2019 Year End Report on Geology of White Rocks Open Space
16 April 2020

Edward J. (Ned) Sterne
Robert G. Raynolds

Outline

XI Table

XII Appendix

XIII Plate

I. Introduction

The White Rocks area has been protected as restricted-access open space by the City of Boulder because of its fragile ecosystems, abundant cultural artefacts, and beautiful sandstone cliffs gracing the north bank of Boulder Creek between 75th and 95th streets (Fig. 1). These prominent bluffs are formed by a resistant Cretaceous age sandstone layer known as the Fox Hills Formation. This report focuses on the surface geology of the Open Space and surrounding areas, on the character and geometry of the Fox Hills Formation sandstones, and on the surface and subsurface structure of the White Rocks area within the context of the larger Boulder-Weld allochthon (BWA) (Fig. 1). The BWA is a sheet of rock covering over 200 mi^2 that has moved up to two miles east above a decollement in the upper part of the Pierre Shale. In studying the whole of the BWA, it has become apparent the outcrops and abundant subsurface control across the White Rocks area provide the critical information for understanding the western part of the system.

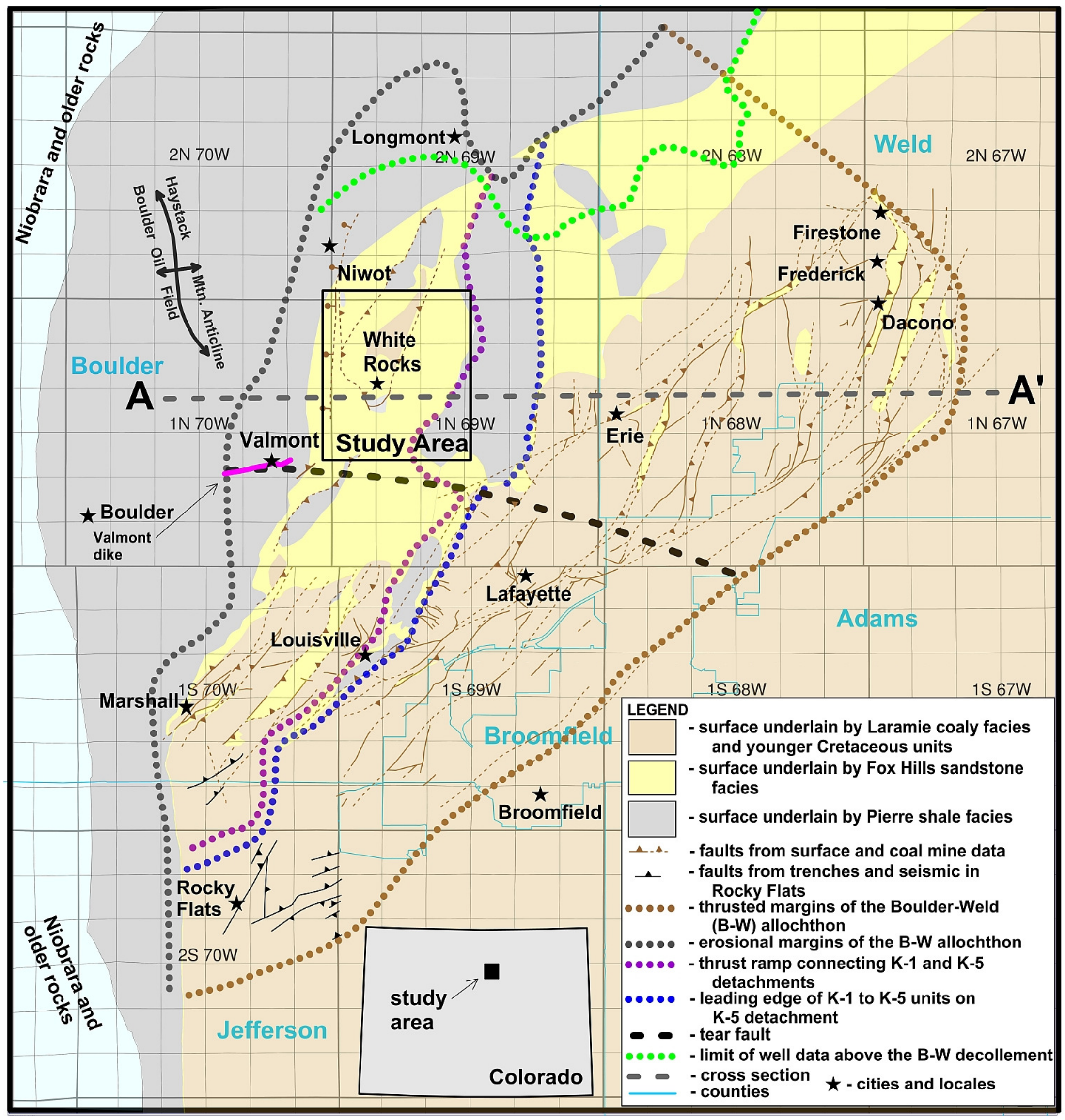

Figure 1: Location map showing White Rocks study area and elements of the Boulder-Weld allochthon.

II. History of Research

The Fox Hills Formation was defined from outcrops along the Missouri River in South Dakota (Meek and Hayden, 1861, p. 419, p. 427). The relatively thin (33-66 feet, 10-20 meters) but extremely laterally persistent (1,000's of mi^2) sandstone beds were recognized from the outset to define near-shore and coastal strata deposited at the transition between the marine shale deposits of the Cretaceous Interior Seaway and the overlying non-marine coal-rich beds variously attributed to the Laramie, Lance and Hell Creek Formations (see for example Hayden, 1877, Emmons et al., 1896, and more recent discussions in Dobbin and Reeside (1929), Waage (1961,1968) and Landman and Cobban (2003) (Fig. 2). In the White Rocks Open Space, the Fox Hills Formation forms resistant cliffs and ledges defining the landscape north of Boulder Creek. The underlying Pierre Shale is easily weathered and does not form good outcrops.

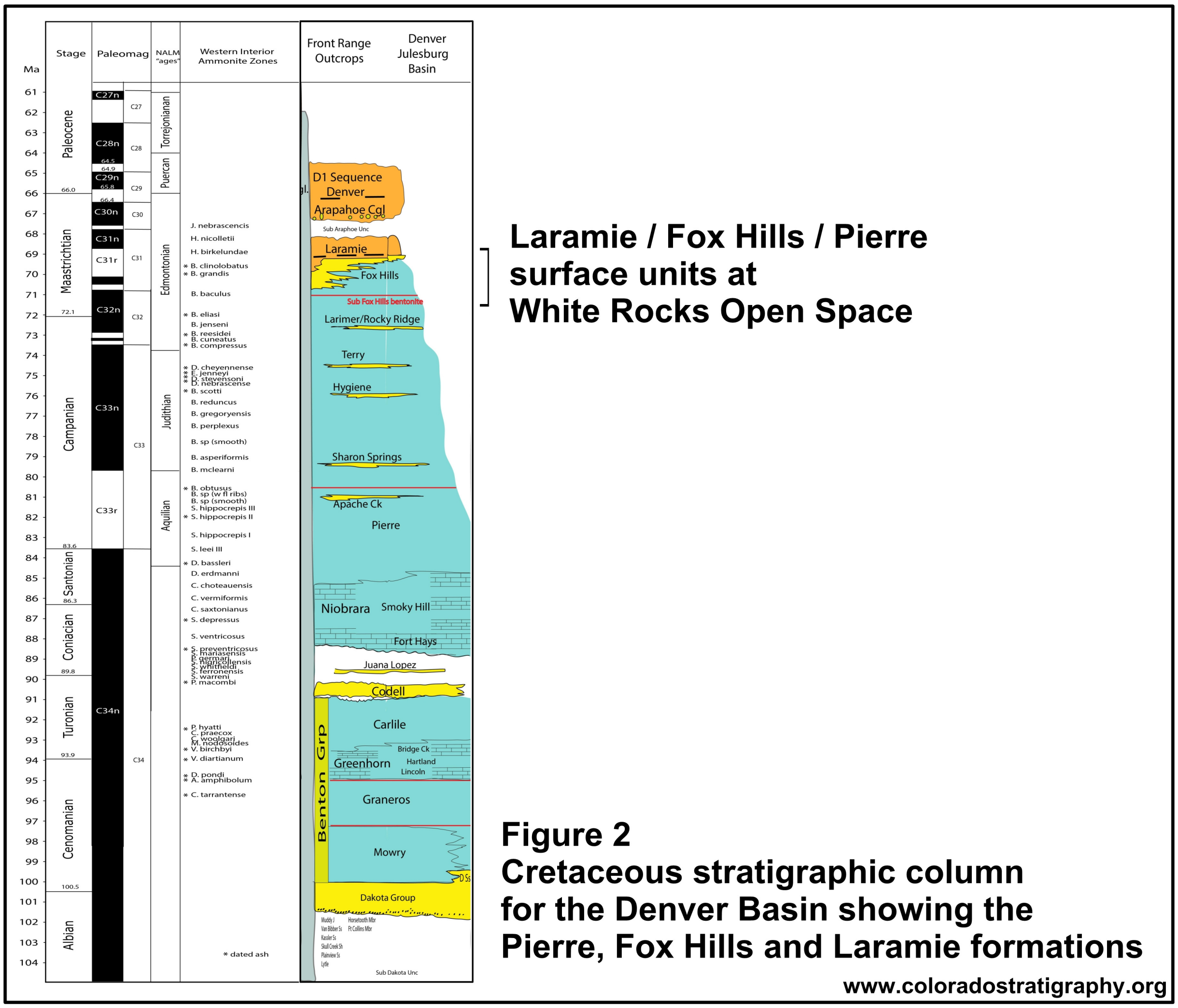

Figure 2: Cretaceous stratigraphic column for the Denver Basin showing Pierre, Fox Hills and Laramie formations.

In the Denver Basin, a broad basin shaped area extending from Fort Collins to Colorado Springs and from Limon to the Front Range (Dechesne et al., 2011), outcrops of the Fox Hills Formation are discontinuous; the full section is rarely observed. Outcrops at White Rocks Open Space represent some of the best exposures of the Fox Hills Formation anywhere in the Denver Basin. As such, they have been the subject of considerable geologic research.

Details of the geology at White Rocks first appeared on the maps by Emmons et al. (1896) and were incorporated into the mapping of the Boulder district by Fenneman (1905). An original unpublished plane table map (Aurand, 1920's) in the Denver Earth Resources Library collection shows details of the geology at White Rocks including faults and numerous strikes and dips. Weimer (1973), with modifications by Bedwell (1974), published the first detailed mapping of White Rocks. Trimble (1975) and Colton and Anderson (1977) showed White Rocks area in the wider context of the Niwot and Erie 7.5' quadrangles, respectively. Davis and Weimer (1976) and Weimer and Davis (1977) presented seismic data in a paper discussing the stratigraphic and structural evolution of White Rocks. Weimer and Tillman (1980) correlated Fox Hills facies in the CSM Heather core (1n-69w-7 sesw) to nearby outcrops exposed in the cliffs at White Rocks. At a more regional scale, the White Rocks area is captured on the Estes Park 30' by 60' quadrangle (Cole and Braddock, 2009) which is complemented by the adjoining Denver West 30' by 60' quadrangle (Kellogg et al., 2008). Scott and Cobban (1965) augmented the surface mapping of these areas by defining and mapping faunal zones across a thick and poorly exposed expanse of Pierre Shale west of White Rocks.

