THE GEOLOGY OF THE CARTER LAKE AREA, COLORADO

By
Howard Ralph Stagner, B. A.,
University of Colorado, 1931

A Thesis Submitted to the Faculty of the Graduate School of the University of Colorado in partial fulfullment of the requirements for the Degree M. A.

Department of Geology

1933

CONTENTS

MAPS AND ILLUSTRATIONS

Plate 1.

A. Faulted Dakota Anticline looking south. The fault trends south up valley toward top of ridge.

B. "Red Beds" anticlinal valley looking south. The structure closes at the high peak in the center background. The Fountain outcrips in the bottom of the valley, The Ingleside forms the first prominant ridge on the left and the Lyons the ridge on the extreme left with the red Lyons "transitional zone outcropping between.

INTRODUCTION

The Carter Lake area includes approximately thirty square miles along the foothills of the Front Range of northern Colorado, between the Big Thompson and Little Thompson Creeks. More definitely the area includes sections 22, 23, 24, 25, 26, and 27, east 1/4 sections 28 and 33 of Township 5 north, range 70 west; and sections 1, 2, 3, 4, 9, 10, 11, 12, and the north 1/2 sections 21, 22, 23, and 24 of Township 4 north, range 70 west. Carter Lake is located in the west central part of the area.

Within this area the sedimentary rocks, whose upturned edges flank the east slope of the Front Range have been distorted by the forces responsible for the Rocky Mountain uplift. Folds and faults trending north-south, and northwest-southeast also occur. It was for the purpose of describing these structures, and studying their relationships to each other and to the general structure of the Front Range that the study of this area was undertaken, and it is with this problem that this paper is chiefly concerned. In mapping the various sedimentary formations the problem of the correlation of the "Red Beds" arose, and a brief study of this problem was made, the conclusions of which are briefly stated in this paper.

The field work was done during the spring of 1932. An enlargement of the United States Geological Survey map of the Loveland Quadrangle was used as a base map. A plane table and telescopic alidade were used to map the geological features. A triangulation net was first established, and the geological features were mapped by stadia traverse, and in a few places by brunton and pace traverse, and tied in to the triangulation net by resection. The plane table map was then transferred to the base map. In certain places slight changes were made in the enlarged topographical map.

Very excellent assistance was given by Mr. Allen Dakan, who acted as instrument man in most of the field work. The writer also expresses appreciation for assistance given by Mr. Louis O. Quam as instrument man and rod man, Ronald Ives, photographer, and to the other members of the Geology Department, University of Colorado, for their helpful suggestions and criticisms.

General Geography and Geology

"The Rocky Mountain Province comprises a large part of the eastern division of the North American Cordillera. It lies between the Great Plains to the east and the Colorado Plateau, Great Basin and Columbia Plateau and Northern Interior Plateau on the west." In Central Wyoming the Green River and North Platt Rivers separate the Rocky Mountains into a northern division and a southern division. The southern division, which reaches its greatest development in Colorado, is formed by several more-or-less parallel ranges trending in a north to northeast direction. The east front of the system is formed by three separate ranges-- the Front

Range, which continues into Wyoming as the Laramie Mountains, and Medicine Bow Range, and the Wet and Sangre de Cristo Ranges. These ranges are offset westward in an echelon arrangement, and are separated by north and northwest trending valleys or parks. West of the Front Range lie North, Middle, and South Parks, and west of the Wet Mountains is Huerfano Park. These parks form a series of lowlands between the Front Range element and the chain forming the west side of the Rocky Mountains in Colorado. They represent down-warped, or down-faulted parts relative to the large domical uplift which is the essential structure of the Colorado Rockies.

The main ranges are composed of a core of granite, gneiss, and schist into which have been intrded numerous stocks and dikes, chiefly of monzonitic character. On the flanks and in the down-warped portions of the system, Paleozoic, Mesozoic and Tertiary sediments occur. Some of these sediments without doubt formerly extended entirely over the major dome-like uplift, but have been completely removed from most of the mountain area by the extensive erosion that followed the various elevations of the mountain area.

