R. 83 W. and continuing to the northwest for several kilometers (see Hitchens, 1999, pls. I and III–V) beyond coverage by Figure 6, the Walcott Syncline itself becomes an overturned recumbent fold in which the fold's axial surface appears to dip to the northeast. Upper Cretaceous strata southwest of the synclinal hinge line within the Coal Bank Basin dip generally less than 35° to the northeast. Two fundamentally important differences from Hitchens' (1999) structural interpretations exist as shown time the rate and total magnitude of deposition was not reduced in the area now representing the southern Hanna Basin. That is, even though the greatest thicknesses of Phanerozoic strata today are preserved in a west–east-oriented zone parallel to the Hanna Basin's northern border (see Fig. 9B), the true depositional axis of the original eastern parts of the greater Green River Basin would have been much farther to the south. Walcott Syncline, Coal Bank Basin, and Dana Ridge Anticline Eastern ends of the Walcott Syncline and adjacent Dana Ridge (Pass Creek Ridge of older literature) Anticline dominate the southwestern side of Figure 6. Together they form a small sub-area of the southern Hanna Basin known as the Coal Bank Basin. Beckwith (1941), Chadeayne (1966), and Hitchens (1999) conducted almost all mapping, including rock-attitudinal measurements, shown in Figure 6 for those structures. Most of my own field-based efforts toward preparation of this part of the map were conducted in vicinity of Coyote Canyon (sec. 15, T. 21 N., R. 83 W.) and along the curve in strata near the eastern end of Dana Ridge, including southwestern edges of the Dana Klippe. A landowner denied access for the conduct of most requested research between those two areas parallel to the southwestern margin of the Dana Klippe. Like the Hanging Wall of Elephant Rock Thrust is complex through sections 8–10 of T. 21 N., R. 81 W. To the southwest and northeast of the center of sec. 9 can be seen two quite unusual, probably minor in displacement, thrust faults that appear to tectonically converge toward one another. Both apparently emanate from the thrust fault that courses through, and probably is responsible for the existence of, Limburger Spring (in NW ¼ of sec. 9, T. 21 N., R. 81 W.). The more westerly of these faults is quite unexpected. Both probably represent contractional adjustments resulting from compression of the Hanna Syncline's eastern flank against the northwestern flank of the rising Bloody Lake Anticline. The Ferris Formation as represented parallel to cross section F–G is relatively undeformed (aside from being generally steeply dipping), and as discussed above it reveals the unexpectedly great thickness of the formation (Figs. 6, 7F–G, and 8). That thickness drives home the realization, however, that during latest Cretaceous and earliest Paleocene their subsequent maps, I have recognized no supporting field-based evidence for their existence. Physical contact between the base of the Ferris Formation and the underlying Medicine Bow Formation (as indicated in the eastern part of Fig. 6 by a dashed line) is unexposed throughout its length. Although that contact is clearly faulted in sec. 1 of T. 21 N., R. 81 W. (in Fig. 5), its stratigraphic equivalent farther southwest may well be represented by a conformable contact all the way westward to beyond the eastern edge of Dana Klippe.
in Figure 6 within the northeastern rim of the Coal Bank Basin. First, based upon a pair of seismic profiles developed several kilometers to the northwest of Figure 6, Hitchens projected continuation of an out-of-the-basin thrust fault southeastward (coursing through the Lewis Sh.) along the southwestern, lower rim of the Dana Ridge Anticline, nearly to the eastern end of the Coal Bank Basin. Specifically, that proposed fault’s trace, if hypothetically plotted on Figure 6, would have extended from the W-central edge of sec. 22, T. 21 N., R. 83 W. to the S-central edge of the SE 1/4 of sec. 32, T. 21 N., R. 82 W.

I suggest, however, that although the fault trace in issue unquestionably exists northwest of coverage by the present Figure 6, within the E-central part of sec. 14 of T. 21 N., R. 84 W. the mapped fault turns in a broad curve to the northeast, toward the NW ¼ of sec. 12. The fault in question probably courses between the northwestern end of Dana Ridge Anticline and the more southwesterly topographic feature known as Saint Marys Hill. The latter is simply an anticlinal continuation of Dana Ridge, displaced less than a mile to the southwest by the out-of-the-basin thrust under discussion. In short, I have recognized no evidence for the existence of that fault to the east of sec. 13 of T. 21 N., R. 84 W. The seismic transect shown by Mount et al. (2011, figs. 3, 5, and 6), as discussed below, traverses the gap between the northwestern end of Dana Ridge Anticline and the southeastern end of Saint Marys Hill Anticline.

The second consequential structural difference from Hitchens’ interpretation presented in Figure 6 involves the nature of Dana Ridge Anticline’s axial surface trace. First, notice in map view of Figure 6 that the topographic crest of Dana (Pass Creek) Ridge is set minimally 300 m (984 ft) southwest of the structural anticinal hinge line. The topographic crest is dominated by strongly cemented sandstone facies in the Pine Ridge Formation of the Mesaverde Group. The fault’s axial surface trace, in contrast, is stratigraphically significantly lower in the Mesaverde Group’s section, set within the Allen Ridge Formation. Typically, the anticline’s structural hinge line also is about 400 ft (122 m) lower in elevation than Dana Ridge’s topographic crest. The most important difference here from the Hitchens interpretation is that I recognize the anticlinal crest to be a major out-of-the-basin thrust in which strata on the hanging wall (northeast of the fault) dip steeply to the southeast, but strata of the footwall (southwest of the fault) dip steeply to the southwest.

Data available in Appendices 1 and 2 (Book 6), within sections 29, 30, and 32 of T. 21 N., R. 82 W. indicate at least seven precise positions for the structurally chaotic, lithologically shattered, strongly slickensided thrust plane within the Allen Ridge Formation along with good example exposures of both the footwall and hanging wall. The footwall and hanging wall both show extraordinary levels of fracturing, general chaotic rock orientations, and finely comminuted intervening gouge. Sets of subsidiary thrust faults having relative tectonic transports to the northeast are especially pronounced in the footwall. The footwall’s siltstone and fine-grained sandstone beds are strongly indurated. The general area of a prospective well platform in the NE ¼ of sec. 30, T. 21 N., R. 82 W. appears hydrothermally altered, and that is especially the case at measurement site 4423, just northeast of the prospect. Carbonaceous to lignitic shale beds are more common in the hanging wall. Once permission can be gained from the landowner, a researcher should carefully trace this fault all the way to the northwest along this northeastern flank of Dana Ridge to its termination.

All field evidence surrounding the plane of the thrust fault defining the hinge line of Dana Ridge Anticline suggests existence of a relatively giant analog of the Dragonfly Thrust (see Lillegraven and Snoke, 1996, photo on front cover; and Lillegraven et al., 2004, p. 36, figs. 4B–C and 18) as seen in the northeastern corner of the Hanna Basin. In particular, it includes strongly distorted, belly-to-belly stratigraphic relationships (i.e., original stratigraphic ‘up’ exists in both directions perpendicularly away from the axial surface of the thrust). I interpret the deformation as most probably the result of distributed frictional drag. A structural ‘great wall’ thus exists on Dana Ridge in which original stratigraphic ‘up’ exists both to the southwest (on the fault’s footwall) and to the northeast (on the fault’s hanging wall). Such expressions of ‘great walls’ are common all around the margins of the eastern Hanna Basin, and they occur at all scales. Sometimes the ‘great wall’ itself is topographically clearly expressed (as in ‘The Breaks’), but more commonly it lacks clear topographic prominence (as here, along lower elevations of the northeastern flank of Dana Ridge).

Another feature characteristic of ‘great wall’ structural relationships in the Hanna Basin is almost universal presence of a ‘footwall syncline’ that closely parallels the trace of the thrust in outcrop and is set forward of the direction of relative tectonic transport expressed by the fault’s hanging wall (see Lillegraven et al., 2004, fig. 4B–C). Footwall synclines are highly variable in size and structural definition, probably mostly dependent upon the nature of the affected lithology and the magnitude of the fault’s throw. Compare, for example, the relatively great width and tightness of folding in ‘The Great Tortilla’ (Lillegraven et al., 2004, fig. 4B, NW of center of sec. 10, T. 23 N., R. 80 W.) to the much narrower configuration seen farther to the northwest along the Dragonfly Fault in the NW ¼ of sec. 4 of the same township. The Walcott Syncline, in my interpretation, is a greatly scaled-up footwall syncline that matches the massiveness of the Dana Ridge Anticline. With that anticlinal thrust–footwall syncline system we are seeing a major contractional feature of the southern Hanna Basin that is in a league comparable to the fold known as the Hanna Syncline.
The above-mentioned seismic transect provided by Mount et al. (2011) contributes valuable information about Laramide tectonics at depth as seen northwest of the present paper's Figure 6. They presented one of 17 proprietary, regional 2-D seismic lines that incorporate parts of the Hanna Basin. Their figure 5 (p. 277) shows compiled 2-D reflectance data (both in uninterpreted and interpreted formats), scaled both for reflectance timing and approximate depths of reflectors. Location of the SW–to–NE-oriented transect is plotted on their tectonic reference map (fig. 3) of the Hanna Basin's general vicinity.

The above-mentioned reference map lacks numerical geographical coordinates to aid reader orientations. But using geologic cues from within the map itself, I interpret the approximate end-points of the SW–to–NE-oriented transect as follows: SW end $\approx$ 41° 38' N., 106° 56' W. (T. 19 N., R. 85 W.); and NE end $\approx$ 41° 58' N., 106° 41' W. (T. 23 N., R. 82 W.). When that transect is plotted onto the Love and Christiansen (1985) Geologic Map of Wyoming, it is seen to begin near the North Platte River south of the Kindt Basin (a saucer of Lewis Sh. atop a table of Mesaverde Gp.; see the present paper's Fig. 1B) and terminates just south of the Medicine Bow River a short distance east of its entry into Seminole Reservoir. As stated above, the transect passes through the topographic gap between adjacent ends of the Saint Marys Hill and Dana Ridge anticlines.

Most importantly, the seismic line presented by Mount et al. (2011, fig. 5) indicates faulted wedges at depth that involve both the Precambrian basement and the overlying sedimentary cover. The authors also present a three-step, tectonic-evolutionary model (fig. 6) that is compatible with nearly all components of the out-of-the-basin, southwest-directed thrusting proposed in the present paper along northeastern flanks of the Dana Ridge Anticline and the footwall-synclinal nature of the Walcott Syncline. The present paper's surface-derived attitudinal data gained from across the northeastern flank of much more southeasterly parts of the Dana Ridge Anticline, however, are incompatible with interpreted details of near-surface geology in Mount et al.'s (2011) figure 5.

Dana Klippe

Introduction to Dana Klippe

Dominating central parts of Figure 6 is a second major feature of the eastern Hanna Basin area here interpreted as allochthonous. To it, I apply the name Dana Klippe. Although its entire lateral margin is erosional, the present area occupied by the plate totals roughly 46 square miles (119 km$^2$). In essence, the klippe covers much of the Hanna Syncline of the southern Hanna Basin. Its east–west extent is roughly five times greater across the western flank of the syncline than across its eastern flank.

The southwestern edge of the Dana Klippe is placed on the Allen Ridge Formation (Mesaverde Gp.) along most of the hanging wall of the Dana (Pass Creek) Ridge Anticline. At the northeastern corner of the rim of Walcott Syncline, however, the Dana Klippe extends across the Mesaverde Group's Pine Ridge and Almond formations to terminate on stratigraphically low parts of the Lewis Shale. A narrow but north–south-elongated erosional cleft is cut through the klippe from its southernmost end to nearly a mile (1.6 km) north of Interstate Highway 80 (I–80). The klippe's southeastern edge courses across the Lewis Shale along topographically low parts of Halleck Ridge's northwestern slopes. The klippe's eastern edge climbs up-section to encounter the Medicine Bow Formation just south of I–80 and then the Ferris Formation a short distance north of the highway.

For most of the remaining northern length of the klippe's eastern edge, its relatively well-indurated basal strata have led to erosional sculpting (by wind and water) that has resulted in the topographically obvious and ventifact-rich Wilson Ridge. Uneroded remnants of that ridge continue north-northwestward along the eastern flank of the Hanna Syncline to terminate just beyond intersection with the synclinal hinge line. The northern erosional edge of the klippe then turns almost due west, continuing a down-section course across the vast expanse of the Ferris Formation forming the Hanna Syncline's western flank. The klippe's edge encounters the Medicine Bow Formation near the center of adjacent boundaries of sections 6 and 1 of T. 21 N., R. 82–83 W., respectively. Thereafter, the klippe's margin continues in a west-southwest course, across the Medicine Bow Formation and Lewis Shale, to complete the circuit around the klippe on the Allen Ridge Formation, just beyond the western boundary of Figure 6 in the Walcott topographic quadrangle.

Modern erosional edges of the Dana Klippe generally are poorly exposed at contacts with the older, usually much more steeply dipping strata. Nevertheless, many small-area exceptions exist to that generalization, and they can be examined around all edges of the plate. Ingle (1977) considered maximum thickness of the plate to be 687 feet (209 m) as based on well data from sec. 26 of T. 21 N., R. 82 W. The great bulk of the plate, however, is much thinner. Lithologically useful exposures across surfaces of the plate are widely scattered, generally small, and usually limited to within depths of rapidly eroding modern drainages. Emphasis in the present study is centered upon the plate's edges, with data gathered from both above and below the contact of the plate with older strata.

Prior to the present research, workers had universally considered that contact to be an ancient erosional surface secondarily covered by angularly unconformable deposition. The most thorough prior discussion of local stratigraphy of this plate was provided by Ingle (1977). From studies based on outcrops, well logs, and limited geophysical data, he characterized composition of the plate as follows (1977, p. i):
“The Browns Park Formation generally consists of: A basal conglomerate up to 285 feet [87 m] thick, overlain by a mudstone–fine-grained sandstone unit up to 365 feet [111 m] thick. The Browns Park unit is up to 509 feet [155 m] thick. The North Park Formation consists mainly of fine-grained sands, sandstones, siltstones, mudstones, thin tuff beds, and occasional thin limestone and gravel beds. The maximum thickness of North Park Formation found in the basin is 400 feet [122 m].”

The Browns Park Formation underlies the North Park Formation under that interpretation. Both formations were identified on the basis of lithologic similarities with the much thicker rock units holding those names in the Saratoga Basin (Fig. 1B), directly to the southwest. I have independently confirmed the sequence of lithologic components existing within that generalized rock column and have no reason to question accuracy of the maximum thicknesses cited by Ingle (1977). Based upon evidence discussed below, however, I differ strongly with Ingle’s geological interpretation of the plate itself. Also, I apply an alternative formational terminology.

**Basic Lithologic Generalizations of Dana Klippe**

This lithologic characterization begins at the contact with older strata that underlie the Dana Klippe. Most prior workers have referred to the lower parts of the plate as the ‘basal conglomerate.’ My observations suggest that features of lower parts of the klippe may continue up-section slightly over 200 feet (61 m). Usually, however, they are limited to roughly the lowest 100 feet (31 m) above the base. Strikes of these lower beds almost always parallel the plate’s margins, and dips consistently are toward the plate’s center.

Almost universally, the lower-level strata are coarse- to very-coarse-grained, angular sandstone, bearing diverse thicknesses of pebble and cobble conglomerate of great lithologic diversity. Occasional boulders (up to 97 cm [38 in] in greatest dimension) are found in place, scattered in a seemingly random distribution. Although many individual layers exhibit definite signs of bedding and cross-stratifications, more commonly the coarser layers of pebbles and cobbles have a ‘dumped in’ appearance. Sometimes the conglomeratic sequences are cross-supported, but more commonly they are matrix-supported. The sandy matrix itself generally is poorly sorted, and cementation varies from strong to essentially unconsolidated. Occasional bands with prodigious numbers of tiny, well-sorted pebbles also exist.

The generally well-rounded pebbles and larger clasts are greatly varied in composition, but the dominant representatives are granite, granite gneiss, dark metamorphic rocks, forms of banded-iron, several forms of quartzite, and highly silicified petrified wood. Although volumetrically minor, occasional thin beds of soft mudstone do exist among the coarse-grained dominants. Lignite, or even carbonaceous shale, is rare, nearly to the point of absence. Thin beds of siltstone to fine-grained sandstone also exist, but those facies represent definite minorities. Rather surprisingly, there exists no obvious trend either in clast sizes or relative abundances of lithologic species across any transect of the plate. Small boulders most commonly are composed of milky-white Medicine Peak Quartzite, and they occur as consistent elements in all observed margins of the klippe.

In virtually all aspects of lithologic composition and sedimentological features, the depositional assemblages found in lower parts of the Dana Klippe match the braided-stream deposits characteristic of the northern Medicine Bow Mountains (south of Elk Mountain) and adjacent Pass Creek Basin as described by Gries (1964) and later, in more detail, by Weichman (1988). Despite the general coarse-grained nature of this lower part of the plate, the term ‘basal conglomerate’ hardly seems appropriate in light of the depositional integrity and consistent heterogeneity of involved fluviatile facies.

Directly overlying the complex of coarse-grained materials low in the Dana Klippe is a widespread but usually covered sequence of clearly fluvial, thin- to medium-bedded, poorly sorted sandstone sets that differ dramatically in orientations from one another. Grain size varies from very fine- to coarse-grained. The best exposures are represented in the vicinity of measurements 4262, 4263, and 4265 (Fig. 6; Appendices 1 and 2), located in S-central parts of sec. 18, T. 21 N., R. 81 W. The sand grains are well-rounded, frosted clear quartz in a white matrix. The bedding holds no clastic elements larger than the sand grains, there exist no root traces, and compositionally seems devoid of ash or flow-related volcanic materials. Strikes of this bedding are unchanged from the lower sequence, and the dips are comparable or greater, again toward the plate’s center. Ingle (1977) included this sequence, along with the underlying ‘basal conglomerate,’ in the Browns Park Formation. Weichman (1988, p. 101) reported similar sand units (e.g., Lee Creek Section, unit 2) on flanks of the Medicine Bow Mountains.

Stratigraphically still higher strata within the Dana Klippe are exposed only more distantly from the plate’s margins, and generally they are best exposed in close proximity to the Hanna Syncline’s hinge line. Dips are shallow to flat lying. Weakly indurated, white to gray mudstone, siltstone, and fine-grained quartz sandstone dominate; the section is nearly devoid of pebbles or other coarse clastic materials. Ashy beds are common, with a few appearing to represent quite pure volcanic ash. Occasional thin beds of freshwater limestone exist. Abundant root casts and various burrows (mostly horizontal) are commonly expressed. Because of the input of volcanic materials, this uppermost part of the section is substantially different from underlying parts of the section described above. Ingle (1977) referred this uppermost lithologic complex to the North Park Formation. In addition
to strata overlying the axial surface trace of the Hanna Syncline, Ingle recognized a second patch of the North Park Formation farther west on the plate, specifically in sections 7–9 and 17–18 of T. 21 N., R. 82 W., plus sec. 13 in R. 83 W.

I am aware of no area on the plate in which an exposed contact can be seen between the volcanically influenced package and the older units, described above. Unquestionably, however, these upper strata differ strongly lithologically, and they probably are significantly younger. If only they were reliably mappable, this unit clearly would warrant a separate formalizational designation. Such is not the case, however, because hardly any of it is actually exposed to view. It is my opinion, therefore, that it is best to avoid expressing greater geological certainty of interpretation for the area than warranted. Toward that end, I have chosen to refer to the entire plate as 'Hanna Formation of Dana Klippe.' I discuss the reasoning behind that decision below.

Evidence in Support of an Allochthonous Origin

Prior interpretations have invoked simple deposition of strata identified as middle Tertiary Browns Park and/or North Park Formation upon a deep erosional surface cut into tectonically deformed Cretaceous and Paleocene strata of the Hanna Syncline in the southern Hanna Basin. The present work suggests, in marked contrast, a gravitationally displaced origin for that plate. Evidence suggesting that the entire plate is an allochthon follows.

Examination of footwall strata close to the contact with the hanging wall shows little evidence for differential weathering of the former. That comes as a surprise, because an erosionally beveled surface is required either if the contact represents an unconformity subsequently buried by sediments or a low-angled fault plane across which a klippe traversed under the influence of gravity. Under either scenario, late-Laramide erosion necessary to form the plane may well have been followed so closely by deposition or long-runout landsliding that duration of its exposure was inadequate to allow development of clear features of weathering in the substrate.

Much more important is the observation, examined at many individual exposed contacts, that there is no evidence in support of a depositional gradation between the generally steeply dipping beds that form the contact’s base and overlying, younger sedimentary rocks. Quite to the contrary, observations chronicled in Appendices 1 and 2 show that, almost without exception, strong deformation is localized close to the contact, either in the hanging wall or the footwall or in both.