Within the regional structure, White Rocks lies in the northwestern part of a mass of rock several townships in size that moved almost 2 miles east above a fault detachment within the upper part of the Pierre Shale (Fig. 1; Sterne, 2020). Such displaced features are known to geologists as allochthons, so we have chosen to call the feature the "Boulder-Weld allochthon" (BWA). Its eastern and southern portions consist of a complex of anastomosing faults long recognized from coal mines and surface exposures between the towns of Marshall and Firestone as the Boulder-Weld fault zone (BWFZ). Its western margin lies west of White Rocks where it is truncated by erosion along the eastern flank of the Front Range basement uplift.

III. Stratigraphic framework of the Fox Hills Formation at White Rocks

Environment of deposition

The sandstone beds contain marine fossils (for example Landman and Cobban 2003) and trace fossil assemblages (Weimer and Tillman, 1980) that indicate open marine to near-shore environments. The facies distribution patterns corroborate the paleontological record and correspond well with patterns observed on modern coastal systems and in other regressive shoreline sequences (see for example Reading and Collinson, 1996). Figure 3 illustrates environments of deposition and Figure 4 shows the Fox Hills shoreline during *Baculites clinolobatus* time (69.5 million years ago) stepping eastward toward the White Rocks area as the Cretaceous seaway retreats.

Fox Hills Formation outcrops in the Denver Basin

A recent review of the Denver Basin Fox Hills Formation literature is provided by Landman and Cobban (2003) in conjunction with an appraisal of the ammonite faunas in the uppermost Pierre Shale and Fox Hills Formation. These authors note that confusion has arisen concerning the boundaries of the Fox Hills Formation in the Denver Basin because of the complex vertical and lateral inter-fingering relationships coupled with poor exposures.

Most workers have recognized the transitional nature of the basal contact with the Pierre Shale. This may be seen at a uniquely well-exposed outcrop located on Rooney Road south of Golden (Weimer and Tillman, 1980). Combined with lateral facies changes and subtle variations in sandstone thickness, the exact bottom of the Fox Hills is a bit subjective. The base of the sandstones is not a simple interface, but is a feather edge of interbedded sandstones and shales, making it difficult to consistently pick the contact.

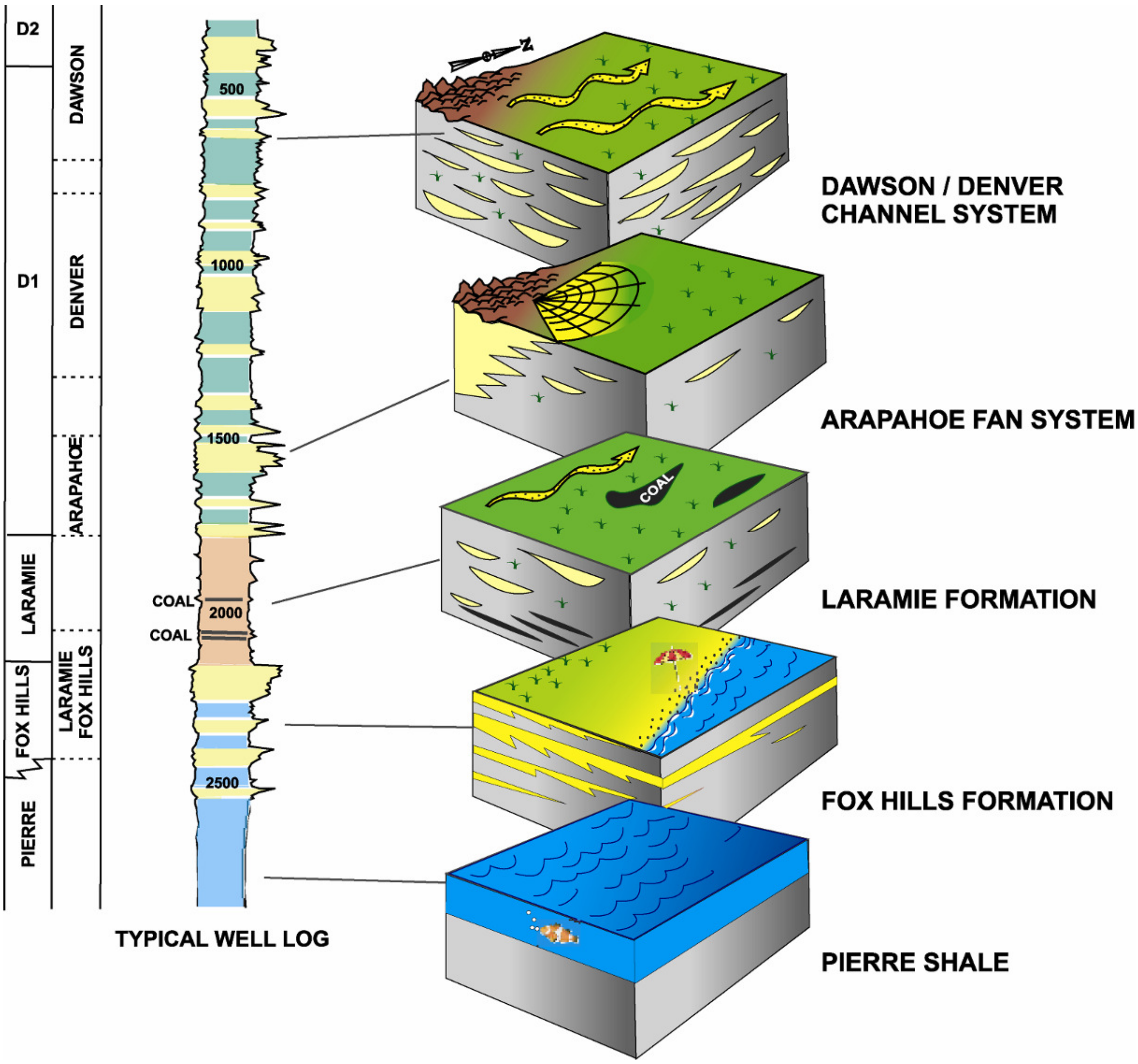

Figure 3: Environments of deposition.

The sharp upper contact with the Laramie Formation is well exposed in the Greasewood Flats area of the eastern Denver Basin and has been mapped in outcrop just north of White Rocks (Trimble, 1975). The top of the Fox Hills Formation is picked on electric logs as the abrupt transition from low resistivity and high gamma shales of the Laramie Formation into the high resistivity and low gamma of the uppermost Fox Hills beach sandstone. The Fox Hills Formation frequently demonstrates a funnel-shaped electric log pattern characteristic of marine sandstones. Spikes of high resistivity in the basal Laramie are often indicative of coal beds representing swamps developed landward of the Fox Hills marine shoreline sandstones.

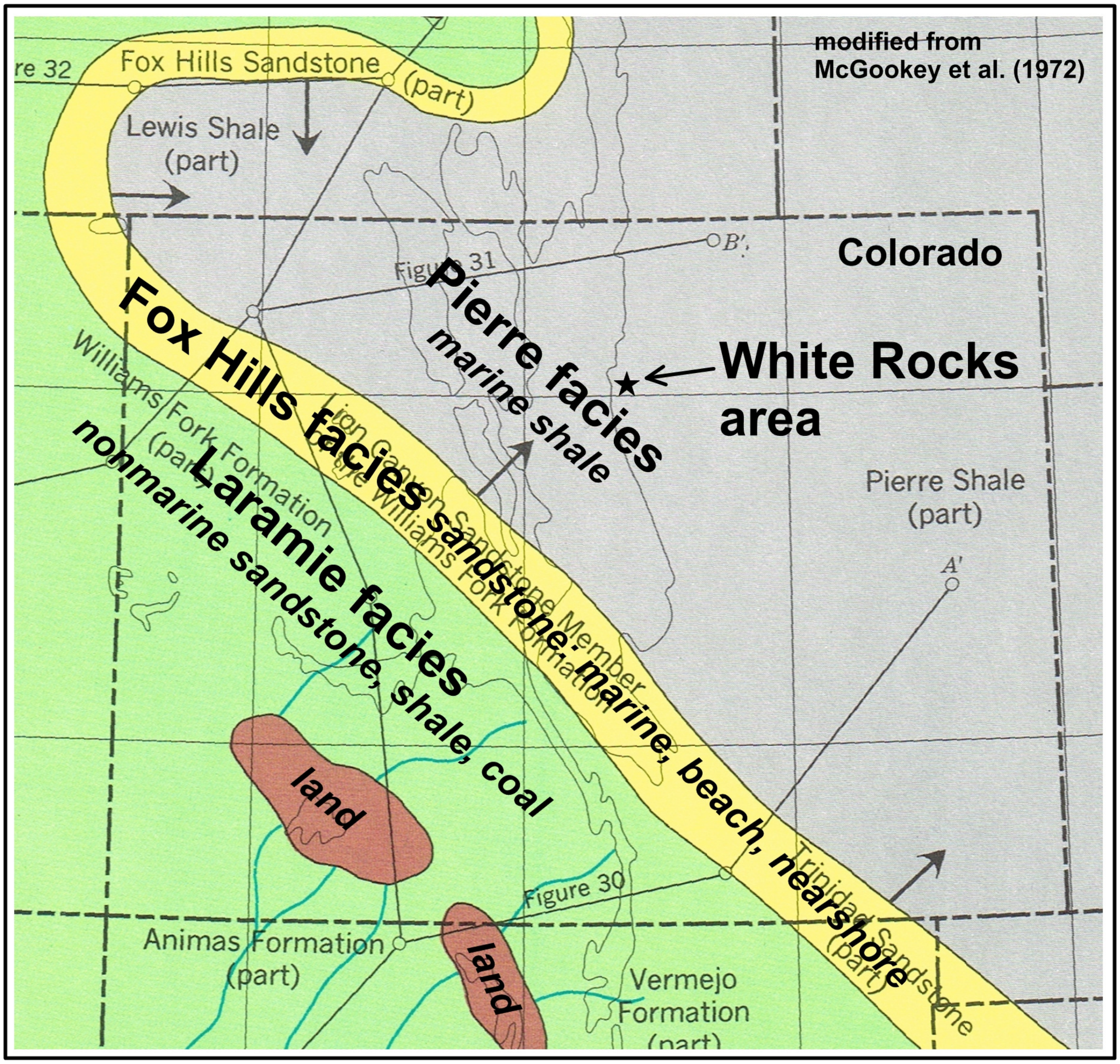

Figure 4: Fox Hills shoreline advancing eastward toward White Rocks during *Baculites clinolobatus* time (~69 Ma).