Mesozoic formations are conformable in dip to late Paleozoic formations. Where early Paleozoic beds outcrop they are unconformably below the late Paleozoic beds. Cenozoic beds overlap all the earlier series, and the entire sedimentary section overlies the pre-Cambrian metamorphic and igneous rocks with a very decided angular unconformity.

PHYSIOGRAPHY

The topography of the Carter Lake area has been influenced by both the rock formations that outcrop along the foothills and the structural features of the region. Where the sedimentary beds have their normal east dip the more resistent formations form long continuous ridges paralleling the main mountain front, while the softer strata between have been eroded to form parallel valleys. In other places where the formations have been folded and faulted, these structures too are reflected in the topography, controlled by certain resistent beds. The important of these topographic forms will be described.

Topography Controlled by Tilted Sedimentary Beds

Strike Valleys

Along the west border of the area mapped, Chimney Hollow, a strike valley extending for six miles from the Little Thompson Creek north to Cottonwood Creek, has been eroded out of the lower part of the Fountain formation. To the west of this valley, schists and gneisses form a rather rugged and high series of mountains of which Blue Mountain and Bald Mountain are the most conspicuous. The east side of this valley is a steep slope on which various resistant members of the Fountain formation form minor cliff-like outcrops.

A second important strike valley has been formed by the erosion of the Lykins shale. Meadow hollow is of this

A. Cross-bedding in Lyons formation on the north side of Cottonwood Creek.

B. Cross-bedding in Ingleside formation, on north side of Cottonwood Creek.

origin, and extends from Little Thompson Creek northward to Carter Lake. To the west this valley is bounded by the Lyons-Ingleside dip-slope, and to the east by the west-facing Dakota hogback. The Berthoud cut-off road follows a similar Lykins valley from the point where it enters the foothills, northward, past Cottonwood Creek. Minor strike valleys have been formed in the lower Lyons formation west of Carter Lake, and locally in the soft middle Dakota shales.

Hogbacks

The Lyons, Ingleside and top of the Fountain formation constitute a resistent series of beds which are responsible for the highest north-south hogback. Where it is most prominant between Chimney Hollow and Meadow Hollow, the west-facing escarpment is steep, and is largely covered with talus broken from the top of the hogback. The eastern slope is a more gentle dip-slope. Usually the lower Lyons and Ingleside form the top of this ridge, and the typical cross-bedded Lyons sandstone forms a minor ridge about half way down the eastern slope. But, in some places, the typical Lyons and Ingleside formations form equally prominant ridges, and the result is a double topped hogback, or a flat topped ridge.

To the east, making the east side of the Lykins valley, the Dakota formation forms a second prominant hogback. As in the case of the Lyons-Ingleside hogback, the escarpment faces west, and the east slope is a more gentle dip-slope. Large blocks of the sandstone and pebbly conglomerate that form the crest of this hogback have been broken away, usually along joint planes, and now occur half buried in the soil and talus down the west slope of the ridge. These large blocks of rock, slowly creeping downward, are characteristic of the west slope of the Dakota ridge throughout northern Colorado.

The lower part of the Dakota consists of several conglomeratic and sandstone beds, any one of which may form the top of the main ridge. If the lowest conglomerate forms the crest, the other higher sandstones usually form minor ridges down the east slope of the hogback. In other places the conglomerate bed may be buried beneath talus, and a higher sandstone forms the top of the ridge. Such a shifting of the responsible position from one bed to another causes a minor offsetting of the main ridge to the east as a higher sandstone takes the place of a lower member, and westward as a lower bed replaces a higher one on the crest. This occurs notably east of the Berthoud cut-off road. In this same location the Morrison formation in places protrudes from beneath the Dakota, and forms the highest part of the hogback. The rounded, smooth contour of such a Morrison ridge contrasts sharply with the usual sharp, low, broken, west-facing cliff formed by the Dakota, and reflects the massive and uniform nature of the Morrison shales and limestones. In such places the Dakota formation forms a second prominant ridge a short distance to the east, and the result is either a double-topped ridge, with a shallow valley between, or a rather flat-topped ridge. This condition is exactly similar to that caused by the Ingleside and Lyons formations described above.