The forms of deformation are many. Penetrative jointing and/or fracturing have led to localized chaotic stratigraphic orientations or more organized folding of the rocks. Lithologic gouge has developed within the contact plane, having churned recognizable granules from strata above and below the fault plane. In the uncommon situation in which both the footwall and the hanging wall involved strongly indurated rocks, the trace of the intervening fault may be pencil thin. But as the usual case, wherein softer rocks are involved at the contact, the breadth of the disturbed zone has become smeared out, expanded many meters both above and below the original fault contact, or now exhibits complications from subsidiary faults developed above and/or below the contact. The footwalls commonly have developed step-faults and/or frictionally bent sandstone fins directly below the thrust plane; both phenomena help in recognizing the direction of transport of the hanging wall relative to the footwall. Slicksided strata are common above, below, and within the thrust plane, although I did not systematically pursue a record of their vectors. Examples of all of the above phenomena are now identified around the entire circumference of the Dana Klippe.

Useful indicators of tectonic direction of motion (referred in the preceding paragraph) strongly and consistently suggest generally northward translation of the hanging wall relative to the footwall. That observation immediately leads to the question, ‘Where did the Dana Klippe come from?’ As a working hypothesis, I bring the reader’s attention to the pair of digital-elevation models in the lower right-hand quadrant of Figure 11. The left-hand image provides gross topographic relationships calibrated in elevation with color. The right-hand image covers the same geographic area, but it is supplemented by identifications of geographic areas of primary importance to this discussion. Added are patterned remaining distributions of strata commonly referred to the Paleocene–Eocene Hanna Formation, uniquely including the Dana Klippe. The various patches are based upon the authority of Beckwith (1941), Gries (1964), Love and Christiansen (1985), Blackstone (1987), Weichman (1988), and the present research.

Attitudinal data provided in Figures 6 and 7 indicate that the Hanna Syncline, including the main, coal-bearing body of the Hanna Formation (as shown in the NE corner of Fig. 6), is remarkably tightly folded. Discounting the klippe, the youngest strata involved in that syncline as shown in Figure 6 represent the Hanna Formation. All shown strata of the syncline in Figure 6, including the Hanna Formation, predate Eocene time (see Lillegraven et al., 2004, fig. 5), and are no younger than the late Paleocene Clarkforkian Land Mammal Age (middle of leg 17 of The Breaks section, as compiled by Lillegraven et al., 2004, fig. 11).

The time of folding of the Hanna Syncline, therefore could be no older than very late Paleocene. Although the Dana Klippe appears as a relatively flat-lying plate atop the sharply folded syncline, it also is clearly deformed in partial conformation with the underlying syncline. Note that lateral margins of the Dana Klippe commonly dip 20°–40°, and sometimes well beyond that, in direction of the plate’s center. Also, even the very youngest strata on the
Dana Klippe (i.e., strata identified by Ingle, 1977 as North Park Fm.) marginally express attitudes that reflect the underlying position of the axial surface trace of the Hanna Syncline. Deformation of the Hanna Syncline, therefore, may have continued at a minor level through the entire emplacement history of the klippe. Prior studies of this, as based on regional comparisons with the nearby Saratoga Basin (Montagne, 1991, fig. 4), have universally suggested an early Miocene depositional date. Useful results of dating volcaniclastic strata from Chalk Bluff in the northern Hanna Basin remain only forthcoming. Judging by the presence of volcanic ash, however, that probably would be late in the early Eocene at the very earliest.

Quite in contrast to the area of the southern Hanna Basin underlying the klippe, the Hanna Formation as seen along flanks of the northern Medicine Bow Mountains and Pass Creek Basin is, with minor exceptions, relatively flat-lying (see Gries, 1964, pl. 1 and Weichman, 1988, figs. 4 and 5). Even though strata of the Hanna Formation of the Pass Creek Basin are dominantly coarse grained, Weichman (1988, p. 15–18) reported Hanna assemblages of palynomorphs characteristic of zone P5 as conceived by Nichols and Ott (1978). On that basis, Weichman concluded (p. 17): “Thus, the Hanna Formation in Pass Creek Basin is late Paleocene in age.”

Subsequent to Weichman's evaluation, however, Dunn (2003) reported palynomorphic assemblages characteristic of Nichols and Ott's (1978) zone P5 in the northern Hanna Basin (Fig. 5) that underlie early Paleocene (Torrejonian Land Mammal Age; Higgins, 2003b) mammal-bearing strata of the Hanna Formation (see Lillegraven et al., 2004, figs. 11 and 16A–B). McKenna and Lillegraven (2005, 2006) and Lillegraven and McKenna (2008) suggested that the Nichols (1999, 2003, 2009), Nichols and Ott (1978, 2006), and Ott (1964) system of Paleocene palynomorph stratigraphy was controlled more by paleoenvironmental constraints than being representative of discrete segments of geologic time. Note the implications of that possibility to geologic interpretations of the Hanna Basin presented by Perry and Flores (1997, p. 51–54 and table 1). At the very least, however, the fossil pollen has been useful in confirming that the Hanna Formation of the Pass Creek area was deposited, most probably, sometime during the Paleocene epoch.

With the information presented in the preceding four paragraphs as necessary background, we can now return to the question: ‘Where did the Dana Klippe come from?’ Refer again to the: (1) southern part of Figure 6; (2) cross sections H–I and F–G’ of Figure 7; (3) right-hand digital-elevation model in the lower right-hand quadrant of Figure 11 plus Figure 11A; and (4) the various cross sections in plates 1 as provided by Beckwith (1941) and Gries (1964). That complex of graphics serves to focus scrutiny onto structural relations (surface and at depth) extending from southern parts of the Hanna Syncline, over the imposing mass of today’s Elk Mountain, to across the Pass Creek Basin to the northern Medicine Bow Mountains.

Study of that broad transect clearly suggests that uplift of the massif of Elk Mountain by way of the Elk Mountain Thrust Fault (Fig. 6 and Beckwith, 1941, pl. 1), folding of the Hanna Syncline, and general upturning of the southern Hanna Basin by way of the Rattlesnake Pass and Halleck Thrusts significantly post-dated deposition of a continuous sheet of Hanna Formation that extended northward from the northern Medicine Bow Mountains all the way across the modern Hanna Basin — and beyond (see Lillegraven et al., 2004, fig. 15). As discussed below in relation to analysis of Figure 11A–C, the working hypothesis is that all but the youngest elements of the Dana Klippe (i.e., North Park Fm. of Ingle, 1977) originated from Hanna Formation that originally were deposited stratigraphically above the then-future positions of Elk Mountain and the northern Pass Creek Basin. Ashley (1948, p. 64–65) emphasized the landslide-prone nature of Kennaday Peak on the northern flank of the Medicine Bow Mountains.

INTRODUCTION TO THREE MODELED EVOLUTIONARY SCENARIOS

Figures 9–11 present step-wise, cross-section-based hypothetical models of the Laramide tectonic and erosional history for three key transects across the eastern Hanna and Carbon basins. Specifically, they are:

Figure 9 — a SW–NE transect using reference points 1, 2, and 3 across the Hanna Basin from the southwestern flank of the Coal Bank Basin to the southernmost topographic expression of the Freezeout Hills;

Figure 10 — although involving a sharp mid-point change in course, this is a basically W–E transect using reference points 4, 5, and 6 from just west of the Hanna Syncline's hinge line to across Simpson Ridge Anticline into the southwestern Carbon Basin, then terminating on the southwestern flank of Flat Top Anticline; and

Figure 11 — a two-part, NNW–SSE transect using reference points 7, 8, and 9 extending sequentially from the eastern extreme of the Dana Klippe to Halleck Ridge and then from a more southwesterly point on Halleck Ridge to across Elk Mountain to terminate in the northern extreme of Pass Creek Basin. Point 8 involves an internal, lateral jump along a stratigraphic marker bed held in common.

Figure 11 is unique within this paper in that roughly the southern half of the transect extends beyond the landscape mapped by me during the present research.

The modeling presented in Figures 9–11 takes profound subsidence as a given, and the models are not necessarily intended to portray, or necessarily even to imply, 'the truth.' Rather, the modeling represents hypotheses of geological evolution as constrained by two simple but all-encompassing
forms of essentially the same question. The more general form was to approach the question, "How could the present geological relationships seen in the Hanna–Carbon basins have come to be?"

Approach to that question began with field work necessary to develop the areal geologic maps presented here as Figures 4–6. Descriptive results of those investigations are presented above, and discrete details are recorded in Appendices 1 and 2. Development of the interpretive cross sections presented in Figure 7, along with the representative thickness measurements constructed as stratigraphic columns in Figure 8, helped in initially grasping fundamental stratigraphic relationships from the ground surface down to 4,500 ft (1.37 km) above mean sea level. All that new data provided highly valuable background information not available in existing literature. But to effectively approach the above-presented question, the investigation needed to be pursued to depths of 15 km (9.3 mi) or more below the modern surface.

As to the second permutation of the question posed above, the following was applied to all available data throughout the modeling as a special constraint to the thought process. Each scenario began with a cross section of the field-tested, present-day geological configuration, to which the following specific refinement of the earlier question was applied: ‘Of the multiplicity of possible alternatives, what is the simplest, most parsimonious series of events involving reasonable elements of faulting, subsidence, rock uplift, and surface exhumation that could have led to what exists today?’ Whether geohistorically correct in interpretations or not, such thinking at least can be useful in showing the minimal magnitudes of tectonism and erosion required to explain what now exists.

Despite the unavoidable pitfalls of such uncertainties, I emphasize that the models presented in Figures 9–11 go beyond simple cartoon drawings in that (with exception of the southern half of the transect in Fig. 11) each step has been constrained to the limits of practicality in drafting through application of original measurements made on the ground. Each measurement taken from the model (all scaled 1:100,000 with no vertical exaggeration) can be verified or refuted by users through their return to specific sites in the field with original data in hand as plotted in Figures 4–8 and more fully recorded in Appendices 1 and 2.

Captions to Figures 9–11 provide fundamental elements of orientation and salient miscellaneous items of information.

CONSIDERATIONS OF FIGURE 9 — SW–NE TRANSECT ACROSS HANNA BASIN

Introduction to Figure 9

Figure 9 focuses on the history of a 43 km- (27 mi-) long transect across the entire Hanna Basin. Figure 9B, which represents present conditions and involves the deepest part of the basin, provides three tie-points (identified as 1–3) to the modern topography. They include: (1) the southeastern flank of the Coal Bank Basin; (2) a site just west of the Hanna Syncline’s hinge line at about mid-basin; and (3) the extreme northeastern corner of the basin at the southern edge of topographic expression of the Freezeout Mountain Anticline (see Lillegraven et al., 2004, fig. 4A–C).

Sacrison (1978, fig. 16) presented a 50 km- (31.1 mi-) long, ground-surface-to-basement, seismic-reflection profile through some unidentified part of the Hanna Basin. The transect was aligned SW–NE, with deepest data shown at 13 km (8.1 mi) below the ground surface. No location coordinates or local landmarks were identified on the published profile. Nevertheless, I suggest that his figure 16 was placed almost precisely along Figure 9B as developed (completely independently) within the present paper. Clearly shown is the cross section of the Coal Bank Basin, deeper parts of the Dana Ridge Anticline, and key reflectors deeper than 500 m through the entire Phanerozoic sequence of the basin to just north of the defining syncline of northeastern Hanna Basin.

Sacrison (1978, p. 49) interpreted his seismic transect as follows:

‘‘Steeply dipping compressional folds such as that near the left side of Figure 16 [referring to the Coal Bank Basin and/or Dana Ridge Anticline] occur in the Upper Cretaceous rocks on the west, south, and east flanks of the basin. These folds have no basement uplift beneath them so are unrelated or at least indirectly related to basement block fault movements.’’

Presumably, the features elsewhere in the basin to which he refers are: (1) to the west, the Rawlins Uplift (see Otteman and Snoke, 2005, fig. 4); (2) to the south, the complex of Bloody Lake Anticline (including Halleck Ridge) and the northern base of Elk Mountain (Figs. 5–8 and 11); and (3) to the east, Simpson Ridge Anticline (Kraatz, 2002, figs. 12–15; Figs. 5, 7–8, and 10). All of those cited examples, however, involve basement-block fault movements.

The present-day transect in Figure 9 would be well over a full township to the southeast of the line presented in figures 3, 5, and 6 by Mount et al. (2011). Also, their transect extended farther to the south and was less extensive to the north than that of present Figure 9.

Discussion of Figures 9A–B

As constructed in Figure 9B, the Dana Ridge Anticline and the adjacent Coal Bank Basin are controlled by a basement-involved thrust fault having relative tectonic transport to the southwest. I have interpreted the Coal Bank Basin itself as an unusually large example of a footwall syncline. For examples elsewhere of footwall synclines having comparable magnitude, see McConnell (1994, fig. 1a and 16 and his p. 1585, item 4). Perhaps, as suggested by
Sacriston (1978), no basement-involved fault is necessary to explain the nature of the conjoined Dana Ridge Anticline and Coal Bank Basin. In that case, the question would seem to parallel the Carter-Knox field of Oklahoma as illustrated by Petersen (1983, figs. 10 and 12). I do propose, however, that the quality of seismic data at the Phanerozoic–basement interface as shown in Sacriston’s figure 16 is inadequate to determine the nature of that contact. It could be the case that the out-of-the-basin thrust fault that defined the hinge of the Dana Ridge Anticline is actually restricted in its origin to some soft and ductile, fine-grained Cretaceous unit such as the Steele Shale. If true, however, it probably would be almost unique within the general Hanna Basin area in its development of a major thrust that does not involve origin within Precambrian basement rocks. Compare the options with the situation showing basement involvement as interpreted by Mount et al. (2011, figs. 3, 5, and 6) well to the northwest of the limits of present Figure 9.

The Dana Klippe (a focus of Fig. 11) laps onto the northeastern flanks of the Dana Ridge Anticline and continues across the eastern end of the Coal Bank Basin. The klippe extends northeastward today across the transect in Figure 9B for about 9.75 km (6.1 mi). The klippe covers from view a minimal thickness of about 6 km (3.7 mi) of moderately dipping, mostly Upper Cretaceous strata, including the Mesaverde Group through more than the lower two-thirds of the Ferris Formation.

Most of today’s surface landscape between tie-points 2 and 3 in Figure 9B involves the Hanna Formation. That formation, at its northernmost outcrops, exhibits clear, angularly unconformable deposition onto steeply west-dipping upper parts of the Steele Shale (Lillegraven et al., 2004, figs. 14C and 16B); unconformable relationships probably continue across younger Cretaceous strata at depth farther south. Remnants of the Hanna Formation terminate by Laramide and modern erosion well south of the topographic expression of the modern Freezeout Hills and Shirley Mountains (see Clemens and Lillegraven, 2013, fig. 7E).

Figure 9 is the simplest of this paper’s trio of model-based transects in that only one earlier step (Fig. 9A) is presented. Recall that the cross sections’ solid colors represent elements of the local stratigraphic record that persist today; all else has been eroded away, precluding indisputable verifiability of anything shown with partially transparent colors. Notice that, although admittedly totally hypothetical, Figure 9A is extended to the southwest beyond tie-point 1 into what today would be northern parts of the Saratoga Basin (existing between the Medicine Bow Mountains on the east and the Sierra Madre to the west; Houston, 1993, p. 82–89; Houston et al., 1993, fig. 9 and p. 143–144).

Figure 9A of the present paper is intended to represent very late Paleocene or perhaps even earliest Eocene time. That was well after both the deposition of most of the Hanna Formation and the advent of consequential uplift plus substantial erosion of southern parts of a previously more complete stratigraphic continuity southwestward. No record of the Ferris Formation in the Saratoga Valley is recognized today, but Montagne (1991, pl. III) suggested preservation of remnants of Hanna-equivalent strata (i.e., usually mapped as Coalmont Fm.) at the south end and southwestern flank of the Saratoga Basin. Mears (1998), however, challenged that formational identification, suggesting the relevant outcrops actually represent basal conglomerate of the post-Laramide Browns Park Formation. On the basis of macrofloras, Brown (1962, p. 25) tentatively considered the entire Coalmont Formation to be of Paleocene age, but recognized that some new discoveries of palynomorphs “…indicate that part of the Coalmont is Eocene in age…”

As summarized by Montagne (1991, pl. 1) and Buffler (2003), the Saratoga Basin today is filled almost completely by middle Tertiary volcanioclastic deposits most commonly mapped as Browns Park Formation. Considerations of surrounding rock sequences both in southern Wyoming and northern Colorado, however, strongly suggest that shallow marine to brackish-water conditions had persisted late into the Cretaceous atop the area now occupied by the then-uniﬁed Sierra Madre/Medicine Bow Mountains basement massif. It is probable that local marine conditions persisted in the vicinity of the present Saratoga Basin at least through times of deposition of the Lewis Shale (Visher, 1952, pl. 1; Davidson, 1966, p. 35–38; Winn et al., 1987; Perman, 1988, 1990) and signiﬁcant lower parts of the Medicine Bow Formation (see: Dobbin and Reeside, 1930, p. 22; Dorf, 1942, p. 9–21; Fox, 1970, 1971; and Lillegraven and Ostresh, 1990, fig. 6B, elements 8 and 9).

Evidence provided by Knight (1953), Houston et al. (1968), Blackstone (1975), Ryan (1977), Weichman (1988), and the present study all suggests that Precambrian rocks of the conjoined massif of the Sierra Madre/Medicine Bow Mountains did not become emergent (i.e., first from beneath the shallow ‘Lewis Sea’ sea and later from scouring of the cover of pre-Cenozoic strata) prior to very Late Cretaceous time. Once underway, however, erosion of upper elevations of the Sierra Madre and Medicine Bow Mountains contributed prodigious amounts of clastic sediment to the accumulating Ferris and Hanna formations throughout the eastern Hanna Basin. Post-Laramide (Neogene) extensional tectonics finally led to development of normal faulting, especially along western margins of the Saratoga Basin. That resulted in the easterly hinged, half-graben setting exhibiting progressively west-downdropped bedding characterizing the modern Saratoga Valley (Mears, 1998, fig. 3).

History of the northern part of the landscape covered by Figure 9A is much better understood than at its southern end. Note that the basement rocks and overlying Paleozoic, Mesozoic, and earliest Paleocene (of Ferris Fm.) strata had been uplifted (as seen broadly below tie-point 3) nearly to
vertical attitudes. Those beds were deeply beveled by erosion prior to deposition of the Hanna Formation upon them, thus forming a clear angular unconformity. Also shown in Figure 9A are traces for then-future positions of the Dragonfly Fault complex (including the Owl Ridge Thrust; Lillegraven et al., 2004, fig. 4B). Those faults would develop out-of-the-basin, northeast-directed relative tectonic transports as massifs of the Freeezeout Hills and Shirley Mountains continued their uplifts well into Eocene time. Those uplifts also resulted in development of the defining syncline of northeastern Hanna Basin.

Also notice the requirement for an obvious change in cross-sectional shape of the basement mass below tie-point 3 between Figures 9A–B. Although much has yet to be learned about the mechanisms by which such alterations became effected, Houston et al. (1968, p. 147–157) provided a classic discussion of the role of basement deformation as related to complex Laramide structures specific to the area of coverage within the present paper: geographically broader and more advanced concepts specific to basement deformation appear in such references as Schmidt et al. (1993) and McClay et al. (2011). Figure 9A also suggests that much of the then-future area of the Freezeout Hills was covered by Paleocene strata of the Hanna Formation prior to their uplift.

CONSIDERATIONS OF FIGURE 10 — BASIC WEST–EAST INTERBASINAL TRANSECT

Introduction to Figure 10

Figure 10D portrays the present-day setting. That graphic reflects the fundamental configuration of rocks along a sharply bent, 32.5 km (20.2 mi) transect that connects three tie-points (identified as 4–6) as follow. Tie-point 4 is placed just west of the Hanna Syncline’s hinge line, at about a mid-latitude in the eastern Hanna Basin. The transect then extends southeastwardly across Simpson Ridge Anticline to tie-point 5 in the southwestern quadrant of the Carbon Basin. The transect then changes to a northeasterly course and extends across the Carbon Basin to tie-point 6, placed on the southwestern flank of Flat Top Anticline southeast of Calvin Bend. The basic intention of Figure 10D is to suggest the net appearance of a west–east, transbasinal cross section that includes uppermost parts of the Precambrian basement. As considered here, the Halfway Hill Syncline (a direct continuation of the defining syncline of northeastern Hanna Basin) represents the northeastern boundary of the Carbon Basin.

Three earlier steps (Fig. 10A–C) present a hypothetical model leading to present conditions. Keep in mind that in Figure 10A the solid colors of stratigraphic units represent rocks persisting today in Figure 10D, and the partially transparent colors represent strata eroded away prior to that modern stage. A potentially confusing exception is shown in Figure 10C, in which an incipient Carbon Basin Klippe enters the picture by way of low-angled sliding from an assumed point of origin on the southwestern flanks of Flat Top Anticline. Most probably, the initiation of translation began during a much shallower tilting of the substrate than shown in the graphic. The relatively steep dip shown in Figure 10C is partially diagrammatic, reflecting something close to late-Laramide conditions. Strata involved in the klippe probably originated north and somewhat east of tie-point 6 during Eocene time after almost all of the original Hanna and Ferris formations as well as much of the Medicine Bow Formation in the evolving Carbon Basin had been eroded away. Additional interpretation of origin of the Carbon Basin Klippe is presented below in association with the specific discussion of Figure 10C.