Geometry of the Fox Hills Formation strata: off-lapping shingles

The Fox Hills Formation is developed as a series of off-lapping and upward stepping beach deposits. Episodic, relatively stable periods of accumulation were separated by episodes of sea level rise, resulted in the deposition of discrete bodies of sandstone. Seen from the side or above these rock units demonstrate overlapping and offset patterns reminiscent of shingles, hence each bed is termed a shingle. A series of these shingles have been mapped in the subsurface using electric logs from wells across the Denver Basin by workers at the Denver Museum (Raynolds, pers. com.). The sandstone shingles young or climb section eastward, building what was once the shoreline of the retreating Cretaceous seaway.

What can be picked as the base of the Fox Hills Formation in the White Rocks area lies some 400 feet deeper in the stratigraphic section than where it is seen 14 miles to the east.

Age of the Fox Hills Formation

The paleontological age of the base of the Fox Hills Formation can be deduced from ammonite collections. Landman and Cobban (2003) conclude that the lower Fox Hills Formation on the north side of the Denver Basin is in the *Hoploscaphites birkelundae* Range Zone of the Western Interior Seaway. This is the third youngest ammonite Range Zone found in the Western Interior Seaway. The *Hoploscaphites birkelundae* Range Zone is referred to the Upper Maastrichtian by Landman and Cobban (2003) corresponding to an age of roughly 67 million years.

IV Surface Investigations at White Rocks

Geologic Mapping

Earlier geologic maps (as cited above) were examined to establish a basis for our research. Considerable variation exists in the published maps and for this study we created a new geologic map (Fig. 5, Pl. 1) of the White Rocks area that incorporates the observations of earlier workers and reflects our fieldwork and analysis of subsurface data. Specifically, bedding attitudes were taken from Aurand (1920's) and Colton and Anderson (1977). Outcrop outlines were modified from Trimble (1975) and Colton and Anderson (1977). Where we did not find faults or outcrops shown on earlier maps, their locations were retained, but flagged with question marks. These maps were made using a very detailed Google Earth photographic image of the surface as a base and the layered drafting programs Adobe Illustrator and Surfer. The maps are carefully scaled and can be readily incorporated into an ArcGIS data management system.

The White Rocks area lies in broad syncline between the flank of the Front Range Uplift to the west and a major thrust ramp to the east. Both of these features bring Pierre Shale to the surface as shown on Figure 1 and the geologic map (Fig. 5). The younger sandstones of the Fox Hills Formation present at White Rocks occupy the structural low between these highs where they are deformed by a variety of faults.

Fault examination and trenching

Our structural research at White Rocks started with an examination of the Big fault because it had been interpreted in the literature both as a reverse fault (Weimer, 1973) and a growth fault, which is a type of normal fault (Davis and Weimer, 1976), and had been cited as evidence for a headwall or breakaway zone in support of a model describing the larger BWA as a gravity slide (Kittleson, 2009). Fortunately the fault is beautifully exposed (Fig. 6), leaving no doubt as to its character. The fault plane dips 42 degrees to the east and puts the top of the Pierre over the Fox Hills, making it a clear example of a reverse or thrust fault. This is further corroborated by hanging wall roll indicating reverse drag into the fault and well-developed ornamentation on the fault plane. Reverse sense Riedel shears and east-west trending, dip-slip stria are evident. Breakaway zones for gravity slides are populated by normal faults, making it clear the Big fault should not be cited as evidence for this type of structure.

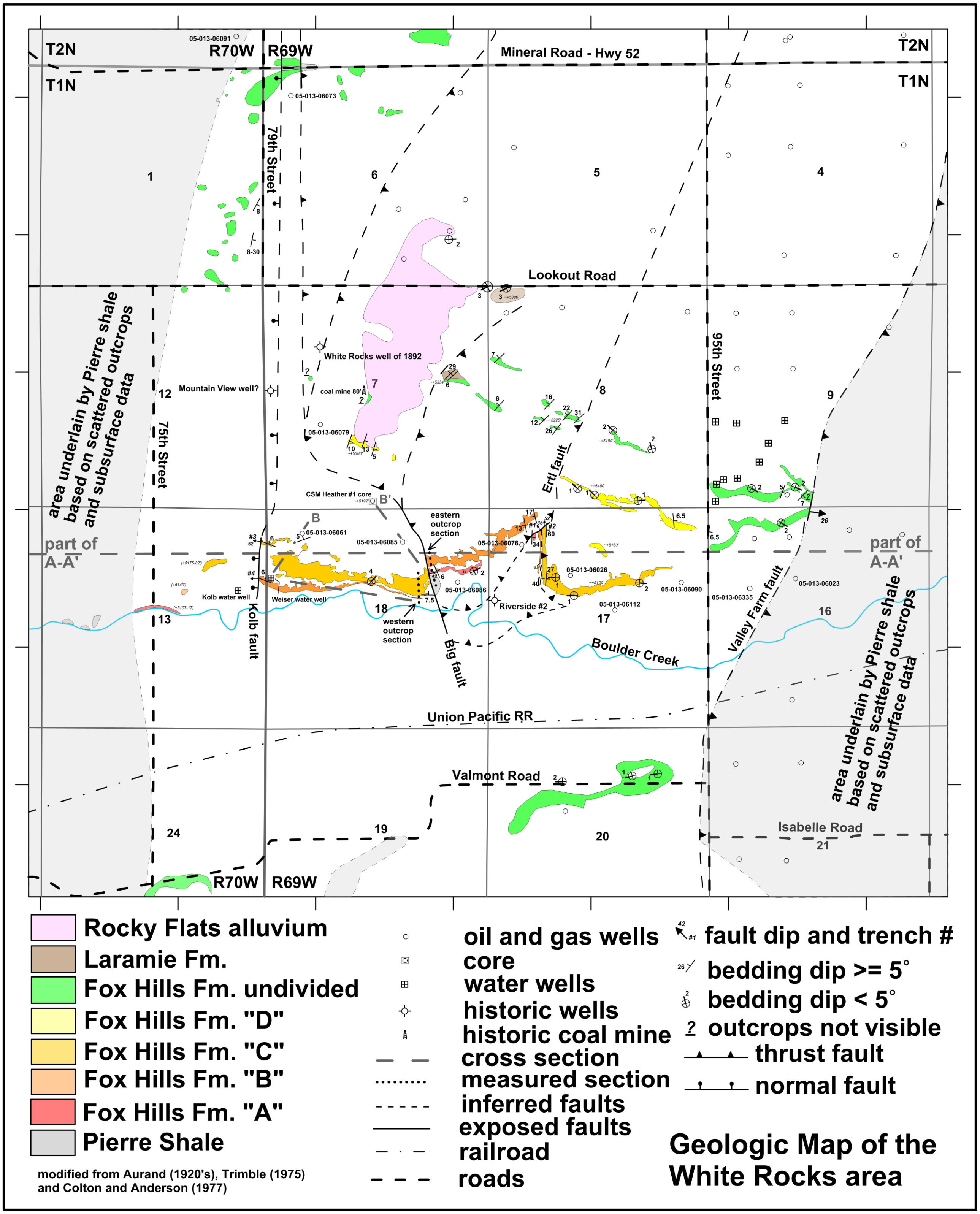

Figure 5: Geologic map of the White Rocks area.

The Big fault, as shown on Figure 5, continues to the northwest in 1n-69w-7 where it cuts the well in the nesw of the section. It then appears to continue northeast where it cuts a well in 2n-69w-33 nenw and brings Pierre shale facies to the surface as seen in water wells (Sterne, 2020) (Fig. 1). We also show a western splay of the Big fault outcropping as the eastern of the two faults mapped by Trimble (1975) in 1n-69w-6 nwnw (Figs. 1 and 5). Our examination of the road cut exposure along Mineral Road–Highway 52 showed bedding dips increasing and overturning to high, east dips heading eastward toward the mapped fault. This pattern indicates the presence of a west-directed reverse or thrust fault or similarly, a west-vergent fold. We did not find the fault plane exposed, but suspect it could be uncovered by trenching. The Valley Farm fault is exposed in the irrigation ditch in 1n-69w-16 nenenw where it dips 26 degrees to the east-southeast with grey shaley sandstone representing possible Pierre in the hanging wall and Fox Hills Formation in the footwall. We found no outcrops east of the fault. The Valley Farm fault

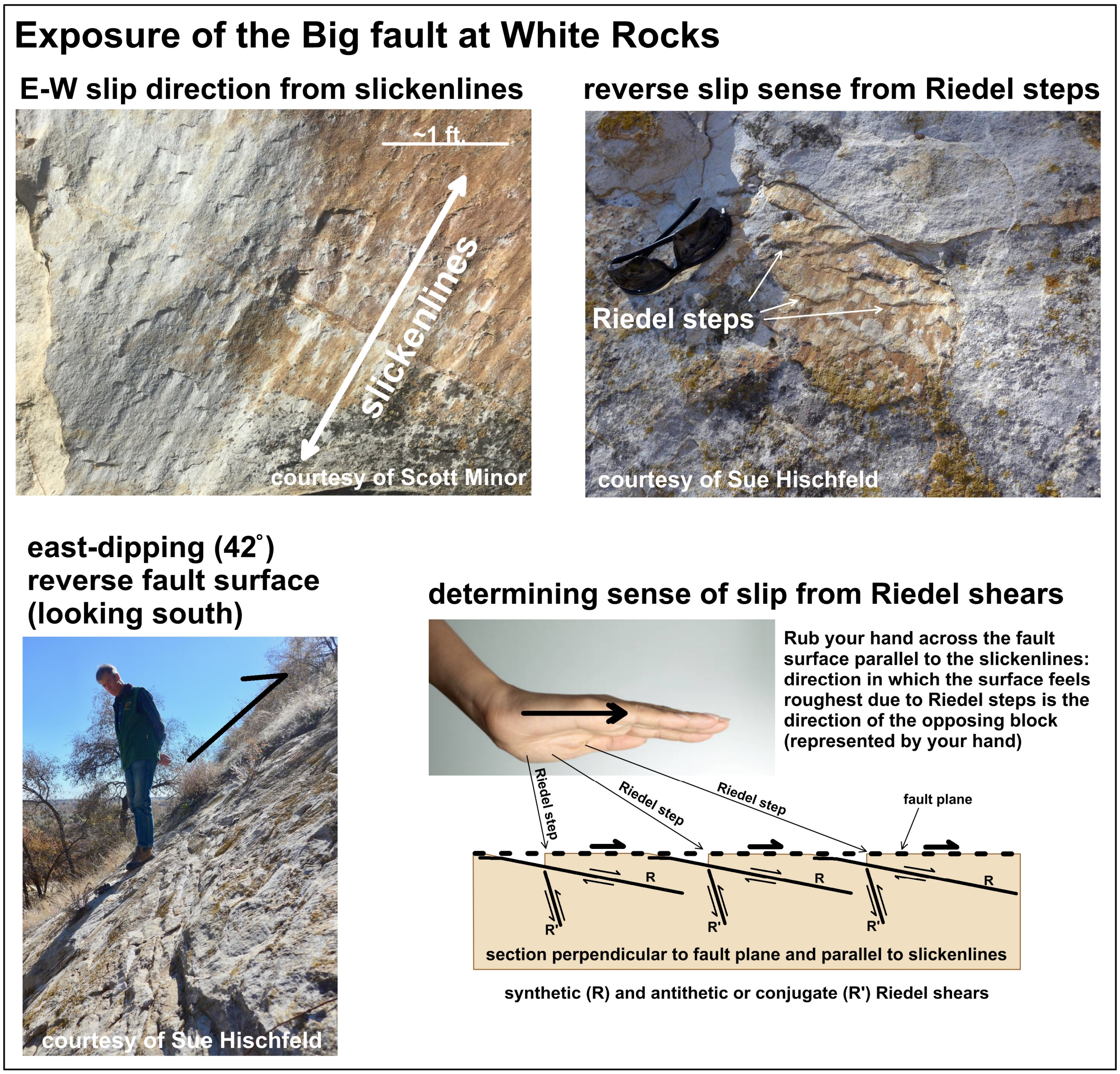

Figure 6: Exposure of the Big fault at White Rocks.