Topography Controlled by Flat-lying Beds

The resistant Lyons and Ingleside formations are nearly horizontal at Flatiron Mountain, and have successfully protected the underlying rock from erosion. The result is a very prominant, rather flat-topped mountain, bounded on the west, north and east by high cliffs overlooking steep talus slopes below. Toward the south these controlling beds again resume their normal east dip, and in this direction Flatiron Mountain merges with the normal Lyons-Ingleside hogback. In other places low, flat-topped mesas occur which owe their existence to a protecting cover of flat-lying upper Dakota sandstone.

Topography Controlled by Structural Features

Dakota Anticlinal Ridge

In the Carter Lake Area the sedimentary rocks have been folded into a long anticline trending almost due north, running the entire length of the area. The south third of this structure shows on the surface in the Dakota formation. Here the structure is almost perfectly reflected in the topography--erosion has removed all the beds above the Dakota and this bed now caps an anticlinal hill about three miles long and 3/4 miles wide. In most places the dip of this bed conforms very closely to the general slope of the land, but in some places streams have cut through this protecting cover into softer shales below.

A. Flatiron Mountain. The Lyons formation caps the mountain, with the Ingleside forming the prominant cliff somewhat below. Between the two occurs the platy Lyons sandstone, and along the north face below the Ingleside the Fountain arkose is well exposed.

B. Looking south along a syncline. Dakota dip slopes on the east and west, and the upper Dakota forms the top of the small flat mesas.

Anticlinal Valley

The north end of the anticline mentioned above involves the "Red Beds" on the surface. Here erosion has cut deep into the axis of the structure forming a long deep valley bounded on all sides by a continuous hogback of resistant outward dipping "Red Beds." In the center of this valley, along the axis of the anticline, erosion has cut into the Fountain formation to within two hundred feet of the granite and schist.

Synclinal Valleys

Parallel to, and west of the above mentioned anticline, is a syncline which forms the foundation for a synclinal valley. The surface in this valley is not, of course, exactly concordant with the downwarped part of the Dakota formation or Lyons formation, but is partly filled with shale of overlying formations. The south part of this valley, west of the Dakota anticlinal ridge, has a floor of soft middle Dakota shale, and here and there a small mesa formed by a remnant of the upper Dakota sandstone stands above the floor of the valley. The north half of this valley, west of the "Red Beds" anticlinal valley, has a floor of Lykins shale. The west limb of the anticline bounds the east side of this synclinal valley, and the normal east dipping hogback marks the west side.

Faults Valleys

The influence of faults on the drainage pattern is well demonstrated in this area. Small faults have determined the location of small gullies, and large faults some of the larger drainage lines. Trending northwest from Flatiron Mountain is a major fault along which a tributary of Dry Creek has developed a deep valley with low-sloping west side and a steep east side. Other smaller gullies and streams follow fault lines as can be seen from the map.

Topography Controlled by Solution

The Lykins formation in this area contains considerable lime and gypsum. Expecially near the base, rather thick beds of limestone have been quarried for local use. The depressed part of the Carter Lake drainage basin, which lies entirely in the Lykins formation, was probably the result of the solution of part of this lime and consequent settling of the surface. Two facts support this explanation. At two places east of the lake, small springs exist in the Lykins formation well below the level of the lake, and which flow throughout the year; and along the valley which runs southwest from the north end of Carter Lake numerous fragments and large masses of a calcareous material resembling travertine are found.

Depositional Forms

Several small gullies have been cut through the Lyons ridge south of Carter Lake. In the softer lower Lyons sandstone a north-south valley of considerable size has been formed. Apparently most of the erosion and transportation of the material cut out in the formation of this valley was by water of torrential rains. Great fragments of angular Lyons sandstone have been piled up to form low, rather flat-topped fans at the mouths of these small gullies. The present stream bed, dry except after rains, has a rather narrow channel through this debris. It is suggested that the unassorted material that composes the fan has been washed rapidly from above during short periods of heavy flow, and that the small volume of water flowing intermittently between times has cut away a part of the fan to form the present small channel.