Discussion of Figure 10A

Figure 10A is intended to represent late Paleocene time, prior to any consequential structural development of Simpson Ridge Anticline. In contrast to concepts of latest Cretaceous structural origin of that anticline as proposed by Ryan (1977), I suggest that this part of Wyoming remained into the late Paleocene as an eastern component of an enormous, originally continuous part of the greater Green River Basin. The eastern component later became subdivided west-to-east into the Great Divide, Hanna, Carbon, Pass Creek, and Laramie basins (see Lillegraven et al., 2004, fig. 19). A general thinning of the uppermost Cretaceous and Paleocene sequences from west to east is suggested along the entire transect of Figure 10A. Notice the huge extent to which the eastern two-thirds of that transect will experience erosional loss of the original stratigraphic pile during later parts of the Laramide Orogeny.

Discussion of Figure 10B

Figure 10B is intended to represent latest Paleocene into earliest Eocene time. It heralds separation of the Hanna Basin from the Carbon Basin (with the latter temporarily remaining contiguous with then-future Laramie Basin) through early development of a basement-involved thrust-fault system having relative tectonic transport to the west (see Kraatz, 2002, figs. 11–15). Most definitely (in contrast to the usual interpretation prior to Kraatz’ study), the fault system responsible for the Simpson Ridge structure was not merely a continuation northward of the tectonically east-directed Elk Mountain Thrust Fault complex. Recognize that the deep thrust associated with origin of Simpson Ridge is much simplified here for diagrammatic purposes in Figure 10 as compared to the elaborate fault system involving deep-wedge structures that were identified by Kraatz (2002, figs. 12–15) from seismic records and almost certainly affected more shallow faults.
Early developmental phases of the Simpson Ridge Anticline would have been a broad arch as viewed in a cross section set normal to the anticlinal hinge line. However, the then-future surface of the highest part of the Precambrian basement under the developing Carbon Basin (i.e., essentially below tie-point 5 in Fig. 10B) would have become vertically elevated by nearly five kilometers (3.1 mi) beyond levels shown in Figure 10A. Such uplift would have led to especially widespread erosion of the Hanna and Ferris formations within the juvenile Carbon Basin, even affecting parts of the Medicine Bow Formation atop the early arching of Simpson Ridge.

Westward relative tectonic transport of the Simpson Ridge fault system (controlling origins for both the Simpson Ridge and Bloody Lake anticlines) also would have initiated folding of the Hanna and Halleck Creek synclines. Definition of those folds probably was accompanied by widespread initiation of out-of-the-basin thrusting from the brand-new, southeastern margin of the Hanna Basin onto the rising western flanks of the Bloody Lake and Simpson Ridge anticlines.

Discussion of Figure 10C

Figure 10C is intended to represent middle Eocene time. It emphasizes continuation of geological processes initiated in Figure 10B such as: (1) completion of uplift and folding of Simpson Ridge Anticline; (2) tightening the folding and expanding out-of-the-syncline faulting within the Hanna Syncline; and (3) virtual removal by erosion of the original Hanna and Ferris formations from the Carbon Basin itself with scouring down into deeper parts of the Medicine Bow Formation.

Figure 10C also exhibits new geological events. Examples include initiation of folding via northern extension of the Big Medicine Bow Anticline along with first expression of the Halfway Hill Syncline. That syncline clearly defined an eastern structural margin for most of the Carbon Basin, separating it from the more easterly Laramie Basin. Most important to the present discussion was development of strong southwesternly dips of strata across the entire southwestern flanks of Flat Top Anticline (an uplift within northwestern extremes of the general Laramie Basin). That provided a vast, dumptruck-like, tilted ramp of bentonite-rich, generally fine-grained Upper Cretaceous clastic marine strata that facilitated southwest-directed, gravity-driven sliding of an enormous mass of superposed strata.

Notice that the tilted ramp itself was both the southwestern flank of Flat Top Anticline and the westernmost edge of the Laramie Basin — with its accumulated strata already being obliterated by erosion and mass movement. According to present interpretation, only a small part of that slide-mass has been preserved as the Carbon Basin Klippe. The diversity of specific forms of evidence leading to the very identification of an allochthonous plate within the Carbon Basin was listed earlier in this paper. And that was associated with observations favoring origin of the allochthon to the north or northeast of its present setting in the Carbon Basin.

Here is a specific working hypothesis. I suggest that the local richly conglomeratic and coaly Hanna Formation that now comprises the Carbon Basin Klippe (of Fig. 5) was deposited as part of the Hanna Formation that formerly presented continuity with the northern Hanna Basin and rested above what is now Flat Top Anticline. That is, strata comprising the klippe originated in the northwesternmost Laramie Basin (Fig. 1B), now east of The Breaks and northeast of the Carbon Basin. Minimally, that hypothesis demands lateral translation via sliding of the klippe, first off the anticlinal ‘dumptruck,’ and then across the ancient land surface for a total of roughly a dozen miles (ca. 19 km).

Such a sliding traverse would have been from northeast to southwest and was terminated by the klippe’s encounter with the newly eroded, generally steeply east-dipping Lewis Shale along the eastern flank of Simpson Ridge Anticline. The anticlinal roll-over nature along much of the western edge of the Carbon Basin Klippe is compatible with such an interpretation. That linear structural feature extends southward along most of the western edge of the Carbon Basin’s Hanna Formation, starting from near Windy Lake in the NW ¼ of sec. 10 in T. 21 N., R. 80 W. (Figs. 5 and 7, cross section M–O).

I surmise that the depositional position of what is now Hanna Formation of the Carbon Basin Klippe was, in the northwestern-most Laramie Basin, perhaps as much as 12 km (7.5 mi) north-northeast of tie-point 6 on Figure 10D. Probably that was far enough removed from the classic Hanna coal fields of the Hanna Basin (i.e., principally north and northwest of the town of Hanna; ca. 30 km [18.6 mi] or more if post-depositional folding is taken into account) that individual coal beds, or even complexes of coal beds, could not have been identified as correlative by Dobbin et al. (1929) or (at least with any certainty) by subsequent workers.

Indicated Amounts of Laramide Landscape Shortening and Relative Vertical Uplift

Egan and Urquhart (1993, fig. 7) attempted to quantify the amount of east–west lithospheric shortening that occurred across southern Wyoming during the Laramide Orogeny. Simultaneously exhibiting markedly less sophisticated procedures but offering much greater detail across lesser components of the landscape, I propose representative values of horizontal shortening and vertical relative displacements for pre- and post-Laramide geologic settings as visualized in Figures 10 and 11. Conceptually speaking, the approach taken in this exercise is in agreement...
with Bekkar (1973, p. 48–58) in terms of importance of origins of observed thrusting within Precambrian basement. The present approach, however, puts greater emphasis on contractional tectonics and landscape shortening via listric thrust planes in contrast to situations in which “... displacement took place along reverse faults that are convex upward” (Bekkar, 1973, p. 55).

Comparing measurements taken from Figure 10A and 10D, the horizontal distance between tie-points 4 and 6 today is minimally 15% shorter than in late Paleocene time. The tectonic process of landscape shortening continued even following emplacement of the klippe into the Carbon Basin. That is evidenced by the regularity of stratigraphic dips around the klippe’s margins toward the basin’s interior along with ubiquity of small, out-of-the basin thrusts observable all around the Carbon Basin’s margin (Fig. 5). Vertical uplift of the Precambrian basement as compared between the models represented in Figures 10A and 10D at the hinge line of Simpson Ridge Anticline was about 7.9 km (4.9 mi). A similar comparison of Laramide vertical uplift measured at the top of the Steele Shale near tie-point 6 (east of the Carbon Basin) indicated about 6.5 km (4 mi).

CONSIDERATIONS OF FIGURE 11 — NW–SE TRANSECT ACROSS ELK MOUNTAIN

Introduction to Figure 11

Although less complex than Figure 10, Figure 11 represents by far the most impressive deformational magnitudes among hypothesis-oriented Figures 9–11. The cross section in Figure 11C portrays modern-day relationships, and Figures 11A–B suggest models of two earlier stages of geological evolution. Figure 11C involves a 17 km- (10.6 mi-) long total transect that links together cross sections H–I and F’–G’, shown individually in Figures 6 and 7.

The three tie-points (identified as 7–9) applied in Figure 11 equate as follow with elements of Figures 6 and 7. Tie-points 7 and 8 represent the same end positions as cross section H–I, and tie-points 8 and 9 represent the same end positions as cross section F’–G’. On the actual modern landscape, the cross-sectional end positions I and F’ are separated from one another by about 3.9 km (2.4 mi) along the crest of Halleck Ridge. In diagrammatic Figures 11A–C, however, I have artificially united end-positions I and F’ at a common tie-point identified as 8. As shown on the geological reference map in Figure 11, tie-point 7 is set on the Dana Klippe near its eastern edge, north of that linear edge’s north–south center. Tie-point 8 is on the crest of Halleck Ridge toward the southwestern third of its length, and tie-point 9 (see Fig. 11C) is at the southernmost edge of Carboniferous strata remaining north of Elk Mountain’s eastern summit. Tie-point 7 marks the northern end of the cross section shown in Figure 11C, but all three cross sections forming Figure 11 extend well to the southeast of tie-point 9.

While tracking equivalents of specific geographic sites through the sequence of Figure 11A–C, it is helpful to keep the following logical feature in mind. In all three cross sections, the distance has been held the same (ca. 19 km) from the left edge of the graphic (as measured along the curving upper surface of the Precambrian basement) to the point equivalent to the southeastern-most extent of Carboniferous strata near today’s east summit of Elk Mountain. That southeastern stratigraphic limit in each cross section defines tie-point 9. Notice also that, in Figure 11A: (1) tie-point 7 is placed several kilometers southeast of the left edge of the cross section; and (2) a thin dashed line curves downward and to the left from tie-point 7, coursing from the Ferris Formation down-section through the Mesaverde Group into a complex of thrust faults. In Figure 11C the equivalent positions of that thin dashed line (as well as the shorter version that extends from the Steele Shale down-section to the basement rocks) have become vertical because of rotation of the strata to much higher dips, thus making the left edge of that cross section congruent with tie-point 7. Figure 11B suggests an intermediate stage.

The left inset map in the lower right-hand quadrant of Figure 11 is a digital-elevation model intended to: (1) indicate names of relevant 7.5 minute USGS topographic quadrangle maps; and (2) clarify the geographic nature of the landscape south of the Hanna/Carbon Basin as far as southern parts of the Medicine Bow Mountains. The right inset map indicates the locations of geologic and geographic features mentioned in the text. Also shown is distribution of irregular patches of strata usually mapped as Hanna Formation in the southern Hanna/Carbon and Pass Creek Basin areas and southward to along northern flanks of the Medicine Bow Mountains. Two of those patches are here considered to be allochthonous (as klippen).

Dominginant of the top of Figure 11 are conjoined cross sections H–I and F’–G’ (of Figs. 6 and 7). The combination is scaled at 1:24,000 but projected downward only to an arbitrarily shallow cutoff of 4,500 ft (1,372 m) above mean sea level. Notice the extraordinarily thick, steeply northward-dipping to overturned, basin-margin sequence of Upper Cretaceous strata north of Elk Mountain (involving the Mesaverde Gp. up-section into the Ferris Fm.). Also note the unexpectedly thin representation of Steele Shale directly south of multiple out-of-the-basin thrust faults underlying the Mesaverde Group at the southern base of Halleck Ridge. Those faults cut down-section through the soft and highly malleable Steele Shale, thereby tectonically removing minimally 1,000 ft (305 m) of its original thickness. As seen on Figure 6, at Rattlesnake Pass (NW ¼ of sec. 23, T. 20 N., R. 82 W.) essentially all of the Steele Shale, expected there to be over 3,400 ft (1 km) thick, has been eliminated by displacements along one or more northerly splay of the Elk Mountain Thrust complex.
Discussion of Figure 11A

Figure 11A is intended to represent latest Paleocene into earliest Eocene time, nearing the end of full deposition of the Hanna Formation. The northern edge of the Medicine Bow Mountains (Houston et al., 1993, p. 140–143), which contributed much coarse-clastic erosional debris to the Hanna Formation of the then-future greater Hanna Basin, was located at least 25 km (15.5 mi) southeast of the right-hand edge of this cross section. Uplift of the Medicine Bow Mountains significantly pre-dated structural origin of Elk Mountain (Knight, 1953), which in this interpretation had not yet started development of its controlling fault complex. Thus today’s Pass Creek Basin, between Elk Mountain and the Medicine Bow Mountains, existed only in the sense of being part of a north–south, much-more-expansive eastern greater Green River Basin (see Lillegren et al., 2004, figs. 15 and 19) that soon was to become tectonically subdivided into the Hanna, Carbon, Pass Creek, and Laramie basins. Strata that eventually would comprise the Dana Klippe in the southern Hanna Basin probably is represented by lower parts of the Hanna Formation seen southeast of tie-point 9 and perhaps in part extending even beyond the southeastern edge of Figure 11A.

Discussion of Figure 11B

Figure 11B is intended to represent early to middle Eocene time. It suggests significant development of uplift of Elk Mountain by way of a complex of faults having relative tectonic transport to the east. That unit of uplift helped define the modern southern boundary of the Hanna Basin as well as the northern boundary of today’s Pass Creek Basin. Vast amounts of erosion would be required following conditions shown in Figure 11B, and the lower heavy red line emphasizes the equivalent then-future positions seen along today’s generally degradational landscape.

In studying Figure 11B, it would naturally seem odd to observe elements of the Elk Mountain Thrust complex both to the north and to the south of Elk Mountain’s main mass. However, I concur with Beckwith (1941, pl. 1), Houston et al. (1968, pl. 1), and Blackstone (1980, fig. 2) that the Elk Mountain structure is fundamentally a thrust-faulted (with a complex, east-directed, scoop-shaped fault trace), highly asymmetric, overturned anticline with a NNW-plunging axial surface trace. By the very nature of positioning chosen for the cross section used in Figure 11, the trace of that fault complex would be expected to appear both to the north and to the south of Elk Mountain’s Precambrian core.

As an aside, in light of Blackstone’s (1980) criticisms, combined with recognition of the ubiquity of evidence for Laramide contractional tectonics across the width and breadth of south-central Wyoming, I cannot consider as convincing the view proposed by McClurg and Matthews (1978, fig. 4) that Elk Mountain should be modeled as exhibiting drape-folded sedimentary sequences along normal faults, thus reflecting vertical uplift.

Figure 11B presents one of the simplest among other possible interpretations for the origin of the Dana Klippe. It is true as well, however, that everything between the two heavy red lines has long-since been eroded away, thus rendering the model into the characterization of ‘informed speculation.’ Nevertheless, this model does actually seem to work toward explanation of remnant geologic conditions. As a preferred modification of Figure 11B, I suggest that northward sliding of the klippe occurred much later than the stage of uplift represented here. If a modification were to be followed, the Lewis Shale, Medicine Bow, and Ferris formations importantly would have attained the nearly vertical dips to the northwest that they exhibit today beneath the plate of the Dana Klippe.

Discussion of Figure 11C

Evaluation of measurements taken from Figure 11C become especially informative in light of comparisons with the preceding two geo-evolutionary stages of this interpretive model. For example, perhaps it is initially surprising that the horizontal measurements between tie-points 7 and 9 are essentially identical among Figures 11A–C (i.e., 11.6, 11.6, and 11.7 km, respectively). From examination of those values alone, one might quite incorrectly conclude that the landscape along transect 7–9 actually lengthened slightly through time.

The following, however, are relevant specifics that negate such a conclusion. During the geologic interval between modeled Figures 11A–B, the horizontal distance between tie-points 8 and 9 decreased significantly (from 8.3 to 5.8 km) through completion of out-of-the-basin thrusting that cut down-section and had relative tectonic transport to the southeast (near what is today the base of Halleck Ridge) to the extent of at nearly three kilometers. The horizontal distances between tie-points 7 and 8 when comparing Figures 11A with 11C are 3.3 and 4.8 km, respectively. That apparent 1.5 km measurement increase through time reflects nothing more than a different viewpoint of the phenomenally thick Upper Cretaceous stratigraphic sequence involved. When that inordinately thick stratigraphic sequence is viewed in a nearly vertical position (i.e., as in Fig. 11C), a greater horizontal distance is measured between tie-points 7 and 8 than when the same sequence viewed along its nearly horizontal, depositional orientation (as in Fig. 11A). Thus, in this particular case, the tie-points intentionally selected for potential use in measurement provide virtually no information of value about landscape shortening (or lengthening) as related to Laramide tectonic processes.

Fortunately, other geographically recognizable features within the models can aid in providing minimum values
for Laramide tectonics-related distances of: (1) absolute landscape shortening (and percent change); and (2) relative vertical elevation or subsidence of basement. The following two paragraphs provide, respectively, quantitative examples for the gaining of absolute horizontal and relative vertical deformational measurements.

Absolute horizontal shortening.—In Figure 11A, the measurement from tie-point 9 (i.e., the southern-most extent of shallow marine Carboniferous strata preserved on Precambrian basement of the northern flank of Elk Mountain’s eastern summit) to the cross section’s left edge (which, following rotation to get to Fig. 11C, is congruent with tie-point 7 in Figs. 11A–B) is 19 kilometers. That equivalent inter-tie-point distance as measured on Figure 11C is only 11.6 km. The difference between those two measurements is 7.4 km, so the specified comparative horizontal distance in the modern setting (Fig. 11C) is 39% shorter than in the early Laramide setting Fig. 11A).

Relative vertical elevation.—The relative differences in elevation of the equivalent points for the east summit of Elk Mountain between Figure 11A (equivalent of then-future summit-point marked with yellow star) and 11C is about 12.9 km (8 mi). Similarly, the relative difference in elevation of the equivalent points for the most southerly outcrop of marine-deposited Carboniferous strata on the northern flank of the east summit of Elk Mountain is about 12.7 km (7.9 mi).

Oliver (1970) produced three maps, covering the entire area of the Hanna/Carbon Basin, showing measured values for Bouguer gravity (pl. 1), regional gravity (pl. 2), and residual gravity (pl. 3). For the most part, anomaly contours of the residual gravity map faithfully reflected known major geological features shown here in Figures 4–7 and 9–11. In Oliver’s (1970, p. 32–33) own words, however: “There is one gravity anomaly within the map area that does not relate to the local geology. Elk Mountain . . . is a large tilted block of Precambrian crystalline rock. A gravity maximum would be expected to be present over this structure. Instead, a gravity minimum of -4.0 mgals is present.” Neither do I see explanation within Figure 11 for the gravity minimum over Elk Mountain and the Pass Creek Basin, unless it relates to the massive amount of erosion (Fig. 11A, partially transparent strata) plus the loss of strata following gravity-driven lateral transfer of sediments now partially preserved as the Dana Klippe.

DISCUSSION

History of Project and Procedural Essentials

Research on structural aspects of this project began early in the 1990s. The structural work formed a necessary complement to vertebrate paleontological studies of the Hanna Formation within the northeastern corner of the Hanna Basin (in ‘The Breaks’; see northern inset map in Fig. 5). That complexly deformed part of the basin was essentially unmapped geologically. Even as a simple paleontologist, I soon recognized that understanding the basic stratigraphy of the local Upper Cretaceous through early Eocene badlands would not be possible until development of a detailed map of The Breaks could be undertaken. That challenge led first to composition of the 2004 paper by Lillegraven, Snoke, and McKenna, with its 1:12,000-scale geologic map and cross section (fig. 4).

Field-based and laboratory research toward that 2004 paper brought many new geological questions to the fore. Primary among them was the structural nature and timing of the Laramide processes of subdivision of the originally contiguous, eastern greater Green River Basin (sensu Lillegraven et al., 2004, fig. 19) into the present Hanna, Carbon, Pass Creek, Laramie, and Shirley basins. The subsequent dozen years following submission of that manuscript were dedicated to detailed field-mapping and construction of the present synthesis. This study, along with the 1988 doctoral dissertation by George B. LeFebre (who first introduced me to field aspects of the Hanna Basin), are the only projects that have undertaken comprehensive geological approaches to understanding the structural development of major geographic components of this basinal complex.

The present work has been based almost entirely upon surface observations. That limitation was largely due to the prodigious thicknesses of the Upper Cretaceous through early Eocene sedimentary units of the Hanna Basin (Fig. 2) along with the paucity of generally available seismic data and information from deep wells. Strong emphasis has been placed on study of the margins of the eastern half of the Hanna Basin plus Carbon Basin along interfaces with adjacent uplifts.