With approval from the City of Boulder Open Space and Parks Department and under the supervision of its archeologist, Christian Driver, we trenched suspected faults at four locales in White Rocks (Fig. 5 and Table 1).

Two trenches confirmed the location and variable north dip of what we call the Ertl fault (Fig. 5), interpreted here as an antithetic thrust to the Big fault, however, no fault plane ornamentation was observed to confirm its sense or direction of slip. Antithetic thrusts sole into and are linked to their paired master thrust, which in this case is the Big fault, but show an opposite direction of movement. Both faults, whether east- or west-directed, act together to accommodate horizontal shortening of the rock package. The paired faults bound the opposing sides of high structural blocks geologists refer to as pop-up structures. Frequent examples of these structures occur across the BWA (Sterne, 2020). Figure 5 shows the Ertl fault continuing to the northeast where it can be bracketed in outcrop in 1n-69w-8 by a change from flat dips on the southeast to high dips on the northwest. The fault plane is not exposed at this location, but might be uncovered by trenching. The Ertl fault may then continue off the map to the northeast where it appears as a second and higher fault in the well in 2n-69w sene (Fig. 1), noted above as being cut by a continuation of the Big fault (Sterne, 2020).

Two trenches were dug at the outcrop termination west of the former Weiser residence along what we call the Kolb fault (Fig. 5). There, numerous west-dipping fractures cut the outcrop (as noted originally by Emmons et al. , 1896) and the fracture face bounding the western limit of the sandstone outcrop dips west, but no hanging wall bedrock was found and no fault plane ornamentation could be seen to determine its sense of offset. However, based on the thickness (180') of Fox Hills recorded in the Kolb water well (1n-70w-13 sene) located west of the fault relative to the base of the sandstones seen immediately east of the fault in the Weiser water well (1n-69w-18 swnw), it appears to be a down-to-the-west normal fault. Of note, however, are possible reverse sense fabrics in the sandstones east of the termination, perhaps indicating earlier reverse slip on the fault (pers. comm., Scott Minor, USGS emeritus). The Kolb fault appears to continue at least two miles to the north where it outcrops as the western of two faults in 1n-69w-6 nwnw (Fig. 5). We did not find an exposure of the fault, but immediately east of its trace as mapped by Trimble (1975), we found west-dipping fractures cutting the Fox Hills that are similar to those seen east of the Kolb fault at White Rocks. The presence of a normal fault is further confirmed by missing section, indicating a normal offset, seen in the well immediately to the west of the outcrop in 2n-70W-36 sese. This same pattern of faulting is seen off the map another 1.5 miles to the north in a well in 2n-69w-30 senw (Fig. 1).

Table 1: White Rocks trench data

Locale	Fault	Location (Nad27)	fault strike	fault dip
1.	Ertl	40.05662º; -105.16707º	130º	35º northeast
2.	Ertl	40.05667º; -105.14572º	100º	52º north
3.	Kolb	40.05592º; -105.16926º	355º	52º west
4.	Kolb	40.05367º; -105.16962º	irregular west-dipping surface	

It is important to note that our correlations of individual Fox Hills shingles across the faults at White Rocks are tied to our structural interpretation as illustrated in a cross section drawn along the front of the outcrops (Fig. 7, Pl. 1). The structural interpretation shown on the cross section is guided by fault patterns seen elsewhere in the BWA (Sterne, 2020), and on a careful analysis of local subsurface control from the

Heather core, oil and gas tests and water wells. The wells included on Figure 7 are listed in Appendix 1. Key features on the cross section will be discussed below.

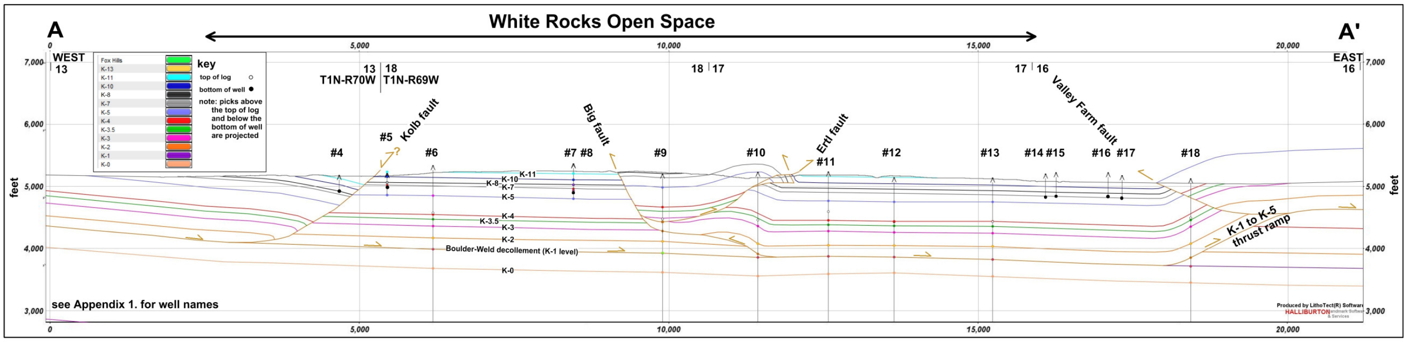

Figure 7: Detailed White Rocks E-W cross section.

Fossils

Invertebrate fossils were pointed out to us by geologist Sue Hirschfeld in thin layers on the eastern margin of the area. Trace fossils (animal tracks and burrows) are common in the sandstone beds. These fossils could be the subject of a separate report.

V Subsurface Investigations

CSM Heather Core #1

Our research included information from the Heather #1 core (1n-69w-7 sesesw) obtained by the Colorado School of Mines in the Heatherwood neighborhood immediately north of the White Rocks boundary. This core is described in detail in Weimer and Tillman (1980). We examined and photographed the core at the Colorado School of Mines core lab (Fig. 8). Based on the presence of Ophiomorpha (see blue tags on the core slabs), we confirmed the upper part of the core is in the marine Fox Hills Formation (as concluded previously by Weimer and Tillman, 1980) and the core is probably not affected by significant faulting

Data used at White Rocks and in the more regional study of the BWA

We have framed the White Rocks area in the broader context of the BWA using subsurface information from over 1000 resistivity logs in vertical oil and gas wells, and numerous lithologic logs from water wells, coal exploration boreholes, and cores across an area including all or parts of townships 2S to 2N and ranges 67W to 70W (Fig. 1; Sterne, 2020). Sixteen marker horizons labeled in ascending order K-0 to K-15, as well as the Fox Hills Formation facies top, were mapped to understand stratigraphic and structural patterns in the upper part of the Upper Cretaceous section across the BWA. The marker horizons represent approximate timelines and are recognizable across the study area. We must emphasize that facies types, characterized by shales of the Pierre, sandstones of the Fox Hills, and coals with mixed shales and sandstones of the Laramie do not follow timelines, rather they climb across the time horizons from west to east. In other words, a timeline might be bounded by Laramie coal facies on the west, by Fox Hills Formation facies farther east, and Pierre shale facies even farther east.

Figure 8: CSM Heather #1 Core photos.

For the Fox Hills part of the section, the marker horizons were carried into the White Rocks area using the lithologic and electric log information provided by the Heather #1 core (Fig. 9, 10). The transgressive surfaces of erosion noted by Weimer and Tillman (1980) above each of the coal occurrences mark the local return of marine conditions due to periodic sea level rises. These surfaces have been correlated to the horizons (K-6, K-8, K-10 and K-11) marking the tops of sandier intervals seen in well logs to the east across what is the more distal or offshore marine part of the system. Figure 9 and 10 also show the transgressive surfaces cap a thin veneer of Laramie facies (including thin coal beds) above the major sandstone benches seen in outcrop, which we have labeled A though D, in ascending order, and have used to make the geologic map (Fig. 5).

Local subsurface mapping

Understanding the White Rocks area requires understanding the spatial relationship between shallow data from outcrop, the CSM Heather core and water wells, and deeper control from oil and gas wells.

Near surface portions of the oil and gas wells were not logged around White Rocks and the water wells and cores do not go deep, so the different levels of data do not overlap. Figure 11 shows how these various elements relate structurally. The CSM Heather core is on the right with the western and eastern outcrop sections measured on either side of the Big fault to its left. Honoring the correlations Weimer and Tillman (1980) made between the Heather core and outcrops along the White Rocks cliffs to the south shows the CSM Heather core and the western outcrop section lie near the same elevation or, in structural terms, along strike to each other. This agrees with the level of the projected K-5 horizon in the intervening deep oil and gas well (05-013-06085) and local southeast-trending strike seen in the regional layer at the K-0 horizon, showing a regionally anomalous, southeast-striking anticlinal nose centered on White Rocks that persists upward through the section and is independent of thrusting in units above the K-1 horizon (Sterne, 2020).