Drainage

Except for the small Carter Lake Basin, Cottonwood Creek on the north, and the Little Thompson Creek on the south drain the area. These two streams are tributaries of Big Thompson Creek, which in turn flows into the South Platt River. Cottonwood Creek and Little Thompson Creeks are consequent streams, and have cut directly through the foothills belt. The intermittent tributaries form a trellis pattern determined chiefly by soft tilted sedimentary rocks, and to some extent by fault zones.

GEOLOGY

Stratigraphy

The sedimentary formations of Paleozoic and Mesozoic age, which are of chief interest in this small area, overlie pre-Cambrian gneisses, schists and quartzites. The latter are continuous from the Wyoming-Colorado line southward to the Little Thompson Creek. Westward the metamorphic series is more or less continuous as far as the continental divide. Mica schists, garnet schists, staurolite schists, and quartz schists are the characteristic metamorphic rocks. Their age is indeterminable, but from work in other districts they have been assigned to the Proterozoic Era. Farther south still older granites form the floor on which the sedimentaries rest.

Considerable doubt exists regarding the ages, relationships, and correlation of the "Red Beds" of northern Colorado. Fossils are sparsely scattered, the beds themselves change in character laterally, and vertically, and the interfingering, and thinning out of beds leads to confusion in their study. Several men have given this problem study, and their conclusions have tempered to a great extent, the ideas expressed in this paper.

It seems best, as far as possible, to follow the original definition of these various formations, and Fenneman's (1905, pages 22 to 25) definition of the Lyons, Fountain, and Lykins formations for the Boulder Area, and Butters' (1913, page 68) definition of the Ingleside formation are used. Where their definitions definitely conflict with more recent information, slight modifications have been made.

The Fountain Formation

The Fountain Formation, named from its type locality at Fountain, Colorado by Whitman Cross (1894, page 2) and correlated for the Boulder District by Fenneman (1913, page 22), overlies the old pre-Cambrian metamorphic and granitic land surface. This formation varies in thickness, partly due to irregularities of the surface on which it was deposited and partly due to uneven deposition. One thousand to twelve hundred feet is the approximate thickness in the Carter Lake district. This formation is a coarse, purplish-red, conglomeratic arkose. Here and there, not continuous for any great distance laterally, and in no particular zone, occur brick-red, shaly sandstones, mottled sandstones, and gray sandstone beds. The formation contains semi-angular pebbles, cobbles and boulders derived from the underlying igneous and metamorphic rocks. It is very poorly sorted, and rather massive, and shows cut-and-fill structures. The above characteristics indicate torrential deposition from a nearby source. (Knight, University of Wyoming, believes the Fountain formation to be a series of alluvial fans.) At various levels in the formation more resistant beds form low, west-facing escarpments on the steep west-facing slope. One such resistant bed near the base and one near the top are fairly persistent in the area. No fossils have been found in this formation from the Denver

Basin region north, except at Box Elder Creek where Henderson (1908, page 491) describes two fossil-bearing horizons. The fossils are in chert pebbles, possibly derived from older Mississippian beds, but Henderson believed the chert pebbles to have been formed in place, and the fossils to be indigenous to the Fountain formation. Later (1920, page 68--71) he expresses the idea that these fossils were derived from an older Mississippian formation, eroded before and during the deposition of the Fountain beds, and overlapped by them. Fossils from two localities definitely place the Fountain formation in the Pennsylvanian. At Manitou, Pennsylvanian fossils are found in the Gleneyrie sandstone which underlies the Fountain formation in this location, and in northern Colorado the Ingleside formation at the top of the Fountain yields Pennsylvanian fossils.