Fieldwork for this project emphasized thoroughness of outcrop-to-outcrop tracing of contiguous or clearly correlative strata, along with gaining densely arrayed measurements of stratigraphic orientations at over 8,000 sites. Most measurements have been geographically pinpointed using satellite positioning technology (Appendices 1 and 2). All 1:24,000- and 1:100,000-scale map and cross-sectional graphics (Figs. 4–11) have been strictly constrained by the new, independently verifiable locality and rock-attitudinal information. The great majority of faults shown on the maps, cross sections, and stratigraphic columns have come from new observations, and are unique to this paper. All geologic mapping, except where specified otherwise, was conducted independently from earlier studies, and all cross-sectional graphics are drafted without vertical exaggeration. In most cases, the present Discussion section is dependent for full understanding upon descriptive and specific interpretive information given in preceding parts of this paper.
Some Generalized Observations

When one hikes the landscape of most parts of the Hanna/Carbon Basin, an observer usually sees placidly rolling hills, a seemingly endless sea of sagebrush, and only limited outcrops of resistant rocks. Across many parts of that landscape an interested geologist must actively search for outcrops within occluding vegetation. Active pursuit of those generally cryptic exposures, however, eventually will lead toward recognition that the Laramide tectonic history of this small area is as complex and rich with geological information as any other Rocky Mountain basin might have to offer (see Fig. 7). And, with few exceptions, local landowners have generously proven themselves welcoming to field-based research.

The detailed, outcrop-by-outcrop pursuit of correlative strata combined with the recording of densely spaced bedding-plane orientations has allowed recognition of many previously unrecognized structural features. Indeed, nearly all of the fault-lines mapped within margins of the Hanna and Carbon basins in Figures 4–8 are new to this study. Essentially all of those linear features are thrust faults, including many of the traces indicated by Dobbin et al. (1929) as normal faults. Most of the faults are of the bedding-parallel, ‘out-of-the-basin’ or ‘out-of-the-syncline’ variety, although a minority is cut transversely across bedding planes (e.g., just south of Calvin Bend in the east-central part of Fig. 5). Even though they may appear at first glance in map view to be normal faults, they are indeed of contractional, reverse-fault nature.

Throughout the process of mapping these thrust faults, it has remained obviously true that much of their relative motion was parallel to bedding planes, commonly following a relatively incompetent stratum such as a coal bed or a relatively soft layer of shale. Many of the faults, however, do clearly exhibit separations that deviate from a particular bedding plane to cut through surrounding strata. To my initial surprise, the more commonly observed pattern in out-of-the-basin thrust faults in this study (and probably elsewhere in Rocky Mountain basins) is for the fault plane to have cut down-section in the direction of transport.

Indeed, ‘rabbit ear structures’ (sensu Mount et al., 2011, fig. 7) resulting from synclinal crowding represent the exception within synclines of the Hanna Basin, not the rule. In rabbit-ear features, the hanging-wall strata are expected to exhibit steeper dips (over the fault’s ramp) than the footwall strata. However, if the plane of the fault were instead to cut down-section within a progressively crowding syncline (thus allowing the hanging wall to escape upward and outward from the fold hinge line), the hanging wall would be expected to show a lesser dip than the footwall in vicinity of the fold ramp. That is precisely the most common situation observed within monoclinal- or synclinal-style situations of stratigraphic crowding throughout vicinity of the Hanna Basin.

A critically important result of that generally unexpected stratigraphic downcutting is placement of younger strata onto older strata (not older onto younger, as seen in other varieties of dominant reverse faulting; e.g., Butler, 1982; and Royse, 1993). Many examples of younger-on-older, out-of-the-basin faulting can be observed in Figures 4–6. A key result of younger-on-older, out-of-the-basin thrusting is significant stratigraphic thinning as the margin of a basin is approached by a reverse fault that cuts down-section in the direction of transport. Recognition of that concept led to development of the dual presentation of stratigraphic columns as seen in Figure 8. The lower tier of columnar representations attempts to estimate the amount of loss of original thickness of the section through tectonism along eroded basin margins. Recognition of the actual cause of thinning is essential when attempting to interpret local geologic history. In many earlier cases, what is described here as the result of tectonic processes was originally interpreted as representing an angular depositional unconformity set upon an ancient surface of erosion.

Disparate stratigraphic situations in Figure 8 show that in some cases the tectonic loss of section along basin margins can be great (e.g., Fig. 8, columns D–L, J–K, etc.) and in other cases it is essentially nonexistent (e.g., Fig. 8, columns F–G, H–I, etc.). Recognition of the structural loss’s general magnitude (or the very absence of loss) can dramatically affect interpretation of a basin’s fundamental history. For example, notice the ‘Qualification on thickness of Ferris Formation’ appended to the bottom of Figure 2’s caption (and repeated in captions to Figs. 7–9).

The qualification on Figure 2 emphasizes the relatively unfaulted nature of cross-sectional leg F–G (shown in Figs. 6 and 7 and as a column on Fig. 8). Uniquely concluded is original thickness of the Ferris Formation in the Hanna Basin to have been nearly five kilometers—rather than the roughly 2.5 kilometers cited as ‘typical’ in Figure 2. Cross section F–G was developed in late stages of this research, and recognition of its significance helps clarify the error of concluding (as did: Lillegraven et al., 2004, fig. 19; Knight, 1951, fig. 1; and many other workers) that the principal axis of basin subsidence and Cretaceous–Paleogene deposition in the Hanna Basin bordered what is now its northern margin.

It is now clearly the case that the Hanna Basin’s principal depositional axis was much broader, involving a more southerly swath that in today’s coordinates contained the latitudes between 41° 45’ N and 41° 53’ N (of Fig. 6 and northward from it). In other words, a roughly north–south stratigraphic cross section of the Hanna Basin representing early Eocene time should be shown as significantly more symmetrical than traditionally considered. Although not drafted, a stage earlier than cross section ‘A’ in Figure 9 would have reflected broad symmetry through both Laramide and pre-Laramide components of the stratigraphic section. As Figure 9’s cross section ‘A’ presently is drawn, the thickness of the Ferris Formation southwest of station ‘2’ is
about 1.5 kilometers too thin. Except in the areas of cross section F–G and its very similar complement on the opposite flank of the Ferris Formation within Figures 4–6 experienced structural thinning that led to a maximum preserved stratigraphic thickness of about 2.5 km.

Related to the above discussion, it remains an important task to closely document the nature of local contacts between the base of the classic Hanna Formation and top of the Ferris Formation (or older rock units) along certain stretches of the central Hanna Basin. As examples, the western edge of the Hanna–Ferris contact remains unstudied (except as a map line provided by Dobbin et al., 1929, pl. 27) along the following course: (1) from the W½ of sec. 23, T. 24 N., R. 83 W. (on Fig. 4); southward to the (2) presumed 'type' base of Hanna Formation near the western edge of sec. 28, T. 23 N., R. 83 W. (outside the southwestern boundary of Fig. 4); and then to southeast at the (3) NW ¼ of sec. 31, T. 22 N., R. 81 W. (on Fig. 6). Investigating the depositional versus tectonic nature of the Hanna–Ferris formational contact along that transect will require corporate permissions for access, heretofore not granted to me.

Elsewhere across almost all of Figures 4–6, however, the classic Hanna-upon-older-strata contact of the Hanna Basin appears to have been tectonic (via out-of-the-basin thrusting), not depositional. There are but two exceptions to that generalization. Both are restricted to the northeastern margins of the Hanna Basin at: (1) the Hanna–Ferris formational contact in Figure 4 from the southern border of sec. 13, to across the southeastern corner of sec. 14, and into the NE ¼ of sec. 23 in T. 24 N., R. 83 W.; and (2) in Figure 5 from the eastern part of sec. 32, into the southwestern edge of sec. 33 in T. 24 N., R. 80 W., across the NW–SE diagonal of sec. 4, and into the southwestern corner of sec. 3 in T. 23 N., R. 80 W.

Within that second exception, the Hanna Formation's depositional base follows an ancient erosional surface that cuts upward through the column with stratigraphic predictability from NW to SE across the Steele Shale, sequentially through each local formation of the Mesaverde Group, and into the Lewis Shale. Elsewhere across Figures 4–6, out-of-the-basin thrust faulting has taken the base of the classic Hanna Formation down-section from the Ferris Formation to stratigraphically as low as the Frontier Formation (near east-central edge of Fig. 4). These various tectonic relationships between the Hanna Formation and older rock units (i.e., from Ferris Fm. down into Frontier Fm.) may represent, at least in part, the ostensible 'unconformity' claimed by Bowen (1918).

**An Initially Unexpected Pair of Allochthons**

**Introduction**

Among the many surprises encountered through this project was the recognition of two moderate-sized allochthonous, long-runout landslides (i.e., ‘klippen,’ pl.; ‘klippe,’ sing., “An erosional remnant of a thrust sheet that is completely surrounded by exposure of the footwall,” Neuendorf et al., 2005, p. 353). I have named the more easterly allochthon the ‘Carbon Basin Klippe’ and the more westerly allochthon the ‘Dana Klippe.’

**Carbon Basin Klippe**

The Carbon Basin Klippe is exclusively composed of all the strata in the Carbon Basin (directly east and southeast of the hinge line of Simpson Ridge Anticline; Fig. 5) mapped as the Hanna Formation. Based principally on lithologic evidence, its depositional origin probably was about 14 kilometers (8.7 mi) to the northeast, on what are now the southwestern flanks of Flat Top Anticline. Gravity-driven transport to its present position is assumed to have been initiated by early uplift of Flat Top Anticline. That southwestward sliding, however, post-dated complete removal by erosion (see Fig. 10, cross sections A and B) of the originally deposited mass of Hanna Formation that must have been deposited across the area now encompassed by the Carbon Basin.

The same pre-transport erosion also involved strata underlying the original Hanna Formation, including removal of almost all of the Ferris Formation, much of the Medicine Bow Formation, and in southern parts of the basin much of the Lewis Shale. That interval of deep erosion across the evolving Carbon Basin almost certainly was associated with early uplift of Simpson Ridge Anticline (Kraatz, 2002) late in the Laramide Orogeny. Markedly reduced today by erosion from its original dimensions, remnants of the Carbon Basin Klippe total about 106 km² (41 mi²) in area, with greatest thickness of about 853 m (2,800 ft). Research by Secord (1996 and 1998) on fossil mammals from the Hanna Formation of the Carbon Basin recorded only Paleocene species. Time represented ranged from possibly latest Torrejonian through very definite Tiffanian North American Land Mammal Ages. Most taxa are characteristic of the latter half of Paleocene time.

Physical evidence for the allochthonous origin and approximate place of origin of the Carbon Basin Klippe is presented above within sections dedicated to description of the eastern map (Fig. 5). Discussion of Figure 10 (focused on evolution of a basic west–east interbasinal transect) includes a hypothetical, stepwise scenario covering the late Laramide origin of Simpson Ridge Anticline, the resulting separations of the Carbon Basin from the Hanna Basin and from the southwestern flank of Flat Top Anticline, and the inauguration of southwestern transport of the klippe.

**Dana Klippe**

The more westerly allochthon, which I here refer to as the Dana Klippe, presents a more complex lithologic picture than the Carbon Basin Klippe (see ‘Basic Lithologic
Generalizations of Dana Klippe,' above). Its principal bulk is composed of: (1) braided-stream deposits of coarse- to very-coarse-grained, angular sandstone with diverse granitic and metamorphic pebble and cobble conglomeratic layers and scattered small boulders of Medicine Peak Quartzite; overlain by (2) poorly sorted, fluvial quartz sandstone layers. Both are characteristic of deposits of the Hanna Formation observable today along northern flanks of the Medicine Bow Mountains. Overlying those units, however, and distributionally restricted to near the Hanna Syncline’s hinge line, are weakly indurated, finer-grained mudstones to quartz sandstones with scattered ash beds and what appears to be quite pure volcanic ash. Horizontal burrows and vertical root casts are common. This uppermost (and highly restricted) unit is unlike any outcrop of the Hanna Formation in the Hanna Basin. Such is commonly seen, however, within the Brown’s Park Formation of the Saratoga Basin only a few miles to the southwest.

Certainly my decision to tentatively combine all three of the above rock types comprising the Dana Klippe as ‘Hanna Formation of Dana Klippe’ (T–B; Figs. 2, 6–9, and 11) is unsatisfactory in several respects. That decision, however, simply reflects current admission of having inadequate petrographic and geochronologic information about the situation. My predictions are that eventually the bulk of the klippe will be shown to represent Paleocene time, and the geographically restricted capping unit (having interspersed palynomorphic assemblages) is likely to prove to be of latest Eocene, Oligocene, or early Miocene age. Whether the younger strata represent deposition prior to emplacement of the klippe or after its transport remains quite unknown. Palynomorphic sampling of the occasional carbonaceous mudstones in basal parts of the klippe would be a likely means to establishing an older limit to its depositional age.

In any case, lithologies forming the bulk of the Dana Klippe are unlike any other outcrops seen in the Hanna Basin proper. They are, however, totally compatible with lithologic compositions mapped as Hanna Formation along the northern Medicine Bow Mountains and in parts of the Pass Creek Basin (Fig. 11, lower-right inset map). Thus there is little doubt that original deposition of most of the klippe took place farther to the south. It is probable as well that the strata were originally deposited above the landscape now occupied by Elk Mountain and possibly northern edges of Tertiary Phanerozoic strata associated with elevation of southwestern parts of Bloody Lake Anticline, the Elk Mountain block, and general areas of the Pass Creek Basin plus Medicine Bow Mountains.

Should Allochthonous Masses be Unexpected Locally?
Admittedly, recognition of the above pair of allochthonous masses for what they are did come as surprises to me. Perhaps, however, that should not have been the case. Indeed, long-runout, older-onto-younger slide masses that moved along shallow glideplanes are common features outboard from the northeastern, northern, and western flanks of the Medicine Bow Mountains as well as along the adjacent Never Summer Mountains and nearby western Middle Park of north-central Colorado. Although most of the local examples are smaller than the Carbon Basin and Dana Klippen, one underlying the Never Summer Mountains (directly south of the western Medicine Bow Mtns.) in northern Colorado dwarfs both. The variety and placement of described local klippen are listed as follows.

Three probable examples of gravity sliding (King, 1964, pl. 1) along the northeastern margin of the Medicine Bow Mountains include Precambrian basement-rock masses emplaced atop Tertiary strata (sec. 1, T. 17 N., R. 78 W.; secs. 22, 26–27, and 34–35, T. 18 N., R. 78 W.; and sec. 30, T. 19 N., R. 78 W.). Blackstone (1976, pl. 1) reported a nearby, fourth example of brecciated allochthonous Precambrian rocks atop Tertiary strata in sec. 24, T. 19 N., R. 79 W. The Carbon Basin Klippe and Dana Klippe, respectively, dominate the Carbon Basin and southern Hanna Basin, both north of the Medicine Bow Mountains. Ashley (1948, p. 63–65) emphasized existence of slide-based topography involving the Hanna Formation along slopes of Kennaday Peak bordering the northern Medicine Bow Mountains and adjacent Pass Creek Basin.

Montagne (1991, pl. 1, cross section H–H’) shows the small ‘Sugarloaf Klippe’ of Precambrian rocks atop pre-Tertiary Phanerozoic strata in sec. 1 of T. 11 N., R. 81 W. in the southwesternmost Saratoga Basin, just south of the Wyoming–Colorado border. In the western part of Middle Park Basin (south of the Rabbit Ears Mountains and west of the Williams Range Thrust) is a prominent landmark called Wofford Mountain (see Tweto, 1957, pl. 1; in secs. 19–20, T. 2 N., R. 80 W.). It represents a klippe of Proterozoic gneiss that slid atop either Upper Cretaceous marine Pierre Shale or nonmarine Tertiary conglomerates of the Troublesome Formation (see discussion of uncertainties in Cole et al., 2010, p. 73 and figs. 3 and 4).

Finally, accepting the model established by Corbett (1966, fig. 9B–D) and followed by Cole et al. (2010, figs.
3 and 4), the Never Summer Thrust carried Proterozoic basement and younger volcanic rocks westward to rest atop Pierre Shale. The klippe is bounded on the east (just west of headwaters of the Colorado River) by the north–south elongated Never Summer Stock (see Corbett, 1966, fig. 9D). Gorton (1953, p. 93 and pl. 3) suggested that the Never Summer allochthon extends north–south roughly 30 miles (ca. 48 km) from just south of the Middle Fork of the Michigan River to southeast of the town of Granby, Colorado (i.e., 40° 29’ – 40° 05’ N lat.). Thus this mountain-range-bearing slide feature is much larger than either the Carbon Basin or Dana klippen.

Putting these Allochthons into Areal Perspective

Although any of the above-listed long-runout, shallow glide-plane, gravity slides are impressive when personally viewed in their natural field settings, none is a record-setter in terms of land areas affected. By comparison, erosional remnants of the early Miocene Markagunt Megabreccia on the Markagunt Plateau of southwestern Utah (Biek, 2013) cover approximately 300 square miles (777 km2); estimates of its original (pre-erosional) area are closer to 500 mi2 (1,295 km2). “It is by far the largest of a dozen or so gravity slides known in Utah” (Biek, 2013, p. 1). Even the eroded remnants of this example from Utah occupy about 3.5 times the area of the combined Carbon Basin plus Dana klippen.

In turn dwarfing the Markagunt Megabreccia is the late Early-Eocene Heart Mountain and South Fork gravity slide complex of northwestern Wyoming’s Absaroka Volcanic Field and western Bighorn Basin (Beutner and Hauge, 2009). Hauge (1993) estimated an area of about 1,300 square miles (ca. 3,366 km2) for the distribution of this enormous gravity slide. It is also impressive vertically, with even distal elements such as on Heart Mountain itself (Hauge, 1993, p. 530, frontispiece) approaching 1,000 feet (ca. 305 m) in thickness.

Age Relationships of Laramide Deformation

Introduction and Generalized Observations

This paper’s introductory ‘Focus of Present Work’ specified that a primary intention of the research was to develop estimates of the oldest reasonable ages of folding, faulting, and erosion related to Laramide orogenesis leading to development of the local landscape. As of this writing, only the rhyolitic ash-flow deposits found at Chalk Bluff of the Hanna Basin’s northern margin (and related patches of volcaniclastic deposits along the southern flanks of the Shirley Mountains) have provided lithologies suitable for radiometric dating (Lillegraven et al., in preparation). Thus, research in the eastern half of the Hanna Basin and Carbon Basin has depended upon relative forms of dating based on observations of litho- and biostratigraphic relationships. Where the local fossil record is temporally diagnostic, it has served as the principal means of correlation to more distant sites that, in turn, have contributed quantitative benefits through appropriate use of isotope-based geochronometric methods.

Most of the preceding text in this paper has been dedicated to descriptive aspects of tectonic and lithostratigraphic relationships. The main sources of information have been developed as: (1) three geologic maps (Figs. 4–6); (2) 26 interpretive cross sections (Fig. 7); (3) paired arrays of pre- and post-tectonic stratigraphic columns (Fig. 8); and (4) three step-wise cross-sectional evolutionary models (Figs. 9–11) representing especially illustrative areas within, and surrounding, eastern parts of the Hanna Basin and the Carbon Basin. Each of those graphical elements is constrained by independently verifiable field measurements that were secured for development of publications involved in this project.

In the following subsections, I have ordered each cross section from Figure 7 into one of seven ‘groups.’ These groups, as well as the cross sections within each group, are listed in the sequence in which they would be encountered through a clockwise tour around the mapped basin margins of Figures 4–6 (or the combined version, Fig. 12). Some generalized observations on relative timing of deformation/erosion are presented in the current section. Brief mention of more specific information characteristic of each of the individual groups follows, below.

Notice on the geologic maps and cross sections that individual antiformal and synformal folds exist as coherent stratigraphic packages, variously encompassing early Paleozoic strata through early Eocene elements (i.e., uppermost levels) of the Hanna Formation. Virtually all rock units within those folds are shot through with intra- and inter-formational, out-of-the-basin (or -syncline), mostly younger-on-older thrust faults. Those thrusts are of varying magnitude and were developed as adjustments to the process of Laramide folding and general basinal contraction (with the latter principally controlled via basinment-involved, much greater thrust faults). Disregarding allochthons within this project’s study area, only the northeastern border of the Hanna Basin (vicinity of ‘The Breaks,’ described by Lillegraven et al., 2004, figs. 4, 6–8, 11, 14, 16–18) exhibits unequivocal evidence of a consequential erosional unconformity followed by deposition of Upper Cretaceous or lower Tertiary strata (see Lillegraven et al., 2004, figs. 14 and 16B).

Summary information presented in the preceding paragraph is central to certain major conclusions emanating from this project. First, persistent subsidence of the greater Hanna Basin area occurred throughout most of Late Cretaceous time, all of the Paleocene, and earliest Eocene. That subsidence led to the hugely thick accumulation of marine and fluviatile strata (Fig. 2) constituting the Mowry Shale upward through the Hanna Formation. Secondly,
the unexpectedly great stratigraphic thicknesses revealed by the Ferris Formation preserved in the Hanna Syncline (Figs. 6 and 7) show that the developing Hanna Basin would have been much more symmetrically configured across its north-south axis than previously realized. But the profound deformation of the originally intact stratigraphic pile within the Hanna Basin was largely restricted to very late in the Laramide Orogeny (i.e., early Eocene and perhaps even later).