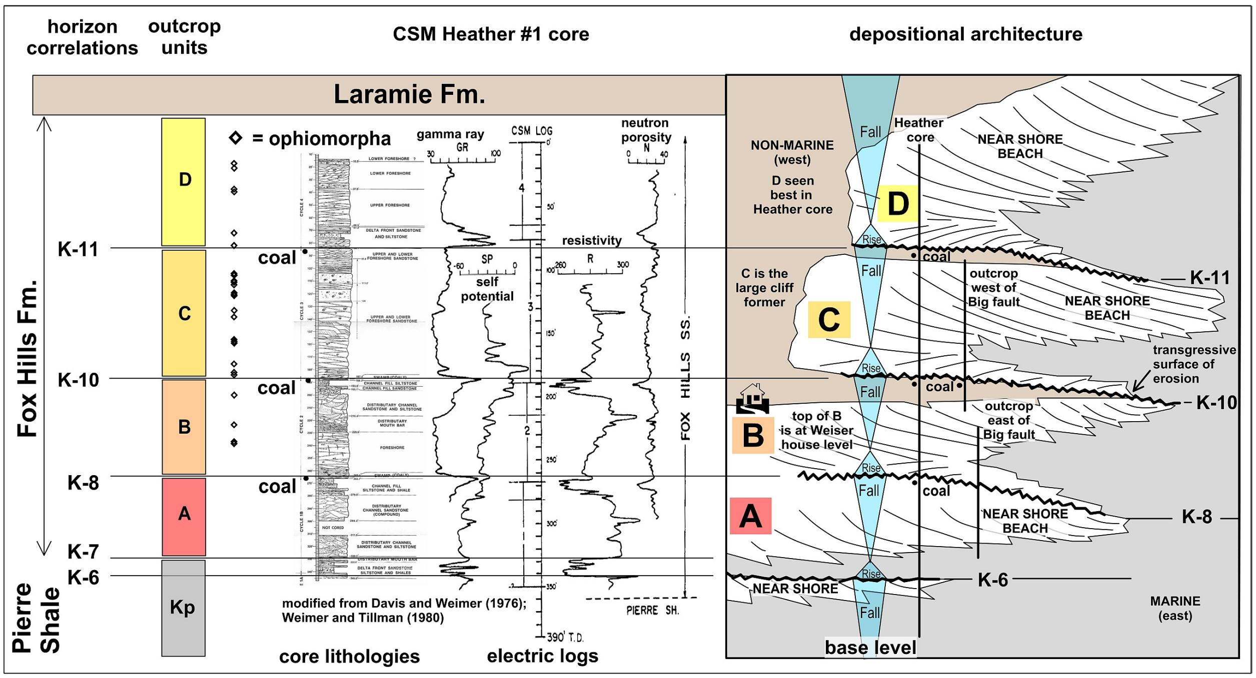

Figure 9: Correlation of the CSM Heather core lithologies and electric logs to marker horizons, outcrop units and depositional architecture.

The Weiser water well is the next point of control to the northwest. We have corrected the location for the well given by the Colorado Division of Water Resources. It is located immediately north of the former Weiser residence (485625 m E, 4433713 m N, WGS84) at a ground level of ~5141’. The well starts near the top of the “B” sandstone bench seen also at the base of the western outcrop section and encounters the base of the Fox Hills Formation facies at 120'. This level correlates stratigraphically to the appearance of offshore shale and sandstone facies at the base of the CSM Heather core marking the transition to the Pierre Shale (Fig. 12). Structurally, the base of the shoreline sandstone facies in the Weiser water well (K-7 horizon), the various outcropping sandstone benches, and the projected K-5 horizon in the oil and gas well (05-013-06061) located 0.24 miles northeast of the Weiser water well all rise 50-60’ west of the western outcrop section, supporting the stratigraphic correlation and indicating the deep, southeast-trending anticlinal nose that runs through the White Rocks area.