The Ingleside Formation

At its type locality at Ingleside, Colorado, Butters (1913, page 68) describes the Ingleside formation as a series of limestones and cross-bedded light pink or red sandstones which are about 125 feet thick and are apparently conformable above the Fountain. Southward this series thins, the limestone horizons disappear, and are not present in the area studied. A calcareous, salmon-pink, sandstone, occurring near the top of the Fountain arkose, however, is probably the equivalent of the Ingleside of the type locality, and was so mapped. At Dry Creek this sandstone is conspicuous and is easily recognised by its color. It is cross-bedded, and is often covered with a calcareous crusting. Here the unit is 140 feet thick, but thins rapidly to the south to about five feet two miles north of Little Thompson Creek. Above the Ingleside as described above, is a friable, coarse buff to yellowish sandstone which changes upward to a finer grained red sandstone. In places some arkose appears at this horizon.

The Lyons Formation

Separating the Ingleside and buff-yellow sandstone from the typical cross-bedded Lyons formation is a series of brick-red, platy sandstones and shales. To the north this series resembles the overlying Lykins shales very closely, but to the south becomes more and more massive, and a mile or two north of the Little Thompson outcrops as a high cliff below the Lyons proper. The correlation of this transition series is difficult. Apparently Fenneman(1905, page 23), in his original definition of the Lyons included this zone in his Lyons formation, although at Lyons, Colorado this transition zone is not well developed. Later writers tend to restrict the name Lyons to the light-colored, cross-bedded quarry rock. Henderson (1920, page 76 to 78) apparently included this formation in his Lykins formation, following Butters (1913, pages 69 to 70), and considered the cross-bedded member a phase of the Lykins formation. Lee (1927 pages 6 and 34; plate 9 B.) included the transition zone in his redefined Ingleside, but this was clearly not the intent of Butters, who originally defined the latter formation. Farther north, Lee (1927, page 36) suggests that similar brick-red beds below the Lyons may correspond to the Satanka shales of Wyoming; and Thompson (1933) , on the basis of lithological character believes the red platy sandstone zone to be Fountain. This interpretation is supported by the occurrence of arkose beds above the Ingleside in various places in the area and to the north. Quam (1932, pages 13 to 15), in the Rabbit Mountain area includes the equivalent horizon, here closely resembling the typical Lyons except for the cross-bedding in the Lyons formation. This follows Fenneman's original definition for this area. However, the Little Thompson marks a change in the character of this series of rocks. Southward it is massive, resistant to erosion, a little darker in color than the cross-bedded Lyons, and with the Lyons forms a single mappable stratigraphic unit. Northward this lower horizon becomes softer, more platy, and a darker brick-red color, and erodes easily to form a valley between typical Lyons quarry rock and the Ingleside. This zone is, however, continuous with and in the same position as the series defined at Lyons, Colorado as the Lyons formation. For this reason this zone has been included in the Lyons formation in the Carter Lake Area, and is called in this paper the lower Lyons, or the red Lyons. The Typical cross-bedded Lyons is a light pink to almost white, quartzitic sandstone, strongly cross-bedded. It is fine-grained and well sorted. At Cottonwood Creek this zone is about 60 feet thick, and it thickens southward to about 150 feet at Little Thompson Creek. This increment is at the expense of the transition zone, or lower Lyons below, and the Lykins formation above.

Lykins Formation

The Lykins formation is in general a brick-red sandy shale, easily eroded, Near the base occurs a massive, light gray limestone, overlain by the "crinkly limestone". The bulk of this formation is shaly and easily eroded and covered with soil. Near the top is a massive shaly sandstone, rather resistent to erosion and usually exposed as a low, west facing escarpment well down the west slope of the Dakota hogback. This bed changes rather gradually upward to a salmon pink, cross-bedded sandstone, resistant enough to show good continuous exposures. The latter is correlated with the Jelm and Sundance of Wyoming by Lee (1927, pages 14, 15, 16, and 33.) Although in stratigraphic position and lithologic character it resembles that formation, since no fossils have been found in it in Colorado, and since the bed cannot be traced through the entire distance, this correlation seems unsafe. Knight (1933) suggests that this, and possibly the overlying white sandstone of the Morrison, be correlated with the Jelm formation of the Laramie basin. The possibility of

Plate 4.

A. South view along strike fault. Prominent ridge in background is the Dakota anticline, and the wooded ridge east of it is the Dakota hogback. Upper Dakota forms the low ridge in the valley, and the slope in the foreground is Morrison. Rabbit Mountain just appears on the distant horizon.