Specifically, deformation became most important late in the Wasatchian North American Land Mammal Age and latter half of the international (European) Ypresian age (i.e., late early Eocene, ca. 50 Ma). How long the active deformation persisted into the latter half of Eocene time remains quite unknown because of the deep and universally expressed erosional surface that has been scoured into the entire basin’s modern surface. Similarly, it remains unknown just when either of the two klippen described here became emplaced. The surfaces of both the Carbon Basin Klippe and Dana Klippe (Figs. 5–7), however, do reflect the folds within underlying strata.

As seen both in map- and cross-sectional views (Figs. 4–7), with rare exceptions specified below, most Laramide strata (i.e., Mowry Sh. upward at least into lower parts of the Ferris Fm.) exhibit generally conformable formational contacts and remarkably stable gross thicknesses (Fig. 8) across the area covered by this project. A consistent exception is the Hanna–Ferris ‘formational’ contact, which almost universally appears to be represented by one or more significant out-of-the-basin (or -syncline) thrust faults. Field evidence clearly shows, however, that the traced Hanna–Ferris ‘formational’ contact, which at the ‘type’ area (hinted at by Dobbin et al., 1929, pl. 27), stratigraphically equivalent horizons could be followed (as done by Clemens and Lillegreven, 1929, pl. 27), stratigraphically equivalent horizons could be followed.

As emphasized earlier (in section within ‘Southern Map’—‘General Features’ entitled Boundaries Between Ferris and Hanna Formations), it has existed, until now, no satisfactory lithologic field-distinction by which the Hanna and underlying Ferris formations can be reliably distinguished. When working close enough to the mapped boundary seen at the ‘type’ area (hinted at by Dobbin et al., 1929, pl. 27), stratigraphically equivalent horizons could be followed (as done by Clemens and Lillegreven, 2013, p. 162–163). In more remote areas of the basin, however, it was usually the recognizability of a structural discontinuity that I used during field mapping to distinguish the ‘Hanna’ from the ‘Ferris’ formations. I recognize and openly admit that convention to have been a singularly unsatisfactory mapping procedure; definitions of ‘formations’ are intended to be based on lithologic criteria. However, it was principally through historical tradition and the great thickness of strata involved that I chose to maintain a nomenclatorial distinction between ‘Hanna’ and ‘Ferris.’ Nevertheless, I opine once again that inception of the distinction in names by Bowen (1918) represents a procedural mistake that, in the actual practice of map-making, has led to endless frustration. Certainly it has introduced an illusion of significantly greater understanding of stratigraphic relationships than is actually warranted.

Cross Sections, Group 1 — South of Shirley Mountains

   Group 1 is covered here within Figures 4 and 7–8 and in figures 4–7 by Clemens and Lillegreven (2013):
   L′–M′ — Southern edge of Shirley Mountains valley of Austin Creek;
   R′–S′ — Southern hinge of Shirley Mountains Anticline to breaks southeast of Charley Brooks Draw;
   N′–O′ — Valley of Austin Creek southeast to north of Medicine Bow River;
   J′–K′ — Eastern dip slope near southeastern corner of Shirley Mountains Anticline; and
   T′–U′ — Loco Road south of Chalk Bluff to southeastern corner of Shirley Mountains at hinge line of Smith Creek Anticline.

Cross section L′–M′ is supported by scanty actual data due to minimal outcrops, so formational thicknesses shown are largely hypothetical. Nevertheless, that section is of interest because all Phanerozoic components are overturned through influences of many kilometers of basement uplift along the Shirley Thrust (see Clemens and Lillegreven, 2013, figs. 6 and 7) having relative tectonic transport to the south.

Cross section J′–K′ represents the best-exposed Paleozoic/Mesozoic outcrops of the Hanna Basin, and also helps in visualizing the ultra-thin, almost veneer-like pre-Laramide section as compared to thicknesses of the local Upper Cretaceous and Paleogene strata. Cross sections R′–S′, N′–O′, and T′–U′ are important in illustrating steep to overturned dips of the Laramide section and the degree to which original (i.e., depositional) thicknesses of the Ferris Formation, especially, have been reduced via down-section thrust overriding by the Hanna Formation. The general steep dips of the entire section (including most of the Hanna Fm.) reinforces the concept that local deformation became most important well into Eocene time.

Cross Sections, Group 2 — South of Bald Mountain of Southwestern-most Freezout Hills

   This ‘group,’ containing only one cross section, is covered within Figures 4 and 7–8:
   H′–I′ — Southwest flank of Bald Mountain to northern Medicine Bow Breaks.

   Although outcrops along transect H′–I′ are few and far between, implications of this paraxial, longitudinal cross section along the southern length of the Bald Mountain Anticline are fascinating. Note that dips of the Upper Cretaceous Steele Shale through Medicine Bow Formation progressively increase to overturned southward, thus becoming a synformal anticline where the thrust fault having relative tectonic transport to the north has brought
the Hanna Formation atop the Medicine Bow. This relationship also suggests continuation of possible earlier uplift involving late-Laramide structural development of Bald Mountain Anticline itself.

**Cross Sections, Group 3 — ‘The Breaks’ and Northeastern Corner of Hanna Basin**

Group 3 is covered here within Figures 5 and 7–9 (note that present cross section P′–Q′ was published at a different scale as cross section A–A′ in fig. 4C by Lillegraven et al., 2004):

- **P′–Q′** — Northeastern Hanna Basin onto southwesternmost Freezeout Mountain Anticline; and
- **D′–E′** — South Pine Draw W of defining syncline of NE Hanna Basin to E of Allen Lake–Leo Road.

Cross section P′–Q′ (= section A–A′ in fig. 4C of Lillegraven et al., 2004) reflects a complex evolutionary history. In large part because of that complexity, this cross section has provided much information to the timing of deformation (and Laramide erosion) of the northeastern margin of the Hanna Basin. That was especially the case as affected by uplift and erosion of southern anticlinal flanks of the Freezeout Hills (most specifically, see Lillegraven et al., 2004, figs. 4C, 14, 16–18). The interpretation by Lillegraven et al. (2004) clearly suggested early-Eocene origin, uplift, and erosion of the southern Freezeout Mountain Anticline, essentially in synchrony with the youngest-preserved deposition of the adjacent Hanna Formation.

Cross section D′–E′ focuses on transition between the northeastern corner of the Hanna Basin and western strata of Flat Top Anticline. The Hanna Basin’s northeasternmost extent is sharply bounded by relative tectonic transport to the east–northeast by the Dragonfly Thrust fault (of Lillegraven et al., 2004, fig. 4B). Several younger-on-older (i.e., characterized by faults that cut down-section), out-of-the-basin thrusts converge on the Dragonfly Thrust, with Hanna Formation having overridden the Ferris Formation at that boundary. Chronology of that faulting could have been no older than the early Eocene. Cross section D′–E′ also helps greatly in appreciating the prodigious thickness of the Upper Cretaceous section that constitutes Flat Top Anticline directly east of the Hanna Basin. Basement-involved uplift of Flat Top Anticline, in conjunction with virtually synchronous development of Simpson Ridge Anticline, occurred late in depositional history of the local Hanna Formation, and those two events led to the currently defined eastern margins of the Hanna and (as considered below) Carbon basins.

Those conclusions stand in marked contrast to the interpretation favored by Ryan (1977, p. 1), in which: “The Saddleback Hills anticline, separating the two basins [i.e., Hanna and Carbon], apparently was active during deposition of the Ferris and Hanna, forming a nearly complete sedimentation barrier between the two basins.”

**Cross Sections, Group 4 — Extending Eastward from Carbon Basin**

This group is covered within Figures 5, 7–8, and 10:

- **B′–C′** — Opposing flanks of Simpson Ridge Anticline from W of No. 5 Ridge to N of U.S. Hwy. 30 / 287;
- **R–S** — Southern Carbon Basin north of Second Sand Creek to eastern Calvin Bend;
- **Q–X** — Southwest corner of Carbon Basin Klippe to Spade Flats north of Halfway Hill;
- **O–Y** — South-central Carbon Basin to east of Halfway Hill;
- **T–U** — Thundermonster Hill to Carbon County Road 3 at Second Sand Creek; and
- **V–W** — Northeast transect across Halfway Hill from NW flank of Big Medicine Bow Anticline.

According to the section above (dealing with final subsection of ‘Eastern Map’) entitled ‘Definition of Limits of Carbon Basin,’ all cross sections in this group except T–U traverse from the Carbon Basin onto strata of Flat Top Anticline. Cross section T–U uniquely projects from the Carbon Basin onto the western base of Big Medicine Bow Anticline. Additionally, all six cross sections in this group are located south of Simpson Ridge Anticline. Cross section B′–C′ (Fig. 5), however, is unique in existing both to the south and to the north of Simpson Ridge Anticline’s hinge line. That apparent conundrum exists because the section’s transect is drawn at right angles across the faulted syncline that bisects Simpson Ridge Anticline into western and eastern components. Importantly, that faulted syncline expresses an apparent component of right-lateral, strike-slip separation across secs. 2 and 11–13 of T. 22 N., R. 80 W.

Cross section B′–C′ is north of the eroded edge of the the Carbon Basin Klippe. Along cross sections R–S and V–W, northern parts of the main body of the klippe rest upon eroded surfaces of the Ferris Formation. Across more southerly and southwesterly parts of the main body of the klippe, however, cross sections Q–X, O–Y, and T–U of Figure 7 are interpreted as resting entirely upon Laramide-eroded strata of the Medicine Bow Formation (publicly available information from test drilling is restricted to shallow edges of the plate). Mammalian fossils documented by Secord (1996, 1998) from strata of northern parts of the Carbon Basin Klippe have revealed only Paleocene species (possibly latest Torrejonian plus definite Tiffanian taxa; Lofgren et al., 2004, fig. 3.2 and table 3.1). Thus transport of the klippe to its present location would have occurred no earlier than late in the Paleocene.

Related to information summarized in the preceding paragraph, another important observation is that strata comprising northeastern extremes of the ‘Carbon Basin Klippe’ itself (as seen along a narrow band that overlaps both ends of the hinge line of Halfway Hill Syncline; Fig. 5 and cross sections O–Y and V–W in Fig. 7) rest on...
the extreme southwestern flanks of Flat Top Anticline. Also, the klippe itself along that narrow band structurally reflects the underlying syncline, which is the arbitrarily defined boundary between the southwestern flanks of Flat Top Anticline and the Carbon Basin. Therefore, structural relationships seen along that boundary show that Flat Top Anticline was still in the process of forming at a time no older than the latest Paleocene — and very possibly, the folding occurred well into Eocene time. The lengthy extension of the Big Medicine Bow Anticline’s hinge line to the northwest (Fig. 5), as reflected by the broadly continuous folds of the Medicine Bow Formation and Lewis Shale (in cross sections R–S, Q–X, O–Y, and V–W) also is structurally compatible with late-Laramide timing.

Cross Sections, Group 5 — Southeastern Hanna Basin, Encountering or Crossing Simpson Ridge

This group is covered within Figures 5–8 and 10:
A’–Z — U.S. Hwy. 30 / 287 W of Hi Allen Spring to Simpson Ridge Anticline on N edge of Carbon Quadrangle;
J–K — Northeast of Hanna Junction to Carbon Basin Syncline;
D–L — Hanna Syncline south of Hanna Junction to Carbon ghost town;
M–O — Sand Hills northeast of Wyoming Highway 72 to south-central Carbon Basin; and
P–Q — Wyo. Hwy. 72 between Bloody Lake Anticline and Halleck Creek Syncline to SW corner of Carbon Basin Klippe.

As discussed earlier in this paper, specific elements within the axial surface trace of Simpson Ridge Anticline in Figure 7 are simplified here from the seismically controlled interpretations presented by Kraatz (2002). Four of the five cross sections in group 5 traverse the anticlinal hinge line from the Hanna Basin into western parts of the Carbon Basin; section A’–Z terminates its path within the very edge of the Carbon Basin, just beyond the anticlinal hinge line. All five cross sections show very similar stratigraphic relationships and formational thicknesses throughout the stratigraphic column. Most of the western half of Simpson Ridge Anticline (i.e., west of the ‘defining syncline of northeastern Hanna Basin’ or its southward continuation as the Halfway Hill Syncline) involves a remarkably symmetrical cross section (Fig. 7) down through its uppermost three kilometers. As seen in Figure 10D, however, the surface-to-basement measurement is much shallower in the Carbon Basin than in the Hanna Basin. That distinction reflects history of the basement-involved thrusting (having relative tectonic transport to the west) within the Simpson Ridge Anticline as combined with the prodigious amount of post-Ferris (and possibly post-Hanna), Laramide-age erosion within the Carbon Basin. That erosion surface later made it possible to receive the gravity-driven, shallow glide-path emplacement of the Carbon Basin Klippe. Original deposition of the sediments within the klippe probably occurred above the present position of Flat Top Anticline prior to its development.

There exists no evidence for erosional unconformities within the Upper Cretaceous section either on the western or eastern flanks of Simpson Ridge Anticline along that structure west of the Carbon Basin. The uniformity of formational thicknesses (see Fig. 10) straight across the anticlinal structure from the Hanna through the Carbon basins up into the Ferris Formation suggests that Simpson Ridge Anticline did not exist prior to Paleocene time. Although this paper records many more adjustment faults on flanks of Simpson Ridge within the Hanna, Ferris, and Medicine Bow formations than in the Lewis Shale, most probably that reflects the generally poor exposures and more limited sandstone layers characteristic of the Lewis.

Cross Sections, Group 6 — Southern Hanna Basin
Southward, Mostly East of Hanna Syncline’s Hinge Line

This group is covered within Figures 5–11:
M–N — Sand Hills northeast of Wyoming Highway 72 to Bloody Lake Anticline northeast of Interstate Highway 80;
C–E — U.S. Highway 30 / 287 east of Hanna Junction to south of Percy Creek;
F–G — Northeastern Dana Klippe to Quealy Gap at Interstate Highway 80;
H–I — Eastern margin of Dana Klippe to crest of Halleck Ridge; and
F’–G’ — Crest of Halleck Ridge to northern part of Pass Creek Basin.

In reality, Simpson Ridge and Bloody Lake Anticlines represent closely parallel but longitudinally offset, en echelon, anticlinal twins. Map orientations of their hinge lines (Fig. 12) are parallel to the northeast. Also, both anticlinal hinges are mostly horizontal, with each developing marked plunges as their northern surface expressions are approached. Southerly components of both anticlines are breached by erosion down into the Steele Shale. Four of the five cross sections in group 6 originate within the southern Hanna Basin and either encounter northern/northwestern flanks of Bloody Lake Anticline or actually cross its hinge line and extend even beyond Elk Mountain into northern parts of the Pass Creek Basin (also see Fig. 11). Cross section C–E uniquely is mostly restricted to southeastern flanks of the Hanna Syncline.

A striking feature of all the cross sections in group 6 is the consistently steep (to locally overturned) dips characteristic of strata in the southeastern Hanna Basin and northwestern flanks of Bloody Lake Anticline (which can be thought of as being disguised under the name of ‘Halleck Ridge’). Those steep dips continue stratigraphically upward, right through the Ferris into the Hanna Formation, almost to the hinge.
line of the Hanna Syncline. The Hanna Syncline of the southern Hanna Basin is a truly dramatic feature. Although improved paleontological control on ages of the Ferris and Hanna formational components of the syncline should be a high priority for any further research, this impressive stratigraphic sequence could have not undergone its intense deformation any earlier than the latest Paleocene or early Eocene. Even though penetrated by many out-of-the-basin thrust faults, the stratigraphic continuity with cross sections of group 6 is unequivocal and highly similar in detail.

Cross sections H–I linked to F’–G’ of Figure 7 (and Fig. 11) highlight the proposed original continuity of Paleozoic through Laramide strata between the Hanna Basin and today’s Pass Creek Basin (i.e., the restricted area between Elk Mountain and northern flanks of the Medicine Bow Mountains; Figs. 1B and 11, lower right-hand inset map). I suggest that Elk Mountain itself could not have existed prior to the early Eocene, and its basement-involved uplift was responsible not only for isolating the Pass Creek Basin but was the principal deformation that led to folding of the Hanna Syncline. Furthermore, it was not until late in this research that I came to appreciate (through establishment of cross sections F–G in group 6 and A–D of group 7) significance of the enormous thickness of the Ferris Formation in southern parts of the Hanna Basin. Rather than the Hanna Basin being asymmetrically configured with its greatest depth along the northern border, it originally had a north–south cross section with much greater symmetry (as suggested in Fig. 9A).

Another part of this hypothesis is that the Dana Klippe (composed principally of coarse-grained Hanna Formation lithologically characteristic of today’s southern Pass Creek Basin) originated atop the area now occupied by Elk Mountain (Fig. 11B). As the massif of Elk Mountain became elevated along the Elk Mountain Thrust complex, prodigious erosion (of the partially transparent strata shown in Fig. 11A) occurred atop the then-future Hanna Basin, providing an eventual platform for receipt of a thin (Fig. 6 and cross sections B–D and F–G of Fig. 7) Dana Klippe onto steeply dipping southern parts of the Hanna Syncline and adjacent areas. Shallow dips across the klippe add to the larger picture of stratigraphic relationships in suggesting very late Laramide emplacement of the slide mass.

Cross Sections, Group 7 — Southern Hanna Basin Southward, Mostly West of Hanna Syncline’s Hinge Line

This group is covered in Figures 6–9:

A–D — Middle of type Ferris Formation to hinge line of Hanna Syncline south of Hanna Junction; and
B–D — Walcott Syncline to Hanna Syncline south of Hanna Junction.

Cross section A–D is a monotonously uniform section that represents: (1) over half the total thickness of the Ferris Formation; in addition to (2) the western flank of the deeply eroded Hanna Formation as it exists in the southern Hanna Syncline. Biostratigraphically diagnostic mammalian fossils from almost anywhere along this section would be highly prized if only they could be found. The Hanna Formation in tightly folded western strata of the southern Hanna Syncline is especially strongly deformed through numerous out-of-the-syncline thrust faults.

Cross section B–D traverses important components of three topographic quadrangle maps. Because of broad cover by the Dana Klippe, however, positions of most interformational contacts in the Upper Cretaceous section along the transect, and their dips, could only be estimated from observations at nearest relevant outcrops. As discussed above, Cretaceous strata within the Coal Bank Basin on either side of the Walcott Syncline’s axial surface trace is interpreted here as an unusually large footwall syncline of the major fault(s) within the Mesaverde Group — awaiting full documentation — that led to construction of Dana (Pass Creek) Ridge. Until access is granted to allow study and detailed mapping of the fault system within Dana Ridge, all that can be said of value about cross section B–D is that the faulting predated emplacement of the Dana Klippe.

Summarized Age Relationships of Laramide Deformation

Enough relevant stratigraphic and paleontologic data are now available to allow the proposal of several important hypotheses for future verification or rejection. The gathering of relatively copious stratigraphic attitudinal data across the entire spectrum of rock exposures in and around the eastern Hanna Basin has made information on formational thicknesses much more reliable. In the subsequent text, the term ‘greater Hanna Basin’ is applied to the eastern half of the Hanna Basin sensu stricto (Fig. 1B), almost the entire Carbon Basin, northwestern flanks of the Laramie Basin, and information from prior studies of the Pass Creek Basin. Not including strata of the Hanna Formation already eroded away from eastern flanks of the Freezout Hills, that assemblage constitutes most of what I consider to have been the original, easternmost extension of the Green River Basin prior to its tectonic fragmentation (Lillegraven et al., 2004, fig. 19).

That information, in turn, has made possible much stronger constraints on: (1) the magnitude of Laramide subsidence (involving Late Cretaceous through early Eocene time) across the greater Hanna Basin; and (2) an evaluation of the probable north–south and east–west cross-sectional shapes of the basin prior to the extraordinary deformation that has led to today’s fragmented configuration. Development of step-wise configurations of specific elements of earlier basin evolution is now feasible using independently verifiable, field-based measurements as constraints.

Thorough and systematic search along the basin’s margins (and within flanks of intra-basinal fold systems) for erosional unconformities and/or faulting led to initially
surprising results. Specifically, unconformable stratigraphic relationships involving secondary deposition upon ancient erosional surfaces has been found to be uncommon — and restricted to adjacent foldbelts and mountainous massifs forming the northern and southern boundaries of the greater Hanna Basin. Thrust faults, in strong contrast, are pervasively represented within remnants of the original, unfragmented margins of the greater Hanna Basin and in intrabasinal flanks of anticlinal and synclinal structures.

Furthermore, it has been recognized for the first time that nearly all of those thrust faults are of the out-of-the-basin (or -syncline) variety, all exhibit most displacements between bedding planes, and a large proportion of the faults involved placement of younger strata of the hanging wall onto significantly older strata of the footwall. Contorting strata became deformed into steep attitudes that dip precipitously away from adjacent uplifts. Those structural relationships led to marked thinning of originally thicker stratigraphic sections along basin margins, and they allowed the posing of dramatically different geohistorical interpretations from those dominating existing literature.