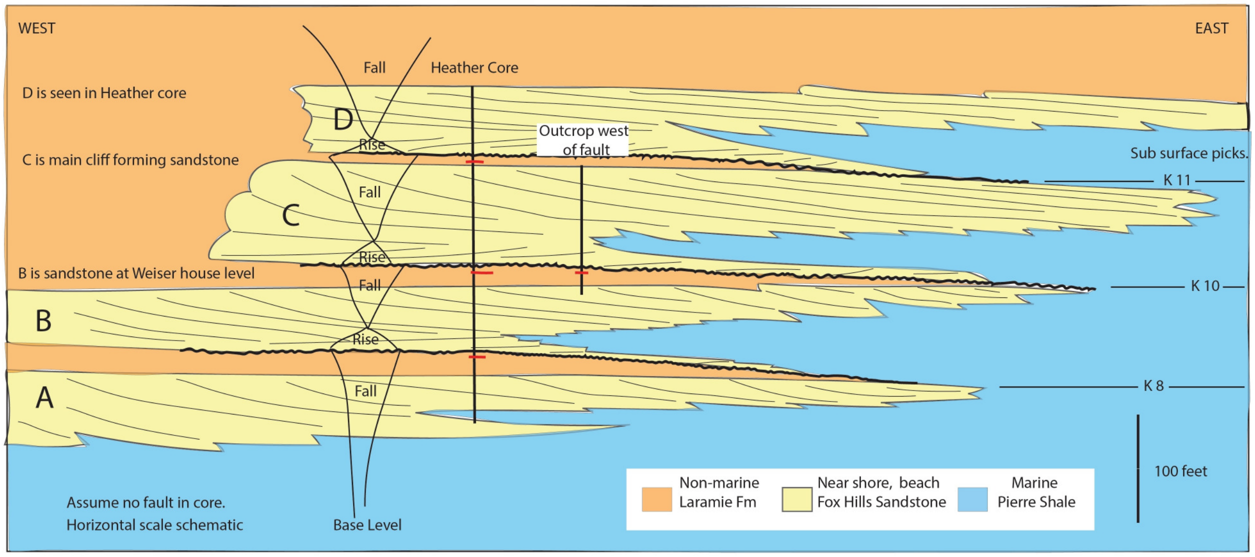

Figure 10: Stratigraphic patterns of the Fox Hills Sandstone at White Rocks

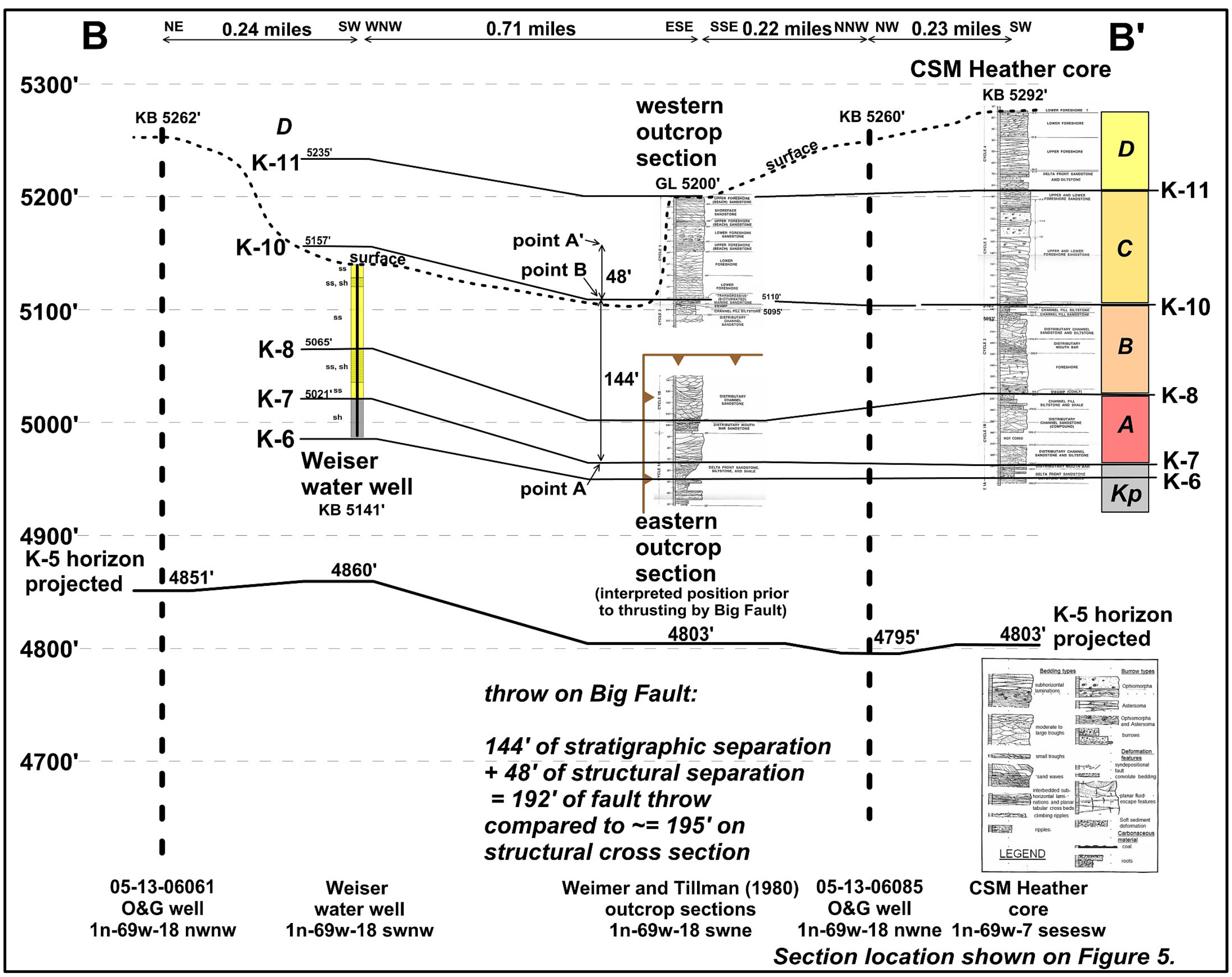

Figure 11: CSM Heather #1 core correlation to outcrop sections and wells

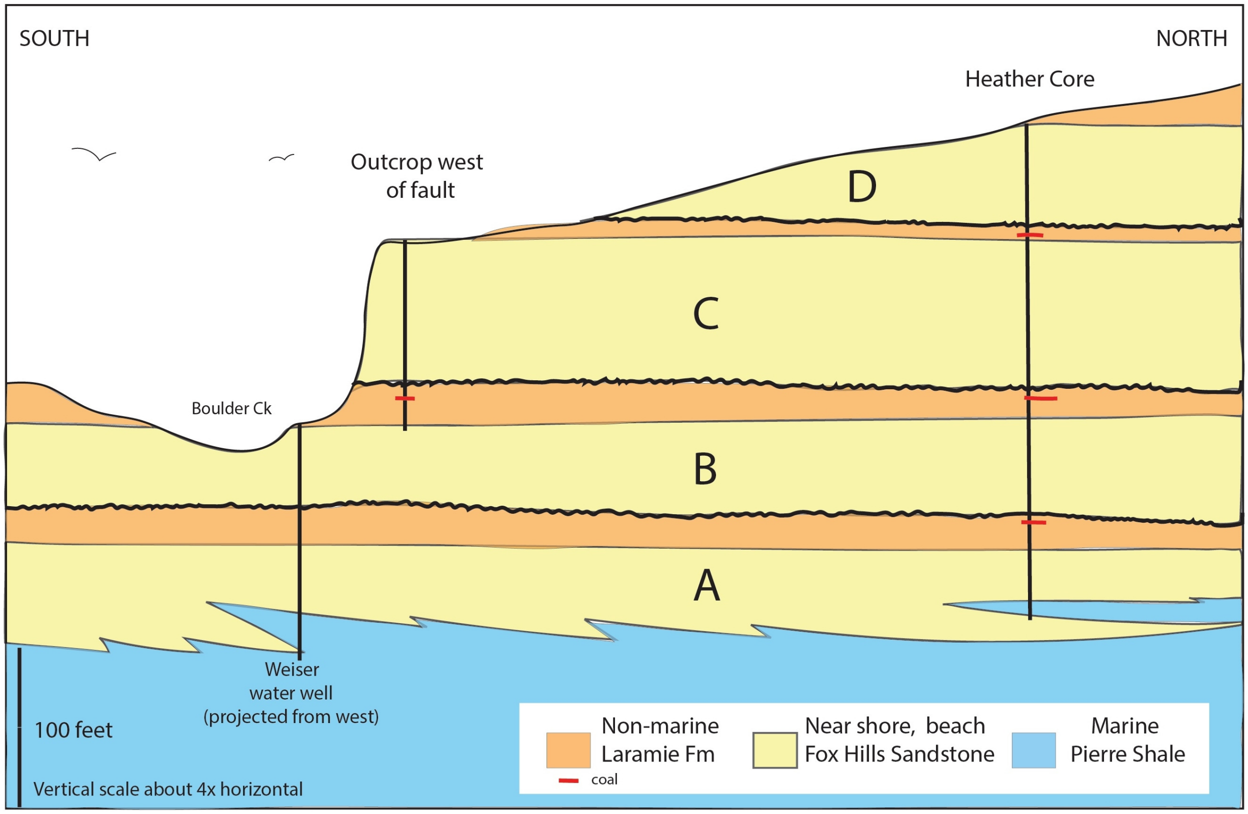

Figure 12: Schematic diagram illustrating core, outcrop, and water well

The base of the lowest massive sandstone on the eastern outcrop section was then hung relative to the base of the lowest massive sandstone in the CSM Heather core and the Weiser water well (K-7 horizon on Fig. 11). This interpretation projects there to be 144' of stratigraphic separation between the base of the shoreline sandstone facies in the eastern outcrop (point A) and the top of the lowest sandstone exposed in the western outcrop section (point B). Point A has been carried by the Big fault and based on detailed LIDAR elevation data now lies 48' structurally above point B in the footwall of the fault. Adding the 144' of original stratigraphic separation to the current 48' of structural inversion between the points gives 192' of throw on the Big Fault, which closely matches the throw encountered across the fault in the 05-013-06086 well (Fig. 5, 1n-69w-18 sene) as shown on the independently-constructed White Rocks cross section (Fig. 7).

We used the highest markers available in local oil and gas wells surrounding the CSM Heather core to project the elevation of the K-5 horizon below the CSM Heather core. This projection shows the K-5 horizon lies approximately 145' below the base of the K-7 horizon, which marks the base of the Fox Hills Formation facies in the White Rocks area. When these relationships are used to construct the White Rocks cross section (Fig. 7), projections of the K-5 horizon downward from the shallow water well and core data match those made by projecting upward from the deep oil and gas well data. This match corroborates the interpretation and allows us to use the structural section to help correlate the surface Fox Hills benches across the faults at White Rocks.

The Big fault and its paired antithetic, the Ertl fault, are the most prominent structures on the detailed cross section for White Rocks (Fig. 7). The position of their underlying thrust ramp is expressed at the surface as the north-south trending panel of high east dips seen east of the Big fault (Fig. 5). The thrust ramp is also indicated by stretched section and a fault repeat in the 05-013-06076 well (Fig. 5). As noted previously, the Big fault is beautifully exposed, dips 42 degrees to the east, and exhibits east-west trending stria and Riedel shears showing reverse dip-slip. We trenched the Ertl fault at two locations and found it dipping 33 degrees northwest to 52 degrees north-northeast. The Ertl fault shows more translation than the Big fault and without it the section could not be restored, i.e., the offset bedding would not fit together once folding and faulting were taken out.

Figure 7 also shows one normal fault. The 180’ of sandstone reported to total depth in the Kolb water well (1n-70w-13 sene) is the control for the down-to-the-west normal offset on the Kolb Fault. As noted earlier, we trenched a west-dipping fracture surface at the suspected outcrop trace of the fault, but found no slip indicators. However, Scott Minor, formerly of the U.S.G.S, saw some possible reverse slip indicators in the sandstones adjacent to the fault, suggesting this may have originally been a thrust fault.

Both the thrust faults and the normal fault sole into a detachment at the K-1 marker horizon, below which lies a regional layer undisturbed by the shallow faulting.

VI Structure and Genesis of the Boulder Weld Allochthon

White Rocks’ context within the BWA

In the broader context of the BWA, White Rocks is best understood by looking at a generalized block diagram (Fig. 13) and a regional structural cross section (Figs. 14). Figure 14 is shown with a 3x vertical exaggeration to reveal details of the shallow deformation, while allowing the whole system to be fit on the page. Keep in mind vertical exaggeration distorts the structure, especially where faults and bedding have high dips. Wells shown on Figure 14 are listed in Appendix 1.

On the west, the regional section (Figs. 14) shows east dips off the flank of the Haystack Mountain anticline (Boulder Field structure) forming the first step up along the eastern flank of the Front Range basement uplift. East of the range front, the K-0 horizon flattens to a dip of approximately one degree to the southeast , which typifies structure within the regional layer below faults of the overlying BWA, except around the southeast plunging anticlinal nose seen in the White Rocks area (Sterne, 2020)

The BWA moved to the east above a fault we call the Boulder-Weld decollement. The decollement dives east from its erosional limit along the flank of the Haystack Mountain anticline into the subsurface below White Rocks where it parallels the K-1 horizon

Just east of White Rocks there is a 900’ thrust ramp that connects bedding-parallel thrust detachments at the K-1 and K-5 horizons. Units in the K-1 to K-5 interval have been thrust up the ramp and carried to the east along the K-5 level detachment as shown by clear repeated log signatures in several wells located immediately east of the ramp (for example the Exeter Deepe 11-22 well in 1n-69w-22 nesw) (Fig. 1). East of the hanging wall truncation of the thrusted K-5 unit, thrusts are restricted to units younger than the K-5 horizon.

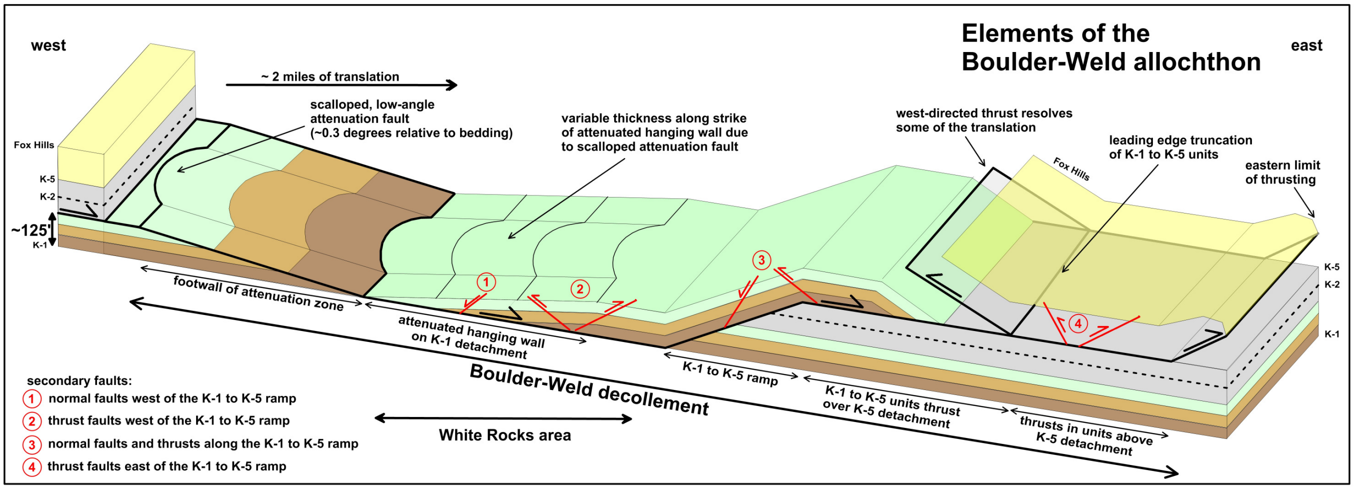

Figure 13: Block diagram showing elements of the Boulder-Weld allochthon

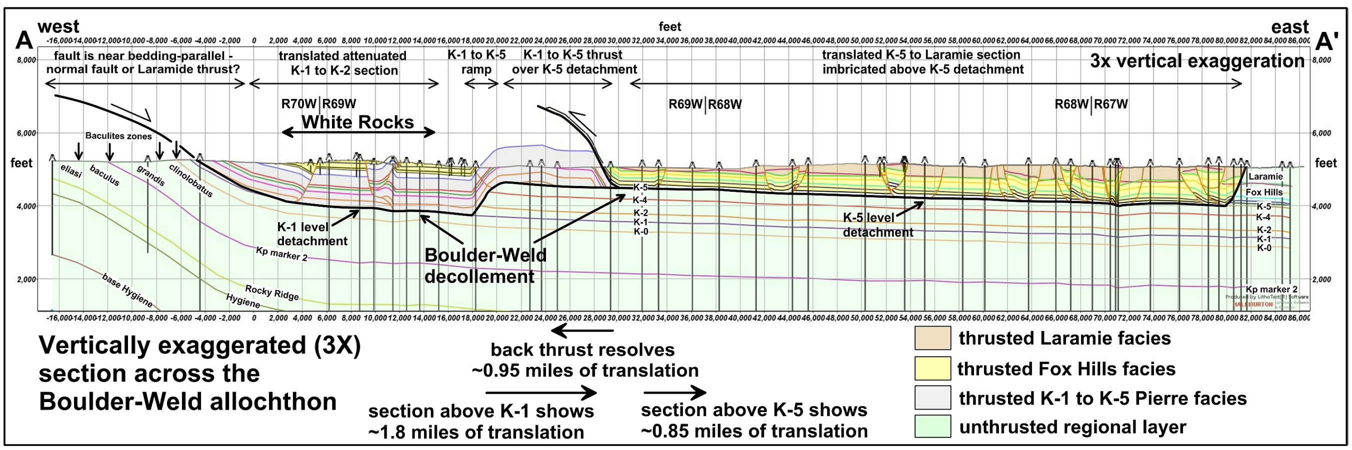

Figure 14: Annotated 3x vertically exaggerated regional section across the Boulder-Weld allochthon (A-A')

Except for the Kolb normal fault at White Rocks, the only other normal faults seen in the BWA occur along the trend of the K-1 to K-5 thrust ramp. Such normal faults likely form as relatively minor extensional overprints on the preexisting thrust ramp (Figs. 13 and 14).

Translation within the northern part of the BWA

The K-1 to K-5 units carried up and east of the ramp exhibit approximately 1.8 miles of translation, however, east of the hanging wall truncation of the K-5 unit, thrusts to the east show 0.85 miles or only about half as much cumulative translation (Fig. 14). This difference in translation between the western and eastern parts of the BWA is shown to be resolved by 0.95 miles of west-directed movement along a back thrust detached at the K-5 horizon (Figs. 13 and 14). The thrust is shown above the topographic surface on Figure 14 indicating it has been eroded away.