B. South view showing rounded Morrison ridge with wooded Dakota ridge to the east. The strike fault of the above photograph follows the valley west of the Morrison ridge, and Rabbit Mountain shows well on the distant horizon.

correlation of these structures with the Dolores and LaPlata formations of the Western Slope is also suggested. But again, correlation of these widely separated beds on the basis of stratigraphic position and lithological character does not seem wise. In this report the salmon pink sandstone is included in the Lykins formation, and the white sandstone in the Morrison.

Morrison Formation

There is a rather well defined break between the salmon colored sandstone of the Lykins formation and the next higher white sandstone, and in some places a thin bed of cherty conglomerate was found at the bottom of the latter. This suggests a nonconformity between the Lykins and Morrison, which the difference in age of these formations further suggests. The white sandstone at the base is fine-grained, friable, and cross-bedded. The change upward is rather abrupt to green, blue, and gray limy clay rock which constitutes the greater part of the Morrison of this locality. Above the Morrison a sharp change to the basal conglomerates of the Dakota formation suggests an unconformity here also.

The Dakota Group

The Dakota formation shows a division into zones which may correspond to the Lakota, Fuson, and Dakota formations of the Black Hills. The basal member consists of a massive cherty conglomerate interstratified with cross-bedded coarse sandstone. Upward this becomes a hard, quartzitic, fine-grained sandstone which usually forms the top of the Dakota hogback--the conglomeratic phase, if always present, being buried by talus. A thin softer sandstone intervenes between this and the top member of the basal Dakota. The latter sometimes forms the top of the Dakota ridge, but usually it forms a minor ridge or terrace down the east slope of the main hogback. All the sandstones of the basal Dakota are very similar, and where exposed alone cannot be distinguished from the other members of the basal group. Above the basal sandstones occur a series of black shales and sandy shales of the Middle Dakota. Toward the top these become a lighter gray and merge into friable, brownish sandstones of the Upper Dakota. The latter is a hard quartzitic sandstone. In this report the basal and middle sands were mapped as one unit, and the upper sandstone as a second unit.

Benton-Niobrara Formations

Above the Dakota occur 350 feet of black shale of the Benton formation, which is capped by a horizon of gray sandy shale. Above the latter, occur the bedded limestones and black shales of the Niobrara formation. The Niobrara is the highest formation mapped in the area. To the east occur the Pierre, Fox Hills, and still farther, the Laramie formation, as described in other reports on Northern Colorado.

Structural Geology

General Features

The Front Range of the Rocky Mountains rises in Wyoming and increases height, relative to the plains, to its climax in northern and central Colorado. From the Poudre River region to Colorado Springs the range maintains an average elevation of over eleven thousand feet. Southward the Front Range becomes less prominant, the Wet Mountains, and farther south the Sangre de Cristo Mountains becoming the main mountain front. Southward each of these ranges is offset to the west in en echelon arrangement. The main crest of the Front Range, roughly paralleled on the west by the Park and Sawatch ranges, lies in a north-south direction, and the general trend of its anticlinal axis, as indicated by the strike of the sedimentary beds along the flank of the range, and ~~by the trend of its anticlinal axis, as indicated by the strike of the sedimentary beds along the flank of the range,~~ and by the trend of the intermountain parks is also roughly north-south.

However, superimposed on this major north-south uplift are numerous structures trending northwest-southeast. In the main mountain area these trends are represented by faults, the nature of which in most cases is masked by the crystalline nature of the rocks. Many of these faults in the Boulder region and southward are associated with the mineralization of that area. Along the foothills this northwest-southeast trend is observed in folding and faulting in the sedimentary rocks. Both the folds and faults seem to die out toward the plains, and increase in intensity toward the crystalline rocks. Also, the anticlines and synclines expressing this trend in the sedimentary rocks, may at their northwest end pass into faults, especially where the axis passes into the crystalline rocks.