Most of those thrusts as observed within the greater Hanna Basin developed individually as relatively minor structural adjustments, limited to within the accumulated stratigraphic pile (i.e., not basement-involved, but most prominently affecting Mowry Sh. continuously upward through the Hanna Fm.). The many small thrusts, however, cumulatively have defined much of the big picture of tectonic evolution observed. Nevertheless, the most dramatic deformation occurred adjacent to contractional influences of much larger and much deeper (i.e., basement-involved) thrust faults (e.g., Shirley Thrust, Flat Top Thrust, and the Simpson Ridge and Elk Mountain Thrust complexes).

Most of the greater Hanna Basin’s deformation and fragmentation appears to have occurred during a single prolonged tectonic contraction acting upon fragmentation of an original, significantly more extensive basin. One must add to that, however, the emplacement of two medium-sized klippen via quite different directions of transport. The entire interval of greatest deformation involved, and probably was mostly limited to, the earlier half of Eocene time (i.e., late in the Laramide Orogeny).

There exists sound evidence that both the Sweetwater Arch (north of the greater Hanna Basin) and the main bulk of the Medicine Bow Mountains (south of the basin) became elevated, topographically significant, broad-arched features late in Cretaceous time (Houston et al., 1968; Love, 1970; and Lillegraven and Ostresh, 1988). Laramide nonmarine strata within the basin itself first developed within the Allen Ridge and Pine Ridge formations of the Mesaverde Group, with marine conditions returning through deposition of the Almond Formation, the Lewis Shale, and most of the Medicine Bow Formation. Although there were occasional intervals of fluvial deposition exhibited in the Medicine Bow Formation, dominant nonmarine conditions of the Hanna Basin began with the Ferris Formation and persisted, as far as known, throughout deposition of the Hanna Formation. Boyd and Lillegraven (2011) reported one brief pulse of marine deposition in upper parts of the Ferris Formation, representing late early Paleocene time.

As documented throughout this paper, most Laramide contractional tectonic activity within the greater Hanna Basin seems to have been restricted to very late in the depositional history of the Hanna Formation, continuing even after completion of its deposition. Original dimensions of the greater Hanna Basin area must have been considerably greater (and especially so in north–south directions; Lillegraven et al., 2004, figs. 14–19) prior to the time of maximal contractional deformation.

Timing of uplift of the main bulk of the Shirley Mountains, Freezecout Hills, Flat Top Anticline, Big Medicine Bow Anticline, Simpson Ridge Anticline, Elk Mountain Anticline, and Dana Ridge Anticline, along with formation of the Hanna Syncline and defining syncline of northeastern Hanna Basin, all were essentially synchronous and limited to late in the Laramide Orogeny. Considerable erosion of the depositional Eocene surface took place throughout the process of deformation, followed by emplacement of the Carbon Basin Klippe and Dana Klippe. I strongly agree with the regional arguments based on limited exhumation as presented by Cather et al. (2012) that, despite the vigor of Laramide tectonism, the basic landscapes among the Rocky Mountain basins remained near sea level until late in the middle Eocene.

Steeply dipping to overturned strata are the rule almost everywhere along the northern, eastern, and southern margins of the greater Hanna Basin. The most dramatically deformed and thickest Laramide sections, however, are south of the Shirley Mountains/Freezeout Hills and north of Elk Mountain (including the Hanna Syncline, which undoubtedly has reflected effects of uplift of the massive Elk Mountain block). This seems to confirm greatest contraction of the original, depositionally horizontal basin along a north–south axis (and, more specifically, along a northeast–southwest axis).

**Nefarious Considerations of Continental Structural Relationships**

Most of the preceding parts of this paper are intended to be readily verifiable or challenged by readers following their reoccupation and direct observation of individual sites. Perhaps unavoidably, the provision and reading of those descriptions are tedious—if not outright boring. In my thinking, however, completion of that original effort most certainly was not intended to be the end in itself. To the contrary, I strongly believe that the geological story presented here leading to present fragmentation of the eastern greater
Green River Basin must have emergent values when approaching the much grander puzzle of geologic history of western North America—or perhaps even Earth’s Northern Hemisphere. Therefore, I see it as important to alert readers about some of the larger questions—and perhaps conceptual biases—that kept me awake many nights as I pursued the baby steps comprising the bulk of the present study. Thus my intention here is to modestly enhance recognition of possible significances of the study area itself. Cautious bumping against the margins of openly admitted speculation, in my opinion, is one of the secret little joys of science that emotionally make possible the long-term pursuit of unimaginably tedious fieldwork and its documentation. However, I have not included my taboo outlooks on these forbidden ramblings either in this paper’s Abstract or Conclusions sections.

As an example of my broader wondering, in addition to reminding us that “The Hanna Basin is the deepest structural basin in the Rocky Mountain region”, Kaplan and Skeen (1985, p. 219) stated (p. 220): “The position of the Hanna Basin within the large-scale structural framework of the [Rocky Mountain] foreland is unique. We propose that the Hanna Basin is a pivot point around which the structures of the Wyoming Province rotated during the Laramide Orogeny in a compressional shear system set up by the Colorado Plateau block and the North American craton.”

Considerable debate has followed in regard to the reality of Laramide counter-clockwise ‘rotation’ of structural elements within the general area of North America’s Wyoming Province/Basin. But, as implied below, I can hardly imagine how conditions could have been otherwise.

The structural (contractional and rotational) relationships referred to above by Kaplan and Skeen (1985) followed conceptual leads provided by workers such as Hamilton (1981, figs. 1 and 2) and Livaccari et al. (1981, figs. 1 and 2). All of them worked within a rapidly strengthening plate-tectonic model involving generally westward transport of the North American craton (gravitationally carried as a result of broad uplift associated with sea-floor spreading in the North Atlantic Basin) that progressively tightened the craton’s original connection with the area now known as the Colorado Plateau (see Erslev, 1993, fig. 15; Bird, 1998, fig. 5). Because that then-future plateau during the latest Cretaceous and early Tertiary was underlain by actively moving parts of the eastern Pacific Ocean’s shallowly subducting Farallon Plate (see Bird, 1998, fig. 9; Tikoff and Maxon, 2001, fig. 1), the incipient Colorado Plateau had a more northeasterly net transport direction relative to the continental cratonic mass to its north and east. Hamilton (1981, fig. 2) and Bird (1998, fig. 5) emphasized minor clockwise rotation of that plateau (linked to influences of monoclinal folding) and synchronously deforming `Laramide belt’ along a wide, leading border of the craton. Both workers visualized an Euler pole of rotation for the Colorado Plateau plus Wyoming foreland relative to interior North America to have been in what today is northern Texas.

Livaccari et al.’s (1981) team was highly specific. They suggested (p. 276) shallow “... subduction of a large oceanic plateau of anomalously thick and buoyant oceanic crust...” (again, as part of the Pacific’s Farallon Plate) beneath the Colorado Plateau and then-future Laramide foreland. Livaccari et al. (1981) proposed that contribution from the floor of the Pacific Ocean “... may represent the oceanic plateau that triggered Laramide events...” of basement-involved thrust faulting, landscape contraction, and the multiplicity of subdivisions developed during the early Paleogene within an originally enormous, latest Cretaceous Western Interior Basin (sensu Lillegraven and Ostresh, 1990).

Hamilton (1981) and Livaccari et al. (1981) agreed that total duration of the resulting Laramide orogenesis extended from late in the Cretaceous well into late Eocene time (ca. 70–80 through 40 Ma). I concur with that total duration, but I re-emphasize below that the most important deformation across the Wyoming Province (sensu Snoke, 1993) occurred late within that interval (i.e., 50 Ma, post-Wasatchian and perhaps significantly still-later in Eocene time).

It remains generally favored that Laramide orogenesis involved, in part, virtually flat ocean-plate subduction combined with general northeasterly trajectory of an overthickened and anomalously buoyant mass of the Farallon Plate beneath the then-future Laramide foreland. Liu et al. (2010, figs. 1–3), for example, proposed that an oceanic plateau (the ‘Shatsky conjugate,’ situated more northerly on the subducting Farallon Plate than the ‘Hess conjugate’ as suggested originally by Livaccari et al., 1981) came to underlie the then-future Colorado Plateau and Laramide belt (of Hamilton, 1981, fig. 2). Dickinson (2004) has provided the broadest existing summary of how elements of the Pacific Ocean’s tectonically active floor, as extended at depth to the eastern face of the Rocky Mountains, have interacted from Proterozoic through Cenozoic history.

Sigloch and Mihalynuk (2013) applied pioneering multi-frequency, seismic-tomographic imagery to what they interpreted as long-lived remnants of subducted slabs in Earth’s lower mantle (to depths of 2,000 km). Their work has led to new interpretations of sea-floor evolution as it occurred on ancient, now-totally-destroyed subduction zones that existed west of the pre-Laramide, North American craton. Even though Sigloch and Mihalynuk (2013) thereby suggested existence of a previously unknown, major chapter of ancient easternmost Pacific Basin history, they too favor the concept (see their table 1, p. 54) that a buoyant but subducting ‘Shatsky Rise Conjugate,’ strongly coupled with the Farallon Plate, matches with the “Laramide orogeny, basement uplift more than 1,000 km inland (85–55
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I reiterate that Laramide orogenesis in the eastern greater Green River Basin of the Wyoming Province became most active significantly after the Paleocene–Eocene epochal transition (i.e., well after 55 Ma).

As quoted above, Kaplan and Skeen (1985, p. 220) suggested that the Hanna Basin uniquely represents a “… pivot point around which the structures of the Wyoming Province rotated during the Laramide Orogeny …” At least physiographically, that long-recognized bend in major Rocky Mountain structures is sharply defined as seen across the landscape between the north–south-aligned hinge lines of giant Laramide structures of central Colorado (i.e., the Southern Rocky Mountains) and the Middle Rocky Mountains physiographic province (of Fenneman, 1931, p. 133–135 and fig. 49; Raisz, 1972) in northwestern Wyoming. The area of the bend itself is the interruption of continuity of the ‘Rocky Mountain System’ recognized by Fenneman (1931, p. 133) as the ‘Wyoming Basin.’

Hinge lines of the largest Laramide fold systems within the Wyoming Basin tend to be oriented with marked northwesterly (or sometimes even west–east) strikes as observed from vantage points in and around the eastern Hanna Basin (e.g., Hamilton, 1981, figs. 1 and 2; Blackstone, 1993b–d; Tikoff and Maxon, 2001, figs. 2 and 9; Bolay-Koenig and Erslev, 2003, fig. 1; Fig. 1 of present paper). For illustration, attempt to visualize a central point of counter-clockwise rotation for that bend within the eastern Hanna Basin. From that vantage point, the observed angle of westward divergence of the southern edge of the basement-involved Sweetwater (anticlinal) Arch from a north–south alignment would be almost 75° (see Raynolds, 2002, fig. 1).

For purposes of clarity in presentation, the preceding paragraph was composed in large part using the ‘physiographic province’ context introduced by Fenneman (1931; Raisz, 1972). As discussed within the important papers by Eaton (1986, 1987, 2002, and 2008), however, more recent progress in understanding the geological context and mechanics of western North American Laramide and Neogene evolution has required re-definitions and re-characterizations of the Southern and Middle Rockies — as well as the intervening Wyoming Basin, the area most-dominantly affected by Laramide-style (Taft, 1997) tectonism. Of strong relevance to local geology, it is illuminating to consider that the deepest sedimentary basin in the Rocky Mountains (i.e., the Laramide-defined Hanna Basin) today resides upon northern components of the summit of Eaton’s (2008) ‘Southern Rocky Mountain epeirogen.’ That complex structural, depositional, erosional, and thermally controlled epeirogenic feature, as characterized by Eaton (2002), is an enormous regional uplift that encompasses entire mountain ranges, intervening basins, and vast plains and comprises “… the largest coherent epeirogenic feature in the conterminous U.S.” That uplifted feature today also exhibits “… the highest mountains along the crest of the Rocky Mountain system …” (Eaton, 2008, p. 764), and it “… has the highest regional elevation on the upper surface of the entire North American plate” (Eaton, 2008, p. 773 and fig. 6A). Neogene geologic renovations, therefore, have profoundly affected all physiographic and thermal aspects of the Laramide-developed Southern Rocky Mountains and Wyoming Basin physiographic provinces.

Returning now to the Laramide Orogeny as expressed near this paper’s study area, all of us would recognize asymmetric, basement-involved, and usually thrust-faulted anticlinal/synclinal folds of various sizes directly to the east and to the north of the above-hypothesized pivot area for the Rocky Mountain chain in the eastern Hanna Basin. Directly bordering the eastern Hanna Basin, for example, there exists an en echelon series of six anticlinal folds having hinge lines that exhibit a progressively varying sequence of northeast–southwest alignments (see Blackstone, 1983, fig. 31; labelled ‘Area of northeast-trending folds’ in the present paper’s Fig. 1B). Folds with northeast–southwest hinge-line alignments are uncommon in the Wyoming Basin. Listed in geographic order from northwest to southeast, these atypically oriented anticlines are named: Freezeout Mountain, Flat Top, Como Bluff, Boswell Spring, Gillespie, and McGill anticlines.

At least two of those anticlines (Como Bluff and Gillespie) have controlling faults that can be traced eastward, cutting deeply into Precambrian basement rocks of the western Laramie Mountains. All six of the anticlines, however, are associated with faults having axial surfaces that issue from Precambrian basement, and all of them exhibit relative tectonic transport of their hanging walls to the north or northwest. Dating the time of origin for any one of these folds is problematic if studied in isolation. That is because Cenozoic erosion across their surfaces has been deep enough that the youngest remaining strata represent Late Cretaceous time. Nevertheless, the time of actual folding and associated faulting could have been (and indeed probably was) during the Paleogene. Prior to origin of these anticlines, the original Paleocene and early Eocene sedimentary cover of the not-yet-separated Hanna/Laramie Basin area would have continued northward from their presently erosionally restricted, more southerly existence to cloak the landscape above the then-future folds. Furthermore, that original Paleogene cover would have been continuous with strata of the eastern Hanna/Carbon Basin before the start of the interval of localized deep erosion east of the newly rising western moieties of Simpson Ridge Anticline. Emplacement of the Carbon Basin Klippe into its present position followed that deep erosion, late in the Laramide Orogeny.

As stunningly expressed in modern topography of the southern Freezeout Hills (partly within but mostly just external to limits of the present study area) there exist still more, sequentially placed, asymmetrical yet very tightly folded anticlinal–synclinal pairs. They form uplands and
valleys aligned almost perpendicular to northern margins of the northeastern Hanna Basin (see Lillegraven and Snoke, 1996, fig. 4). Those folds developed into their full configuration late in the Laramide Orogeny and, as followed from east to west, their hinge lines are seen to become oriented progressively more directly north–south (e.g., Bald Mountain and southern Shirley Mountains anticlines) from initially northeast–southwest orientations (e.g., Freezeout Mountain Anticline). Full development of those anticlines disrupted and underwent erosional removal of almost all previously overlying Upper Cretaceous and Paleogene strata.

Those secondarily vanished Laramide strata originally represented a significantly more extensive depositional area of the Hanna Basin to the north than exists today (Lillegraven et al., 2004, figs. 4, 6A, and 14–18). As documented above, the modern northeastern margin of the Hanna Basin is characterized by strongly up-turned to overturned, highly deformed, strongly thrust-faulted, and deeply eroded edges within what was once a considerably larger depositional basin. The originally more extensive, northern-basin deposits (although now completely eroded away north of the Shirley Fault and Lower Cretaceous strata of the Freezeout Hills; Clemens and Lillegraven, 2013, fig. 7) probably included strata at least as high in the Phanerozoic column as uppermost parts of the Hanna Formation (i.e., uppermost Paleocene and lower Eocene).

If all were plotted on a map, geometrical southern or western extensions of hinge lines from each of the above-identified fold pairs (i.e., those both along the eastern and northern margins continuing from the northeastern corner of the Hanna Basin) would be seen to be radially arranged, with visualized extensions that roughly converge into disparate parts of the eastern Hanna Basin. Stratigraphic relationships around each of those anticlinal elements also suggest progressive rectilinear transport of hanging walls to the north, northwest, or west. In each case, orientations of affected strata suggest transport roughly normal to orientation of the anticline’s hinge line. At least from a geometrical point of view, that radially convergent pattern of hinge lines lends support to Kaplan and Skeen’s (1985) proposition of a generalized pivot point within the Hanna Basin that led to extended counter-clockwise rotation.

Other surrounding but significantly more distant, major structural features also exhibit strikes commensurate with an interpretation involving rotation about a common intracontinental pivot point in or near the eastern Hanna Basin. Possible examples include the: (1) western edge of the highly asymmetrical, anticlinal Casper Arch, linked to the eastern Owl Creek Thrust complex; (2) four en echelon anticlines seen in the southern Wind River Basin emanating from the northern flank of the Sweetwater Arch; and (3) perhaps even the southern half of the Wind River Thrust (Love and Christiansen, 1985; Blackstone, 1993b; and Stone, 1993, fig. 1). The real key to testing this idea of intracontinental rotation, however, would be development of a thoroughly systematic synthesis of kinematic evidence as collected from a wide array of surrounding, consequential Laramide fault and fold structures.

Certainly I do not visualize the nature of ‘rotation’ within the Wyoming Basin as being anything akin to a vinyl record turning slowly as a unified physiographic province upon a turntable independently from the surrounding landscapes. Quite to the contrary, I view existence of a multiplicity of individual thrust faults (most of which, as formerly was the case for the Hanna/Carbon basin, have yet to be discovered and mapped), with anticlinal hinge lines rotating upon vertical axes, and with many having varying degrees of left-lateral oblique shear, broadly distributed and sometimes concentrated in banded zones, across the entire province. Any ‘rotation’ would have been incremental within any given area and variable in magnitude of relative transport from one part of the affected province to the next. My viewpoint, therefore, would be compatible with Neuendorf et al.’s (2005, p. 457) definition of an ‘orocline’:

“An orogenic belt with an imposed curvature or sharp bend, formed by rotation of fold and fault traces around a vertical axis; the trend of structures changes progressively during formation of an orocline.”

A singularly important point relevant to this discussion, however, is that contractional strain across the Wyoming Basin late in the Laramide Orogeny has resulted in prominence of northeast–southwest contraction via faulted anticlines. Furthermore, the relative tectonic transport direction across that northeast–southwest alignment was dominantly toward the southwest (again, compare summary maps by: Love and Christiansen, 1985; Blackstone, 1993b; and Stone, 1993, fig. 1). The research presented by Paylor and Yin (1993) on structural evolution of the North Owl Creek fault system would serve as a model for the suggestion being made here that left-lateral oblique shear may have been a prevalent phenomenon across the Wyoming Basin on thrust faults having consequentially eastward strikes. With these points in mind, one could logically conclude that transpressive stresses had been imposed upon the Wyoming Basin during Eocene time from the north, and especially from the northeast.

As an aside, the above-discussed, radially arranged hinge lines of the folds north of the Hanna Basin involve only the southern components of what was, in mid-Eocene time, a much larger, deeply eroded mountainous area alternatively known as the ‘Sweetwater Arch’ (or ‘Uplift’ sensu Blackstone, 1993b) or ‘Granite Mountains’ (sensu Love, 1970). The main central mass of the Sweetwater Arch (i.e., the ‘Granite Mountains’ sensu stricto) collapsed through extensional normal-faulting (along the North and South Granite Mountains fault systems), as a giant east–west elongated graben (90 mi long by 30 mi wide; 145 x 48 km), late in Cenozoic time (Love, 1970; Sales, 1983, figs. 1 and 3).
Topographically highland remnants that border today’s Sweetwater Arch, both along its northern and southern margins, are not involved in the graben. Specifically, the southern upland blocks include (as sequentially listed from east to west; Fig. 1) the Freezeout Hills, Shirley, Seminole, Ferris, and Green mountains, succeeded still farther to the west by relatively lower ridges that finally converge with strata along the southeastern flanks of the Wind River Mountains. Most of the graben’s surface today (i.e., north of the above-listed remaining highlands that border the northern Hanna Basin) is covered by Mio-Pliocene, mostly fine-grained, distantly derived volcaniclastic aeolian and reworked fluvial deposits. That comparatively soft sedimentary cover is rapidly eroding away from underlying Precambrian granitic rocks, the present surface of which represents partially exhumed, erratically dissected remnants of the early Cenozoic, rugged mountainous landscape (Love, 1970).