Past models for the origin of the BWA

Past interpretations for the genesis of faulting with the BWA have varied widely. Early interpretations by Spencer (1961, 1986), Haun (1968), Weimer (1973) and Bedwell (1974) showed a mix of high-angle reverse and normal faults, despite a preponderance of measured thrust and reverse faults reported from outcrop and subsurface mines (Emmons et al., 1896; Fenneman, 1905; Spencer, 1961). Haun (1968) extended the faults to basement. Spencer (1986) thought they died out in the Pierre Shale above the Hygiene Sandstone Member. Weimer (1973), Rahmanian (1975), Davis and Weimer (1976), and Weimer and Davis (1977) proposed growth on listric normal faults soling out in the Pierre Shale to explain the fault style. Most recently, Trudgill (2015) put a new twist to the growth fault hypothesis by explaining the thrusts as inversions of earlier growth faults. We see little support for any of these models.

The biggest advancement in our understanding of the BWA came with the work of Kittleson (1992, 2009) based on his recognition from well logs of decollement thrusting above a shallow detachment at the K-5 horizon (his Kp2). He interpreted these features as thrusts developed along the toe of a gravity slide. He proposed the gravity slide traveled from northwest to southeast off the Greeley Arch (Wattenberg High) and was triggered by movement along the northeast trending Longmont fault of Weimer (1996). Similarly, Selvig (1994) proposed a southeast-directed gravity slide origin for the BWA based stress inversion techniques used to interpret fault and slickenline orientations in outcrops of the Marshall area.

Proposed models for the origin of the BWA

Based on the geometries revealed in this study, the BWA formed either as a gravity slide or a Laramide thrust. Slickenline orientations across the western part of the BWA (Sterne, 2020), including data from the Big fault at White Rocks, show a common east-west direction of translation for both the western part of the BWA and Laramide thrusts of the neighboring Front Range. While this does not preclude a gravity slide origin, it shows a different direction of movement for the BWA than proposed previously, and a possible link to Laramide thrusting.

Dense well control across the White Rocks area shows hanging wall attenuation at the decollement increasing gradually to the west (Sterne, 2020). Such attenuation (Fig. 13) could indicate the presence of a near bedding-parallel normal fault, which in combination with the Kolb normal fault, could be part of a breakaway zone developed along the west side of the BWA. If present, such a feature would support a gravity slide origin for the BWA.

Alternatively, while thrust faults typically parallel bedding or cut up-section in the direction of transport, there are exceptions especially in areas with preexisting deformation. In this case the decollement cuts across bedding at an angle of 0.3 degrees, so it is almost bedding-parallel. There are faults mapped in the regional layer west of and below the BWA at Boulder Reservoir (Cole and Braddock, 2009; and field observations by Sterne) that could have caused the BWA decollement to locally cut down-section in the direction of transport. In other words, the attenuation seen across the White Rocks area does not preclude the origin of the BWA as a Laramide thrust. If there is a link to Laramide thrusting, Sterne (2019, 2020) shows the BWA would most likely have formed as an east-directed, near bedding-parallel, antithetic thrust linked to and resolving west-directed translation on basement thrusts in the Front Range. In structural terms, the decollement would represent an east-directed roof thrust generated by movement on west-directed basement-involved floor thrusts as part of a triangle zone or tectonic wedge. Figure 15 shows a simple way of visualizing how these antithetic faults conspire to shorten the section horizontally and thicken it vertically. The BWA is analogous to the uppermost index finger while the lower index finger corresponds to the surface thrusts of the Front Range.

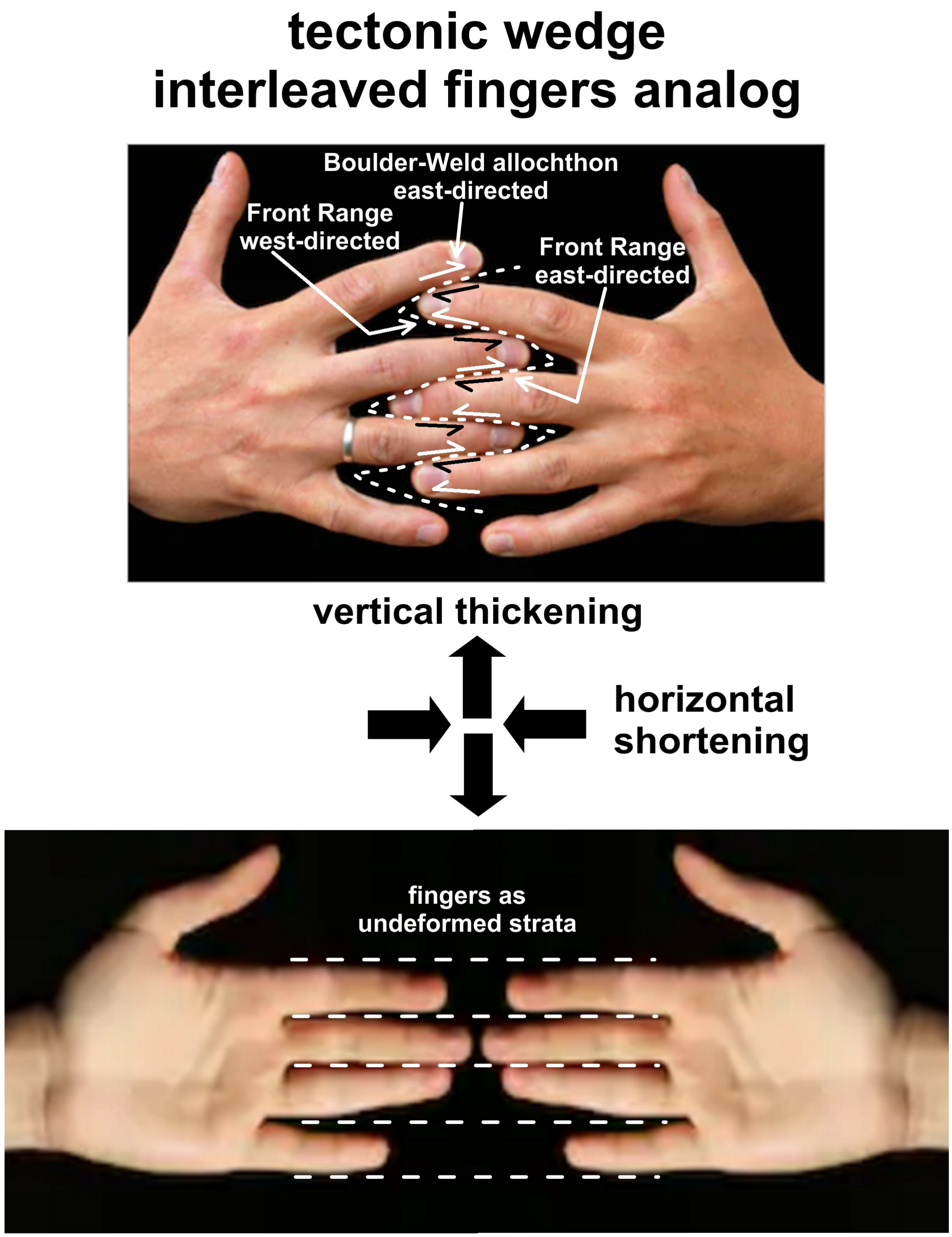

Figure 15: Interleaved fingers as an analog for horizontal shortening and vertical thickening in a tectonic wedge or triangle zone.

For both the gravity slide and Laramide thrust models the diagnostic fault relationships have been removed due to erosion beyond the western margin of the BWA, so it may not be possible to determine which model is correct. It is even possible Laramide thrusting initiated gravity sliding, leaving open the possibility of a hybrid origin for the BWA.

VII Conclusion, Future work and GIS applications

The White Rocks area is an important geologic locale because of its superb exposures of the Fox Hills Formation and the excellent structural information provided by its surface exposure of the Big fault and subsurface well information that reveals key elements of the Boulder-Weld allochthon not seen elsewhere.

This study has for the first time revealed a detailed picture of all of the structural elements of the Boulder-Weld allochthon. What is less clear is its genesis. The more conventional approach would be to view the BWA as a gravity slide developed above an east-dipping normal fault. The alternate would be to link the BWA to Laramide thrusting along the range front. The latter should prompt geologists to look for other examples of roof thrusts that dip in their direction of transport, i.e., thrusts that masquerade as normal faults.

We suggest the geologic map be incorporated into the County GIS data base to be used for further resource inventory and analysis. More detailed mapping is recommended to capture details of rock facies patterns and more subtle features such as the distinctive polygonal jointing (Netoff, 1971), presence of trace fossils, fossil trees, and other features.

VIII Acknowledgements

Sue Hirschfeld introduced us to the geology of the area and helped to foster our collaboration with the City of Boulder Open Space and Mountain Parks Department

Lynn Riedel, Grassland Plant Ecologist, City of Boulder Open Space and Mountain Parks facilitated our access to the White Rocks study area.

Christian Driver, Archeologist, City of Boulder Open Space and Mountain Parks supervised our fault trenching activities at White Rocks.

Scott Minor, U.S.G.S. emeritus, joined us in the field and helped with our structural analysis.

Maria Henry provided the Petra software that made if feasible to pick tops in over 1100 wells across the BWA.

Steve Cumella provided valuable insights into the geology of the Denver Basin

Halliburton’s LithoTect software was used to construct the cross sections.

IX References

Aurand, H.A., 1920's, Original hand-drafted plane table map of the White Rocks area in the collection of the Denver Earth Resources Library showing strikes and dips of bedding and faults.

Bedwell, J. L., 1974, Textural parameters of clastic rocks from borehole measurements and their application in determining depositional environments: Ph.D. dissertation, Colorado School of Mines, 215 pp.

Cole, J.C. and Braddock, W.A., 2009, Geologic map of the Estes Park 30' by 60' quadrangle, north-central Colorado: U.S. Geological Survey Scientific Investigations Map 3039 and pamphlet, p. 56.

Colton, R.B. and Anderson, L.R., 1977, Preliminary geologic map of the Erie quadrangle, Boulder, Weld and Adams counties, Colorado: U.S. Geological Survey Misc. Field Studies, Map MF-882.

Dechesne, M., Raynolds, R.G., Barkmann, P.E., and Johnson, K.R., 2011, Notes on the Denver Basin geologic maps: bedrock geology, structure, and isopach maps of the Upper Cretaceous to Paleogene strata between Greeley and Colorado Springs: Colorado, Denver Museum of Nature and Science and the Colorado Geological Survey, p.35.

Davis, T.L. and Weimer, R.J., 1976, Late Cretaceous growth faulting, Denver Basin, Colorado: Colorado School of Mines Professional Contributions, no. 8., p. 280-300.

Dobbin, C.E. and Reeside, J.B., Jr., 1929, The contact of the Fox Hills and Lance formations: U.S. Geological Survey Prof. Paper 158, p. 9-25.

Emmons, S.F., W. Cross, and G.H. Eldridge, 1896, Denver Basin in Colorado: U.S. Geological Survey Monograph 27, 150 pp.

Fenneman, N.M., 1905, Geology of the Boulder District, Colorado: U.S. Geological Survey Bulletin 265, 101 pp.

Haun, J.D., 1968, Structural geology of the Denver Basin – regional setting of the Denver earthquakes: Colorado School of Mines Quarterly, v. 63, no. 1, p. 101-112.

Hayden, F.V., 1877, Geological and geographical atlas of Colorado and portions of adjacent territory: U.S. Dept. of the Interior, geological and geographical survey of the territories.