As principal causes of Laramide orogenesis, most members of today’s geological community accept the interactive importances of: (1) subduction and shallow northeasterly transport of over-thickened, buoyant plateaus of the Pacific Ocean’s Farallon Plate in leading to basement-rock thrusting and resulting uplifts across the Colorado Plateau and Laramide belt; combined with (2) generally westward transit of the North American craton, reflecting long-established sea-floor spreading in southern parts of the entire North Atlantic Basin. Additionally, however, much internationally conducted research has been completed on the final opening (through northwardly extended sea-floor spreading along the Mid-Atlantic Ridge) of the extreme North Atlantic Basin—through proto-Icelands and between northeastern Greenland and Scandinavia–Svalbard. Still more new knowledge has led to enhanced tectonic understanding of Eocene expansion within the Arctic Basin itself. Expansive tectonism in both of those far-northerly areas, in my viewpoint, would (virtually unavoidably) have had contractional tectonic consequences upon late Laramide evolution of the Wyoming Basin. That would be the case even though its distance from Wyoming’s midpoint is nearly as great as that to the northern Mid-Atlantic Ridge system. Quite interestingly, important elements of this thinking were proposed as early as 1983 (p. 52–53) by Chapin and Cather.

The systematically approached, global review of post-Pangean, relative tectonic-plate positions by Seton et al. (2012) provides an enormously useful resource for paleogeographic thinking and reconstructions. Informative summaries of Late Cretaceous and Paleogene evolution of the northernmost Atlantic Basin and diverse subunits of the High Arctic are presented by Seton et al. (2012) in their figures 3–5 and 25–27 in conjunction with relevant text on pages 220–225 and 258–260. Comprehensive reviews of geology and paleontology as then known from the Canadian High Arctic and Greenland also were provided in the survey by Harrison et al. (1999), within the diverse contributions edited by Mayr (2008), and most recently in the review paper by Eberle and Greenwood (2012).

Particularly helpful in grasping relevance of Paleogene structural evolution in the High Arctic to the Wyoming Basin’s history is the latest Cretaceous through Eocene synthesis provided by Harrison et al. (1999, p. 232–241 and 244–248). They define and characterize 12 geographically widespread, high-latitude depositional sequences established between earliest Paleocene and Pleistocene time. The first five sequences involved Paleocene into late early-Eocene time (encompassing ca. 65–47 Ma). Those sequences were structurally driven via influences of deep-centered, migrating thermal plumes. Although important tectonic activities certainly did continue thereafter up to the present day, the seven younger sequences related more directly to climatic controls.

The ‘Eurekan Orogeny’ (see Eberle and Greenwood, 2012, p. 7 for introduction) began during the latter half of Paleocene time and continued at least to the end of the Eocene. Its influences were widespread across the Arctic region. Driving effects of the orogeny seem to have been broad underplating of relatively shallow lithosphere by perhaps several, simultaneously emplaced magma plumes emanating from an enormous, and much deeper, mantle hotspot. Within the 65–47 Ma interval, the hotspot’s central area of apparent motion was progressively to the east. The hotspot itself remained fixed, but the superficial crustal plate had true motion to the west. The hotspot’s central area started beneath what is now West Greenland. Its effects moved progressively to East Greenland through time, and its apparent motion continued to migrate still farther eastward to exhibit influence beneath the newly formed, northernmost North Atlantic Ocean (including variously existing prototypic ‘Icelands’). Summarized by Harrison et al. (1999, p. 223):

“The eastward migration of the plume jet is matched in time by the apparently diachronous westward expansion of the Eurekan Orogen and progressive rotation of tectonic transport directions [see their fig. 9, p. 245]; from northeasterly- and northerly-directed in mid-Late Paleocene to northwesterly-directed in the latest Paleocene and Early Eocene, to westerly- and southwesterly-directed in the Middle and Late Eocene. A fundamental driving force for orogeny is considered to have been gravitational potential and spreading forces created by sublithospheric underplating and plume-induced regional uplift acting on the ancestral Greenland microplate.”

Upon firm establishment of the mid-Atlantic spreading center between northeastern Greenland and Eurasia within the early Eocene (Seton et al., 2012; Harrison et al., 1999, fig. 9B–D), an almost modern structural configuration of
the High Arctic had come into being by late Eocene time (Harrison et al., 1999, fig. 9D). That involved an almost universally southwest direction of gravity-driven, relative plate motion for all of the North American plate (including Greenland) initiated by sea-floor spreading north of proto-Iceland combined with plume-induced uplift. According to Harrison et al. (1999, p. 248), underplating by magmatic plumes emanating from the hotspot (beneath the new, northernmost Atlantic [i.e., Arctic] Basin by mid-Eocene time) provided thermal uplift that gravitationally allowed a downhill slide by much of the North American continent southwestward, leading to “. . . the creation of the Beaufort Foldbelt, and other classic Laramide thrust belts of western North America.”

Some components of the above scenario were presaged by Gries (1983), challenged by Varga (1993, p. 1117), and yet again championed by Harrison et al. (1999). The Harrison et al. (1999) scenario causally relates components of the dominantly Eocene ‘Eurekan Orogeny’ of the High Arctic to direct effects upon basement-involved tectonism characteristic of youngest elements of the ‘Laramide Orogeny’ (such as dominance of relative tectonic transport toward the southwest) as exists within the Wyoming Basin.

Miscellany on Hydrocarbons, Paleogeography, and Groundwater

Cumulative effects of the Laramide Orogeny led to essentially total renovation of geological and biological processes across all of the Rocky Mountain province and surrounding plains. All aspects of landscapes across that vast territory were functionally changed through effects of that orogenesis. It is also the case that virtually the entire range of possibilities for economic livelihoods today within the greater Hanna Basin area were constrained by events of subidence, deposition, fault-determined contraction of landscape, uplift, weathering, erosion, and impacts of the biosphere that occurred from late in the Cretaceous through much of Eocene time. For the most part, human-sustaining activities across the study area are now centered on exploitation of hydrocarbons (especially coal and petroleum reserves developed in Laramide times), livestock ranching, and tourism (including enjoyment of spectacular scenery, wildlife viewing, and hunting). Ranching and tourism are dependent upon the area’s natural water-storage capacities and the basic topographic evolution that originated during the Laramide Orogeny.

Following the engagement in specifics of the research that dominate this monograph, I now present a summary of localized studies on coal, oil/gas, and groundwater. Greatest emphasis is placed on water resources. The Laramide geological and biological evolution discussed above is principally responsible for the formation and distribution of local hydrocarbons and — ultimately most importantly — making possible the existing disposition of subterranean water resources.

Related to the astonishingly rich and diverse assemblages of Late Cretaceous and Paleocene paleofloras characteristic of Rocky Mountain and adjacent basins of the High Plains (e.g., Knowlton, 1922; Dorf, 1942; Brown, 1962; Leffingwell, 1970; Pocknall and Nichols, 1996; Johnson, 1996 and 2002; and Dunn, 2003), coal has figured importantly in the Laramide’s watery-lowland, geological development of the Hanna/Carbon basin. Occurrences of lignitic to bituminous grades of coal (Unfer, 1951, table IV; Hettinger and Brown, 1978; Hansen and Schug, 1979; Hansen et al., 1980; Ellis et al., 1999; Fort Union Coal Assessment Team, 1999) have been exploited domestically and commercially within the Hanna/Carbon basin (Berta, 1951) since 1856 and 1887, respectively. Coal-bearing sources include the local Allen Ridge, Pine Ridge, and Almond Members of the Mesaverde Group as well as the Medicine Bow Bow and, especially, Ferris and Hanna formations. Occasional low-grade stringers of coal exist even within especially shallow-marine strata of the Lewis Shale, reflecting its intertwining relationships with the lignite-rich Almond Formation at the top of the Mesaverde Group (Davis, 1966, p. 16). Many (if not most) of the thin-skinned, out-of-the-basin thrust faults reported here preferentially developed along relatively weak coal seams.

The centrality of this area’s ancient lowland-swampy-lacustrine setting, regularly interspersed with coarse-grained clastic fluvial injections from rapidly evolving, marginal uplands, naturally calls for ready access to the primary geological literature on coal. Thus disparate aspects of coal geology are distributed throughout this paper. Coal geology was central to establishment of the railroad across south-central Wyoming (see Hodge, 1871), and even today coal resources are considered by many residents to be essential to the state’s economic well-being. Glass and Jones (1974) developed an indexed ‘Bibliography of Wyoming Coal’ that is especially useful for older literature. The papers by Glass (1972) and Glass and Roberts (1979, pls. 1–4) provide useful maps, delineated by specific coal seams, of surface-mining configurations within the Hanna and Carbon basins. Schroeder and Donyk (1978) reproduce lithologic and geophysical logs specific to well holes within coal-bearing sequences of the Hanna Basin. Berg (1980) focused on mining-related subsidence.

Acting in combination, an abundance of Laramide structural traps, appropriate reservoir rocks, fine-grained seals, subsidence criteria favorable for hydrocarbon maturation, and extensive, naturally occurring fracturing to facilitate migration of hydrocarbon-bearing fluids allow recognition of a consequential future for oil and gas recovery within the Hanna Basin (Bierei, 1987, fig. 23A–B; Gries et al., 1992, fig. 9; Wilson et al., 2001; Law, 2002, table 2; Dyman and Condon, 2007; and Mount et al., 2011). Basin-
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Both the Hanna and Carbon basins. As of this writing, (e.g., Freudenthal, 1979) exist in federal reports covering water depths (e.g., Daddow, 1986) as well as water quality important, site-specific information on well records and aspects of groundwater resources have come from graduate Hanna Basin linking geological information to diverse 'dry holes.' Some of the very best research in the greater purposes. The great majority of deep wells, now finished were developed principally for domestic and agricultural basin terminate in alluvium or shallow aquifers and, even though these links most assuredly will need to do with the discovery, evaluation, utilization, and long-term maintenance of water resources. Those ties include flowing or naturally impounded surface waters, shallow alluvial and groundwater, and, much less commonly, deep aquifers. Even though these links most assuredly will need to be strengthened as time goes by, for most of the Hanna/Carbon basin area, access to these resources is limited and tenuous. Most knowledge about geological influences on groundwater in that area remains at 'reconnaissance' or 'preliminary' (e.g., Visher, 1952; Dana, 1962; Lowry et al., 1973; Richter et al., 1981; and Kuhn et al., 1983) levels of sophistication.

Most wells drilled in and near the Hanna/Carbon basin terminate in alluvium or shallow aquifers and were developed principally for domestic and agricultural purposes. The great majority of deep wells, now finished and potentially used for water extraction, originally were intended for hydrocarbon exploration that led only to watery 'dry holes.' Some of the very best research in the greater Hanna Basin linking geological information to diverse aspects of groundwater resources have come from graduate theses (e.g., Saulnier, 1968; and Johnson, 1994). Additional important, site-specific information on well records and water depths (e.g., Daddow, 1986) as well as water quality (e.g., Freudenthal, 1979) exist in federal reports covering both the Hanna and Carbon basins. As of this writing, the U.S. Geological Survey provides no online, currently gathered groundwater data from the Hanna/Carbon basin (http://groundwaterwatch.usgs.gov/ltng/StateMapLTN.asp?sc=56&a=1&d=1). Relevant Wyoming environmental regulatory agencies (e.g., Wyoming Department of Environmental Quality, 2012, p. 37–38) principally exist to validate applicable observations on water resources through reference to in-house mining-permit documents and commercial permit applications.

Although compiled at a reconnaissance level, the four-sheet comparative summary of water resources for the Laramie, Shirley, and Hanna basins provided by Lowry et al. (1973) remains highly useful. Within a formation-based, stratigraphic context, the compilation summarizes the nature of groundwater occurrences (e.g., aquifer thicknesses, basic lithology, nature of cementation, fractures, transmissivities, etc.), ranges of water quality (e.g., major cation and anion concentrations, dissolved solids, conductance, pH, etc.), and potentials for development (e.g., required depths for drilling, expected ranges of water yield, practical aspects related to surface topography and steep stratigraphic dips, etc.). As shown in the caption to Figure 2, Lowry et al. subdivided the local stratigraphic column into eight hydrographic 'units,' extending from Precambrian rocks (Unit 1) through Quaternary deposits (Unit 8).

Notice that formations listed by Lowry et al. (1973) within Units 5 and 6 represent deposition encompassing the entire duration of the Laramide Orogeny. In the Hanna Basin, the composite Laramide stratigraphic sequence as determined within the present research (Fig. 2) totals over 13 kilometers (> 8 mi) in thickness, whereas (excluding Precambrian rocks) the pre-Laramide sequence is only a little over one kilometer (ca. 0.7 mi) in thickness. The differential in thickness between Laramide (Units 5 and 6) and pre-Laramide (Units 2–4) sedimentary accumulations, therefore, markedly exceeds an order of magnitude. Nevertheless, Lowry et al. (1973, sheet 3) point out that rocks of Unit 5 “. . . are the poorest aquifers of the eight units.” That is principally because of the generally fine-grained (dominantly shale) nature of the strata, which yield by plastic deformation that “. . . may not transfer stress to the sandstone.” That is, rock fracturing allowing rapid migration of water is minor. Unit 6, in contrast, contains relatively higher proportions of sandstone, conglomerate, and coal, any of which may exhibit lesser cementation and more zones exhibiting pervasive fracturing. Thus, with exception of the Lewis Shale and marine shales of the Medicine Bow Formation, productive aquifers in Unit 6 are more commonly anticipated than in strata representing the underlying Unit 5. Major yields of water in some areas may be expected from Unit 6 because of its prodigious thicknesses of pervasively fractured, coarser-grained deposits including relatively porous sandstone.

Occurrences of groundwater associated with in situ Precambrian rocks (Unit 1 of Lowry et al., 1973) can be
expected only from near-surface, high-permeability zones that have undergone deep weathering and/or structural fracturing. Despite the relatively thin representation of pre-Laramide Phanerozoic strata (Units 2–4) within the present area of study, most of the water wells yielding at least 1,000 gallons per minute considered by Lowry et al. (1973) came from those rocks. In vicinity of the Hanna Basin specifically, deep wells drilled into the Cloverly Formation (Unit 4; considered to be a ‘Principal Aquifer’ by Richter et al., 1981, fig. II-6) have supplied most of the water for domestic use in the small communities of Elk Mountain, McFadden, and Medicine Bow. The Paleozoic through lowermost Cretaceous rocks of Units 2–4 tend to excel as aquifers because of high porosities, good permeabilities, and strong degrees of faulting and/or fractures in the sandstones combined with presence of extensive voids following diagenetic dissolution within the carbonate-rich strata. Access to these units in vicinity of the Hanna/Carbon basin, however, is greatly hindered by: (1) their outcrop pattern usually being intermittent or narrowly restricted along basin margins; (2) characteristically nearly vertical dips of favored drilling targets below most outcrops; and (3) practical realities in attempts at drilling to reach the extraordinarily great depths of water-bearing strata as they usually occur across the breadth of the basins.

Within the area of present research, the only consequential groundwater from post-Laramide Unit 7 exists within highly permeable, allochthonous sandstone deposits overlying southern parts of the Hanna Syncline (Fig. 6) between Dana (Pass Creek) Ridge to the west and Wilson Ridge to the east. Potential Quaternary aquifers remain essentially unconsidered within this paper. Sound, generalized information on individual aquifers and their structural controls can be found within the reference by Richter et al. (1981). Brief, thematic, highly generalized descriptions of many standard, surface-water and groundwater hydrologic aspects of northern Colorado and south-central Wyoming are presented by Kuhn et al. (1983).

CONCLUSIONS

Following are summarized observations, interpretations, and resulting conclusions drawn from this research. Their primary order of appearance in most cases follows the sequence of geologically described elements presented in the text of this paper. That is, the main subjects within the descriptive coverage begin near the western end of the northern geologic map (Fig. 1), progress eastward to cover all of the eastern map (Fig. 5), and finally traverse to the western edge of the southern map (Fig. 6). But individual conclusions derived from commonly expressed geological features may have been grasped following multiple experiences at many different sites within the mapped area. Therefore, one should not expect lock-step consistency in sequential arrangement of these conclusions. Generalizations derived from analysis of many and scattered sources of information do not lend themselves to rigid orderliness in presentation. Also, many of the individually numbered items below actually represent multiple, conceptually related conclusions.

1. Persistent subsidence of the greater Hanna Basin area (Fig. 1) occurred throughout most of Late Cretaceous time, all of the Paleocene, and earliest Eocene. That subsidence facilitated the hugely thick accumulation of marine and fluvial strata (Fig. 2) constituting the Mowry Shale upward through the Hanna Formation.

2. Today’s Hanna and Carbon basins represent two relatively small, eastern fragments of an originally enormous, Cretaceous and Paleocene greater Green River Basin. During the post-Wasatchian Eocene, this part of Wyoming became tectonically subdivided into the Great Divide, Washakie, Hanna, Carbon, Pass Creek, and Laramie basins. The interval of greatest deformation involved, and probably was mostly limited to, the earlier half of Eocene time (i.e., late in the Laramide Orogeny). More specifically, most Laramide contractional tectonic activity within the greater Hanna Basin seems to have been restricted to very late in the depositional history of the Hanna Formation, continuing even after completion of its deposition.

3. Through Paleocene into early Eocene time (i.e., before completion of basin differentiation), both the Ferris (latest Cretaceous–early Paleocene) and Hanna (early Paleocene–early Eocene) formations almost certainly extended much farther in all directions. They were probably continuous eastward into all of the Laramie Basin landscapes, including what subsequently became folded into Flat Top, Como Bluff, Boswell Spring, Gillespie, and McGill anticlines. The Ferris and Hanna formations also would have been continuous westward into the Great Divide and Washakie basins, with correlatives disguised there today under the differently named Lance, Fort Union, and Wasatch formations. Additionally, upper parts of the Hanna Formation almost certainly covered much of the Freezeout Hills to the north. The Hanna Formation also is known to have extended southward, across what is now the Pass Creek Hills all the way onto northern flanks of the Medicine Bow Mountains. Prodigious erosion during and after Laramide orogenesis led to paucity of remnant correlatives of the Ferris and Hanna formations directly to the north, east, and south of today’s Hanna/Carbon Basin area.

4. Nonmarine facies of the Mesaverde Group, as well as the Medicine Bow, Ferris, and Hanna formations, represent consistently lowland depositional settings not much above local sea levels of their times.

5. Out-of-the-basin (or -syncline) thrust faults are pervasively represented within remnants of the original, unfragmented margins of the greater Hanna Basin and in intrbasinal flanks of anticlinal and synclinal structures. With a few dramatic exceptions, most of these thrusts are
small, exhibiting planes having limited lateral extent and minor displacements. The many small thrusts, however, cumulatively have helped define much of the big picture of tectonic evolution observed. Nevertheless, the most dramatic deformation occurred adjacent to contractional influences of much larger and much deeper (i.e., basement-involved) thrust faults (e.g., Shirley Thrust, Flat Top Thrust, and the Simpson Ridge and Elk Mountain Thrust complexes).

6. Because many of the out-of-the-basin reverse faults have cut down-section in the direction of hanging-wall transport, a common result of that thrusting is significant stratigraphic thinning as the margin of a basin is approached. Recognition of the actual cause of thinning is essential when attempting to interpret local geologic history. In many earlier cases, what is described here as tectonic was originally interpreted as representing an angular depositional unconformity set upon an ancient surface of erosion. Recognition that thinning of gross stratigraphic sections (as usually is observed around basin margins) was not necessarily the principal result of long-term, progressive pulses of uplift followed by repetitive, unconformable deposition upon angular erosional surfaces has allowed the posing of dramatically different geohistorical interpretations from those which dominate existing literature.

7. Disregarding the allochthons within this project’s study area, only the northern border of the eastern Hanna Basin (vicinity of ‘The Breaks’) exhibits unequivocal evidence of a consequential erosional unconformity followed by deposition of Upper Cretaceous or lower Tertiary strata. That short length of depositional contact is important in showing that the southwestern extreme of Freezeout Mountain Anticline was in existence and had become deeply beveled by erosion prior to deposition of oldest local components of the Hanna Formation. Tectonic processes, however, greatly override explanation via angular depositional unconformity around most marginal areas of the Hanna Basin. The amount of stratigraphic thinning along basin margins achieved through down-section, out-of-the-basin faulting can involve several kilometers of stratigraphic loss.

8. A complexly contorted and pervasively fractured, overturned syncline (‘Card-tricks Hill’ of Lilgerawn and Snake, 1996) just south of the Shirley Mountains very probably represents a supremely deformed footwall syncline of the more southerly, overturned and thrust-faulted Austin Creek Anticline. Its original relative tectonic transport was to the north.

9. Chalk Bluff is a small, erosional-remnant mesa located in the northern Hanna Basin, directly south of the Shirley Mountains. The contained deposits are set upon vertical to overturned Cretaceous clastic strata, and the mesa itself is composed of rhyolitic ash flows (welded tuffs) and their eroded detritus. Lithologically identical, volcanic-derived sediments also occur nearby, high on the Shirley Mountains, plastered onto Precambrian granitic and gneissic basement rocks.