Kellogg, K.S., Shroba, R.R., Bryant, B. and Premo, W.R., 2008, Geologic map of the Denver West 30' by 60' quadrangle, north-central, Colorado: U.S. Geological Survey Scientific Investigations Map 3000 and pamphlet, 48 pp.

Kittleson, K., 1992, Decollement faulting in the northwest portion of the Denver Basin, The Mountain Geologist, Rocky Mountain Association of Geologists, v. 29, no. 2, p. 65-70.

Kittleson, K., 2009, The origin of the Boulder-Weld fault zone, east of Boulder, Colorado, The Mountain Geologist, Rocky Mountain Association of Geologists, v. 46, no. 1, p. 37-49.

Landman, N. H., and Cobban, W.A., 2003, Ammonites from the upper part of the Pierre Shale and Fox Hills Formation of Colorado: American Museum Novitates, number 3388; 45 pages.

McGookey, D.P. Haun, J.D., Hale, L.A., Goodell, H.G., McCubbin, D.G., Weimer, R.G., and Wulf, G.R., 1972, Cretaceous System: *in* Mallory, W.W. ed., Geologic Atlas of the Rocky Mountain Region, Rocky Mountain Association of Geologists, p. 190-228.

Meek, F.B. and Hayden, F.Y., 1861, Descriptions of new Lower Silurian (Primordial), Jurassic, Cretaceous and Tertiary fossils collected in Nebraska by the exploring expedition under the command of Captain W.F. Raynolds, U.S Topographical Engineer, with some remarks on the rocks from which they are obtained: Philadelphia Academy of Natural Science Proceedings, p. 415-447.

Netoff, D.I., 1971, Polygonal jointing in sandstone near Boulder, Colorado, Mountain Geologist, Rocky Mountain Association of Geologists, v. 8, p. 17-24.

Rahmanian, V.D., 1975, Deltaic sedimentation and structure of the Fox Hills and Laramie Formations, Upper Cretaceous, southwest of Boulder, Colorado: Master's Thesis, Colorado School of Mines, 83 pp.

Reading, H.G., and Collinson, 1996, Clastic coasts, Chapter 6 in: Reading, H.G., ed., Sedimentary Environments; processes, facies, and stratigraphy: Blackwell Science, Oxford, p. 154-231.

Scott, G. R., and Cobban, W.A., 1965, Geologic and biostratigraphic map of the Pierre Shale between Jarre Creek and Loveland, Colorado, U.S. Geological Survey Misc. Geological Inves. Series Map I-439, scale 1:48,000.

Selvig, B. W., 1994, Kinematics and structural models of faulting adjacent to the Rocky Flats Plant, Central Colorado: M.S. thesis Colorado State University, Colorado, p. 132.

Spencer, F.D., 1961, Bedrock geology of the Louisville Quadrangle: U.S. Geological Survey Quad Map GQ-151.

Spencer, F.D., 1986, Coal geology and coal, oil, and gas resources of the Erie and Frederick Quadrangles, Boulder and Weld counties: Colorado, U.S. Geological Survey Bulletin 1619, 50 pp.

Sterne, E.J., 2019, Palinspastic restoration of the eastern flank of the Colorado Front Range at Coal Creek, constrained by outcrop geology, wells and a pre-stack depth migration of the Rocky Flats deep seismic line, reveals a system of stacked triangle zones: poster presented at the AAPG Rocky Mountain Section Meeting, Cheyenne, WY.

Sterne, E.J.,2020, Structure and genesis of the Boulder-Weld allochthon, Denver Basin, Colorado – gravity slide, Laramide thrust or a hybrid?, in review by the Mountain Geologist, Rocky Mountain Association of Geologists.

Trimble, D.E., 1975, Geologic map of the Niwot Quadrangle, Boulder County Colorado: U.S. Geological Survey Map GQ-1229.

Trudgill, B., 2015, Unraveling the geometry and origin of a northeast-southwest striking linked array at Marshall Mesa, western Denver Basin: a (possible) solution through integrated digital mapping: AAPG Search and Discovery Article #10755.

Waage, K.M., 1961, The Fox Hills Formation in its type area, Central South Dakota: Wyoming Geological Association Guidebook, p. 229-240.

Waage, K.M., 1968, The type Fox Hills Formation, Cretaceous (Maestrichtian), South Dakota, part 1: Stratigraphy and paleoenvironments: Peabody Museum of Natural History, Yale University, Bulletin 27, p. 1-175.

Weimer, R.J., 1973, A guide to uppermost Cretaceous stratigraphy, Central Front Range, Colorado: Deltaic sedimentation, growth faulting and early Laramide crustal movement: The Mountain Geologist, Rocky Mountain Association of Geologists, v. 9, nos. 2-3, p. 241-267.

Weimer, R.J., 1996, Guide to the petroleum geology and Laramide Orogeny, Denver Basin and Front Range, Colorado: Colorado Geological Survey Bulletin, No. 51, p. 1-127.

Weimer, R.J., and Davis, T.L., 1977, Stratigraphic and seismic evidence for Late Cretaceous growth faulting, Denver Basin, Colorado: AAPG Memoire 26, p. 277-299.

Weimer, R. J. and Tillman, R.W., 1980, Tectonic influence on deltaic shoreline facies, Fox Hills Formation, West-Central Denver Basin. SEPM field trip guidebook: Colorado School of Mines Professional Contributions, number 10, 131 pp.

Appendix 1: Key to wells on Figures 7 and 12

well number on section A-A" White Rocks section	Township	Range	Section	Spot Call	Well Name	Well Number	API Number	Datum	Projection to section
1	1N	70W	9	NWNWSE	WINTER HAWK LEWIS	9-1	05013060250000	5228	5200' SW
2	1N	70W	10	NESE	BOWEN	1	05013400040000	5200	4700' SW
3	1N	70W	11	SWSWNE	EAST VIEW GUNBARREL	1	05013099990000	5261	4350' SW
4	1N	70W	13	SENE	KOLB WATER WELL			5105	950' N
5	1N	69W	18	NWSWNW	WEISER WATER WELL			5141	600' N
6	1N	69W	18	NE NW NW	ERTL	18-2	05013060610000	5262	450' S
7	1N	69W	7	SWSWSE	CSM HEATHER CORE	1		5292	1300' SE
8	1N	69W	18	NWNE	ERTL	4-18	05013060850000	5260	300' SE
9	1N	69W	18	NE	ERTL	5-18	05013060860000	5127	700' N
10	1N	69W	17	SE NW NW	ERTL	17-3	05013060760000	5157	200' S
11	1N	69W	17	NW SE NW	ERTL	1	05013060260000	5161	500' N
12	1N	69W	17	SW SW NE	CULVER	5-17	05013061120000	5070	1450' N
13	1N	69W	17	C SE NE	CULVER	3-17	05013060900000	5064	800' N
14	1N	69W	9	NWSWSW	MERVAR WATER WELL			5128	1550' S
15	1N	69W	9	NWSWSW	FITZGERALD WATER WELL			5148	1675'S
16	1N	69W	9	NESWSW	JOHNSON WATER WELL			5150	2050' S
17	1N	69W	9	SESW	LASS WATER WELL			5102	1350' S
18	1N	69W	16	NE SE NW	CULVER	MC16-6	05013060230000	5052	775' NE
19	1N	69W	22	C NW NW	STEINBAUGH	1	05013050120000	5073	5000' NNE
20	1N	69W	22	NE SW	DEEPE	11-22	05013060050000	5102	7650' NNE
21	1N	69W	15	NW SE	LEYNER	15-1	05013060490000	5042	2700' NNE
22	1N	69W	14	NE SW	JASPER	23-14	05013064560000	5047	2475' NNE
23	1N	69W	14	C NE SE	WISE	1-14	05013061550000	5084	1475' NNE
24	1N	69W	13	NW SW	NEWMAN SHAFFER	13-13	05013065390000	5087	2300' NNE
25	1N	69W	13	SW NE NE	WIGGETT	13-1	05013060520000	5029	100' S
26	1N	68W	18	NWNW	SOSA	12-18	05123262390000	5031	300' NNE
27	1N	68W	18	SW NE NE	ERIE CHAMPLIN B	1	05123123770000	5081	375' NNE
28	1N	68W	17	SW NE NW	EAST ERIE 2-17	1	05123144470000	5096	900' NE
29	1N	68W	16	NE SW	STATE	11-16	05123243970000	5206	2650' NE
30	1N	68W	16	SWNE	WELD M.O.F. CORE	1		5155	1800' NE
31	1N	68W	16	NESE	WELD M.O.F. CORE	4		5174	2400' NE
32	1N	68W	16	SENE	WELD M.O.F. CORE	5		5163	1850' NE
33	1N	68W	16	SWSE	WELD M.O.F. CORE	8		5189	3950' NE
34	1N	68W	16	SW NE SE	STATE	16-9V	05123161050000	5191	3500' NE
35	1N	68W	15	SW SW	UPRR 43 PAN AM-W	1	05123100710000	5173	3675' NE
36	1N	68W	15	NW SE SE	UPRR 43 PAN AMERICA	2	05123143880000	5152	3600' NE
37	1N	68W	14	C NE NW	UPRR 43 PAN AM-Y	1	05123125470000	5098	200' SW
38	1N	68W	14	C NE SE	UPRR 43 PAN AM-I	32	05123098730000	5140	2600' NE
39	1N	68W	13	NW SW	UPRR 43 PAN AM-I	30	05123098900000	5141	3250' NE
40	1N	68W	13	C SW NE	SCHWAB 32-13/1-68/	1	05123084280000	5114	1300' NNE
41	1N	68W	13	C NE SE	UPRR 43 PAN AM 1	3	05123084730000	5078	2750' NE
42	1N	67W	19	NW	UPRR 43 PAN AM H	10	05123088980000	5111	5400' NE
43	1N	67W	19	NW SW	UPRR 43 PAN AM-H	12	05123089240000	5133	8000' NE
44	1N	67W	19	SW	UPRR 43 PAN AM-H	12-A	05123090230000	5134	8000' NE
45	1N	67W	18	C SW NE	HINGLEY	4	05123083880000	5094	2200' NE
46	1N	67W	18	SE	LAURIDSON-A	1	05123079920000	5132	4000' NE
47	1N	67W	17	NE SW SW	UPRR 42 PAN AM N	1	05123081050000	5137	5050' NE
48	1N	67W	19	SE NE NE	HOPKINS 41-19/1-67/	2	05123080760000	5170	8000' NE
49	1N	67W	17	NE SE	UPRR 42 PAN AM-N	1	05123112020000	5112	3900' NE
50	1N	67W	17	SW SE	HSR-UNDERHILL	15-17A	05123204330000	5126	5400' NE
51	1N	67W	16	C SW	SHEIDT J-STATE	4-16	05123115420000	5071	3500' NE
52	1N	67W	16	NE SE	SCHEIDT STATE	VV16-4D	05123160860000	5039	3300' NE
53	1N	67W	21	SW NE	UPRR 42 PAN AM O	1	05123083490000	5029	6750' NE