10. The so-called ‘defining syncline of northeastern Hanna Basin’ has long been known to constitute a lengthy structural feature. It now can be said to be an inter-basinal structure that is the most extensive tectonic element known from the Hanna Basin. Its surface expression extends from the northeastern flanks of Hanna Basin southeastward to Halfway Hill of the Carbon Basin, it then turns northeastward to pass through the northern margin of Como Anticline, and then continues still-farther eastward to become lost within western flanks of the Laramie Mountains. En route, this sometimes-faulted syncline severs the full transverse width of Simpson Ridge Anticline, displacing the anticline’s eastern moiety significantly southward.

11. The north–south-oriented hinge line of Bald Mountain Anticline forms a junction between the Shirley Mountains and Freezeout Hills along the northeastern margin of the Hanna Basin. As the anticline courses southward toward the Hanna Basin, its hinge line markedly increases in steepness of southward plunge, becoming overturned (and thus synformal following erosion) near the point at which it becomes overridden by the out-of-the-basin faulted Hanna Formation, which had relative tectonic transport to the north.

12. In the northern Hanna Basin, extending from just east of the hinge line of the Shirley Mountains Anticline nearly to the basin’s northeastern extreme, all sign of the Upper Cretaceous Mesaverde Group has vanished. It was completely overridden by out-of-the-basin thrust faulting of the younger Lewis Shale, Medicine Bow Formation, and even part of the Ferris Formation; all had relative tectonic transport to the north.

13. Surface expression of the basement-involved Shirley (thrust) Fault, which had relative tectonic transport to the south, terminates within stratigraphically low strata of the Frontier Formation at the southeastern base of the Shirley Mountains. Prior workers have sometimes incorrectly presumed its surface extension many miles farther to the east. The confusion usually was initiated at Nelson Spring (located NNE of Chalk Bluff), where the: (1) true eastward course of the Shirley Fault was not recognized in the field; and (2) more southerly (and much more extensive to the east) out-of-the-basin (having relative tectonic transport to the north) thrust faulting of the Medicine Bow, Ferris, and Hanna formations was misidentified as the basement-involved Shirley Fault.

14. This is the first study to attempt documentation of Simpson Ridge Anticline’s northern terminus. The hinge line of the anticline that defines the boundary between the Hanna and Carbon basins does not terminate by plunging directly northward. Rather, northern parts of the hinge line
turn sharply to the northeast, where it becomes multiply sheared by small faults, and then the broad entirety of the hinge is cut through by the faulted ‘defining syncline of northeastern Hanna Basin.’ From that point, the anticlinal axial surface trace of Simpson Ridge is displaced over two kilometers to the southeast. The displaced eastern moiety of the anticlinal hinge line then courses northeastward across U.S. Highway 30 / 287, where it becomes overturned on its northern side and effects a grand arc to the east and then southeast, finally continuing onto a more easterly quadrangle, beyond the edge of the study area. Thus the complete Simpson Ridge Anticline has both a western moiety (as traditionally considered) as well as an eastern part, previously unrecognized as the fault-displaced continuation of its western component.

15. Both to the west and to the east of the zone through which the ‘defining syncline of northeastern Hanna Basin’ cuts and displaces the axial surface trace of Simpson Ridge Anticline, the Ferris Formation exhibits unusually rusty-red, siderite-rich coloration and roughened texture. The color and structure differ markedly from most of the Ferris Formation of nearby surrounding outcrop areas, and the unusually iron-rich strata may exhibit effects of moderate but prolonged heating and diagenetic hydrothermal alteration.

16. Detailed lateral tracing of correlative layers including the Pine Ridge Formation (Mesaverde Gp.) upward through the Ferris Formation show that individual beds are continuous between the Hanna and Carbon basins across the northeastern hinge line of Simpson Ridge Anticline’s western moiety. This is not the case, however, for the overlying Hanna Formation between the Hanna Basin and the Carbon Basin. Indeed, as interpreted here all strata of the present-day Hanna Formation within the Carbon Basin are allochthonous.

17. As seen within southwestern flanks of Flat Top Anticline (north of the eastern moiety of Simpson Ridge Anticline), the soft and bentonite-rich Steele Shale is so intra-formationally deformed and locally detached from stratigraphically overlying strata that the gaining of reliable thickness measurements of the formation becomes a major challenge.

18. Basement-involved, faulted uplift of Flat Top Anticline having relative tectonic transport to the north, in conjunction with virtually synchronous development of Simpson Ridge Anticline, occurred late in depositional history of the local Hanna Formation. Those two events led to the currently defined eastern margins of the Hanna and Carbon basins. Simpson Ridge and Bloody Lake anticlines represent closely appressed and parallel, but longitudinally offset, anticlinal twins.

20. The Upper Cretaceous Mesaverde Group exposed along Halleck Ridge represents the northwestern flank of Bloody Lake Anticline and, in turn, continues to the southwest as the southeastern border of the Hanna Basin's Hanna Syncline.


22. West of the Carbon Basin, along most of the western and northwestern flanks of Simpson Ridge Anticline, exists strong out-of-the-basin faulting (mostly from eastern parts of the Hanna Syncline). Principal rock units involved are the Medicine Bow, Ferris, and Hanna formations. The anticline came into existence only after deposition of continuous sheets of those (and older) rock units across the landscape now occupied by the Hanna and Carbon basins and intervening Simpson Ridge. The uniformity of formational thicknesses straight across the anticlinal structure from the Hanna through the Carbon basins shows that Simpson Ridge Anticline did not exist prior to Paleocene time.

23. Around margins of the Carbon Basin, all adequately exposed and hand-excavated contacts between the Hanna Formation and underlying strata are here identified as structural in nature, not representative of an erosional angular unconformity. Much of the western edge of the Hanna Formation, where it lapped westward onto the Lewis Shale of the eastern flank of Simpson Ridge Anticline, exists as a north–south-elongated, pervasively fractured, roll-over anticlinal fold above a basal décollement fault zone.

24. The faulted anticlinal hinge line of Simpson Ridge, having relative tectonic transport to the west, became elevated by about eight kilometers during orogenesis. When that anticline finally started development, the attached Carbon Basin became differentially elevated nearly four kilometers relative to the Hanna Basin, leading to progressive erosion of the Carbon Basin floor. Finally, the Carbon Basin Klippe entered the basin from the northeast, bringing ‘immigrant’ Hanna Formation from its more northerly source across the erosional surface to its present-day contact with eastern flanks of Simpson Ridge Anticline.

25. The greatest magnitude of erosion near the center of the Carbon Basin prior to emplacement of the Hanna Formation of the Carbon Basin Klippe would have exceeded four kilometers. And along the eastern margins of Simpson Ridge and western flanks of Big Medicine Bow anticlines, the magnitudes of pre-Hanna erosion downward through the existing stratigraphic cover probably ranged from five to over seven kilometers. Stratigraphically, the erosional gaps represent section lost from the originally deposited Hanna and Ferris formations down-section into near the base of the Lewis Shale.

26. As a working hypothesis, the locally conglomeratic and coal-rich Hanna Formation that now comprises the Carbon Basin Klippe was deposited as part of the Hanna Formation that formerly had continuity with the northern Hanna Basin and rested above what is now Flat Top
Anticline. That is, strata comprising the klippe originated in the northwestern-most Laramie Basin (Fig. 1B), now east of 'The Breaks' and northeast of the Carbon Basin. Minimally, that hypothesis demands lateral translation via sliding of the klippe, first off the bed of the anticlinal ‘dumptruck,’ and then across the ancient land surface for a total of roughly 14 km. Markedly reduced today by erosion from its original dimensions, remnants of the Carbon Basin Klippe total about 106 km². Remaining surfaces of the klippe reflect folds within the underlying strata, suggesting that its transport preceded completion of deformation of the Carbon Basin. As based on mammalian fossil assemblages, transport of the klippe to its present location would have occurred no earlier than late in the Paleocene; probably, however, emplacement was significantly younger than that.

27. Existing maximum thickness of the main body of the Hanna Formation in the Hanna Basin is roughly 4.8 km, and in the Carbon Basin Klippe it is about 853 m. Both areas exhibit deeply eroded upper surfaces.

28. The Calvin Bend Thrust is south of Calvin Bend (along the southwestern flank of Flat Top Anticline). The fault cuts transversely (having relative tectonic transport to the southeast) across the very top of the Steele Shale, through the Mesaverde Group, and minimally across the lower half of the Lewis Shale. Stratigraphic separation is minor, and the fault shows an apparent right-lateral strike-slip component in map view. The fault is associated with flowing springs.

29. There exists no known, generally applicable, basin-wide lithologic field-distinction by which the Hanna and underlying Ferris formations can be reliably distinguished. Although it may not have been recognized at the time, the mapping by Dobbin et al. (1929) across most of the Hanna Basin followed tectonic discontinuities between those two 'formations,’ not lithologic criteria. The present research, working quite independently, did the same. In plotting contacts between the Hanna and Ferris formations, the present Figures 4 and 5 generally are in close agreement with what was originally proposed in plate 27 by Dobbin et al. (1929). Present interpretations of placement of the formational boundary diverge markedly, however, once the Hanna Syncline is approached. The lithologic characters that ostensibly distinguish the Hanna from Ferris formations (as proposed by Bowen, 1918) are not reliable beyond the original 'type’ area of their definitions. Field evidence also shows, however, that the traced, ostensible Hanna–Ferris ‘inter-formational’ thrust plane varies significantly in position up- and down-section among stratigraphic horizons. Continuing attempted recognition of lithologic distinctions between Hanna and Ferris formations has introduced an illusion of significantly greater understanding of stratigraphic relationships than is actually warranted.

30. The Hanna Syncline, broadly considered, defines the fundamental structure of the Hanna Basin proper. It includes the bulk of coal resources that have been mined in the area (exclusive of the Carbon Basin). Even though the northern end of the Hanna Syncline’s hinge line is topographically some 390 m lower than its southern end (southwest of Elk Mountain), the exposed northern rocks are stratigraphically roughly 11.8 km higher in the section. This impressive stratigraphic sequence could not have undergone its intense deformation any earlier than the latest Paleocene. More probably it happened in the early Eocene, in association with late Laramide emergence and uplift of Elk Mountain.

31. Essentially all faults recognized by Dobbin et al. (1929, pl. 27) in the Hanna/Carbon Basin were then interpreted as normal faults. As examples, a series of four, NW–SE-oriented normal-fault traces are shown on their map along the southeastern flanks of the Hanna Syncline, cutting through the Hanna and Ferris formations. Although many other workers have reiterated plots of those putative normal faults within subsequent maps, I have recognized no supporting field-based evidence for their actual existence. Only the most southwesterly of those faults exists at all, and new mapping shows it to be an out-of-the-basin, younger-on-older thrust. Normal faults within the strongly contractional tectonic regime characteristic of the greater Hanna Basin are rarities — if any exist at all.

32. The Ferris Formation, as represented in southern parts of the Hanna Basin’s Hanna Syncline, is relatively undeformed (aside from being generally steeply dipping). It reveals the unexpectedly great thickness (nearly 5 km) characteristic of the formation’s pre-deformational state. Such a thickness suggests that, during latest Cretaceous and earliest Paleocene time, the rate and total magnitude of subsidence and deposition was not reduced in the area now representing the southern Hanna Basin. Thus, even though the greatest thicknesses of Phanerozoic strata today are preserved in a west–east-oriented zone parallel to the Hanna Basin’s northern border, the true depositional axis of original eastern parts of the greater Green River Basin was much farther to the south. An essentially north–south cross section through the eastern Hanna Basin representing an interval prior to the high point of Laramide deformation (see Fig. 94 for an approximation) would appear much more symmetrical than in today’s world.

33. Although located beyond western boundaries of the present study area, the topographic feature known as Saint Marys Hill originally was a northwesterly anticlinal continuation of the Dana (Pass Creek) Ridge Anticline. Those two components today, however, are separated by displacement of Saint Mary Hill roughly 1.5 km to the southwest via an underlying, out-of-the-basin thrust. Contrary to an earlier interpretation, available evidence does not support that fault’s continuation southeastward along the western flanks of Dana Ridge Anticline.

34. The structural hinge line of Dana (Pass Creek) Ridge Anticline is placed well to the northeast of that ridge’s topographic crest. The anticline itself consists of a major
out-of-the-basin thrust, in which strata on the hanging wall (northeast of the fault) dip steeply to the northeast but strata of the footwall (southwest of the fault) dip steeply to the southwest. With that ‘belly-to-belly’ (or ‘great wall’) configuration, the Dana Ridge Anticline represents a relatively gigantic version of the Dragonfly Thrust (as seen in ‘The Breaks’ area of the northeastern Hanna Basin; Lillegraven and Snoke, 1996, cover photograph; and Lillegraven et al., 2004, fig. 4B; cover photo, this issue). Footwall rocks, hanging-wall rocks, and rocks of the fault plane itself show extraordinary levels of fracturing, generally chaotic rock orientations, and finely comminuted intervening gouge. There also is localized evidence for hydrothermal alteration of the immediate fault zone.

35. Similarly faulted expressions of ‘great walls’ (in which original 'stratigraphic-up' orientations project away from opposing sides of the fault planes) are common all around the margins of the eastern Hanna Basin, and they occur at all scales. Sometimes the ‘great wall’ itself is topographically clearly expressed (as with the Dragonfly Fault in ‘The Breaks’), but more commonly it lacks clear topographic prominence (as along lower elevations of the fault’s course existing upon softer strata dominating the northeastern flank of Dana Ridge Anticline).

36. Extensive and prominently developed footwall synclines commonly parallel ‘great wall’ anticlinal structures within the eastern Hanna Basin. Under interpretation applied here, the Walcott Syncline/Coal Bank Basin is a greatly scaled-up footwall syncline that fits the massiveness of the Dana Ridge Anticline. It is the largest footwall syncline recognized to date within the eastern Hanna Basin.

37. A second allochthonous mass occupies an area of roughly 119 square kilometers within the southern Hanna Basin. The Dana Klippe is a remarkably thin plate (maximum thickness is 209 m). Strata of the klippe are comparatively flat lying, and they cover much of the southern Hanna Basin’s Hanna Syncline and lap onto northeastern flanks of Dana Ridge Anticline. The plate overlies steeply dipping, mostly Cretaceous strata including components of the Mesaverde Group as well as the Lewis Shale up-section into the Ferris Formation. Conformation of the klippe itself distinctly reflects distortion of the underlying Hanna Syncline. That suggests transport of the klippe predated the syncline’s completion of structural folding.

38. Strata within the Dana Klippe previously have been identified as correlatives of the Browns Park and overlying North Park formations of the Saratoga Basin, nearby to the southwest. However, all but the klippe’s highest stratigraphic levels lithologically match more closely the Hanna Formation as it exists along northern flanks of the Medicine Bow Mountains and within the adjacent Pass Creek Basin. Thus terminology applied here is ‘Hanna Formation of Dana Klippe.’ That, at least tentatively, includes the generally poorly exposed, capping layers that lithologically closely match the partly volcaniclastic strata deposited in the early Miocene within the Saratoga Basin. Clearly, my assigned terminology does not represent a perfect solution to a nomenclatural dilemma.

39. Footwalls of the Dana Klippe commonly have developed step-faults and/or frictionally bent sandstone fins directly below the thrust plane; both phenomena help in recognizing the northerly direction of transport of the hanging wall relative to the footwall. Slickensided strata are common above, below, and within the thrust plane. Examples of all of the above phenomena are now identified around the entire circumference of the klippe.

40. Gravity-driven, long-runout slide masses transported along shallow glideplanes are common features outboard from the northeastern, northern, and western flanks of the Medicine Bow Mountains and continuing southward along adjacent mountains and basins in north-central Colorado. Although the Carbon Basin Klippe and Dana Klippe are rather impressive structures, even when combined they are dwarfed by the Never Summer Thrust (having relative tectonic transport to the west) that allowed a north-central Colorado mountain range (including Proterozoic basement and younger volcanic rocks) to override Upper Cretaceous marine strata of southeastern North Park Basin and northeastern Middle Park Basin.

41. Roughly 12 vertical kilometers of uplift of Elk Mountain’s massif occurred by way of the basement-involved Elk Mountain Thrust Fault complex. That uplift, in turn, influenced tight folding of the Hanna Syncline. General upturning of strata in the southern Hanna Basin by way of the Rattlesnake Pass and Halleck Thrusts significantly post-dated deposition of a continuous sheet of Hanna Formation that originally extended northward from the northern Medicine Bow Mountains all the way across the modern Hanna Basin — and beyond. The proposed working hypothesis is that all but youngest strata of the Dana Klippe (i.e., the North Park Fm. of Ingle, 1977) originated from elements of the Hanna Formation that were deposited stratigraphically above the then-future, structurally defined positions of Elk Mountain and the northern Pass Creek Basin.

42. Elk Mountain itself could not have existed prior to the early Eocene. Its basement-involved uplift was responsible not only for isolating the Pass Creek Basin, but along with evolution of Bloody Lake and Simpson Ridge anticlines, constituted the principal stresses that led to folding the mass of strata now comprising the Hanna Syncline.

43. When one simultaneously takes into account the impact of Elk Mountain’s late Laramide disruption of the Hanna Basin’s original southern extent along with the early Eocene burial of the Freezeout Hills (by upper levels of the northernmost Hanna Fm.), it becomes reasonable to suggest
that the total Paleocene–lower Eocene sedimentary cover comprised a north–south depositional dimension for the Hanna Basin nearly twice that of today.

44. The profound deformation of the originally intact stratigraphic pile across the Hanna Basin area was largely restricted to very late in the Laramide Orogeny (i.e., early Eocene and probably even later). Specifically, deformation initiated its greatest importance late in the Wasatchian North American Land Mammal Age and latter half of the international (European) Ypresian age (i.e., late early Eocene, ca. 50 Ma).

45. How long active deformation related to the Laramide Orogeny persisted into the latter half of Eocene time across the Hanna Basin remains quite unknown because of the deep and universally expressed erosional surface that has been scoured into its modern surface.

46. Steeply dipping to overturned strata are the rule almost everywhere along the northern, eastern, and southern margins of the greater Hanna Basin. The most dramatically deformed and thickest Laramide sections, however, are south of the Shirley Mountains/Freezeout Hills and north of Elk Mountain (including the Hanna Syncline).

47. One previously unconsidered, special point of interest illuminates the magnitude of physiographic changes in North America’s western interior beginning late in Paleogene time. The deepest sedimentary basin in the Rocky Mountains (i.e., the Hanna Basin) developed its entire Laramide stratigraphic column at elevations close to sea level. Today, however, and beginning near the end of Eocene time, the Hanna Basin has been residing upon northern parts of the summit of "... the largest coherent epeirogenic feature in the conterminous U.S." (Eaton, 2008).

CHALLENGES IN CLOSING

The text and graphics presented above deal principally with diverse features observed from a specific area within North America’s Rocky Mountains. Therefore, testing the reliability of included observations and conclusions will depend much less upon geological theoreticians than upon those individuals interested enough to carry a rock hammer and use the provided maps and geographic coordinates to enter the study area and judge situations for themselves.

The structural history presented here differs in many fundamental ways from interpretations of previous researchers. But real progress will have been made only when present interpretations are tested using better data combined with stronger thinking. The welter of attitudinal measurements probably, in the long run, will prove to have been this paper’s single most important contribution. Those measurements represent hard-won new data that do provide invaluable constraints upon flights of structural fancy — and their very gathering makes one move slowly enough across the landscape to allow close observations of other details.

A primary example would be recognition that out-of-the-basin, younger-on-older thrust faulting around Laramide basin margins has been so perversively misidentified as angular unconformities developed on ancient surfaces of erosion. Distinction between those two phenomena makes an enormous difference in interpretation of geologic history, and the distinction cannot be evaluated adequately in the absence of excavation and cleaning of the contact.

In my opinion, the greatest immediate needs for testing this paper’s worth are: (1) more concentrated effort in locating biostratigraphically useful fossil-bearing localities — especially for mammalian remains in the Ferris and Hanna formations (most of the mapped area lacks any such controls); (2) liberal accessibility to, and geographically broad use of, modern-day seismology, applied at all scales across the areas of clear deformation; and (3) a willingness by investigators to physically excavate the geologic contacts under study so that proclamations of tectonism versus erosion are based upon actual evidence. Tediuous? You bet it is! But those very activities out in the wind also provide intervals of great personal enjoyment and outright fun based on experiences of discovery.

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REFERENCES CITED


Laramide Fragmentation of Eastern Greater Green River Basin, Wyoming


Espenschied, E. K., 1957, Stratigraphy of the Cloverly Formation, Thermopolis Shale, and the Muddy Sandstone around the
Glass, G. B., 1972, Mining in the Hanna Coal Field: Geological Society of America, Rocky Mountain Section, Guidebook, ii + irregular numbering.
Hamilton, H. E., 1964, Stratigraphy and depositional history of the Freezeout Mountain Formation in the Freezeout Mountains area,


foreland [Ph.D. diss.]: Laramie, University of Wyoming, xiv + 240 p.


McElhaney, D. A., 1988, Depositional environments and provenance of the lower Tertiary Ferris and basal Hanna...


1978b, Coal resource occurrence and coal development potential maps of the Elk Mountain Quadrangle, Carbon


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