This feature of the structure of the foothills was first described by Marvine (1873, page 132) :

"There are here several such offsets or jogs in the mountain-border caused by its component ridges being arranged en echelon, north and south of each other. The trend of these spans is somewhat west of north, while their echelon arrangement is such that a line touching their southern ends trends east of north and west of south, with a flat concavity presented to the east. As is so often the case in the West, these peculiar topographic features are but the surface expressions of a similar and important geologic cause. These ridges, and the included valleys, indicate that here the folding of the rocks have also taken place en echelon. The ridges are uplifted or anticlinal folds, the valleys depressed or synclinal folds, both dying away southward into the flatness of the plains, though the west side of the westward synclinal is always preserved in the normal uplift along the main mountain base. With such a structure, and since the sedimentary rocks have been, to a very great extent, eroded from thesummits of the ridges and worn down to a pretty uniform level, it is necessary that the outcropping strata should be found bending around the southern ends of the spurs, their strike first swinging westward, that of the lower beds bending on still farther to the northwest to form the eastern side of shallowing synclinal basins, which finally terminate to the north, the reverse in all respects, to the anticlinal ends, while the uppermost beds, those farther out, do not necessarily bend around into the synclinals, but after turning somewhat westward, again resume their southern course with the others.

2 "The most interesting feature of these folds, next to their general echelon arrangement, is the fact that in the anticlinals the western side of the fold is always more abrupt than the eastern side, and may become a fault, the downthrow being upon the western side. That is to say, the tendency of the forces forming the folds seems to have been to lift up the eastern relative to, and push it over against, the western side; and the expression of this tendency has been either an abrupt downward bend of the west side, or a direct downward faulting of the west side, or by both combined,

And along the same fold these three forms of arriving at the same result are interchangeable."

Along the Front Range such echelon folds occur in the Poudre River region, two in the Big Thompson River area, in the Carter Lake area, and in the Little Thompson Creek area. Only small echelon, and few major faults are found in the sedimentaries south of the Little Thompson. But, in the crystalline area west of Boulder, several northwest trending dikes may have filled faults parallel to the structures farther north--Maxwell, Hoosier, and Livingstone dikes. It may be of some significance that the Maxwell dike is almost directly in line with a northwest trending fault between Green Mountain and the Flatirons, southwest of Boulder. The faults and echelon folds having this trend are abundant enough in the region and large enough to constitute a characteristic structural feature of the Front Range. Any attempt to explain the origin of the Front Range must consider both the general north-south trend of the range as a major unit and the northwest-southeast structures that have been superimposed on it.

Only in places have north-south minor structures been described. In the Carter Lake region, and at Rabbit Mountain are north-south folds and faults. At Golden, Zeigler (1917, pages 21 to 26) describes north-south strike faults of high angle under thrust nature. And possibly at Boulder, if Zeigler's interpretation of the elimination of part of the stratigraphic section holds for this region, similar faults may occur. The relationship of the north-south structures to the northwest-southeast structures, is not clear in most

Plate 5.

A. Axis of anticline in lower Fountain beds in the bottom of the anticlinal valley.

B. Small fault in the basal Dakota sandstone.

places. At Carter Lake, however, the two sets intersect, and although a covering of alluvial material prevented a study of the small details an examination of the major features disclosed some facts that may aid in the solution of this structural problem.

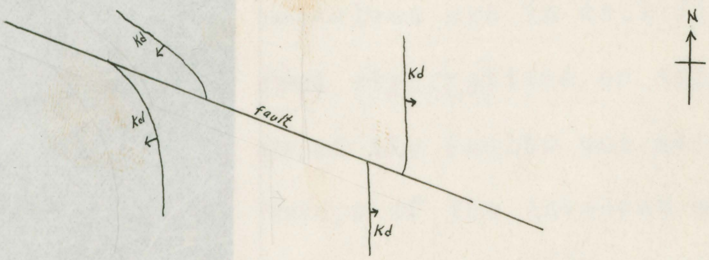
The Structures of the Carter Lake Area

Both of the structural trends described above occur in the Carter Lake area, and both are manifested in folding and faulting. A long anticlinal axis extends through the entire area from the south to the north. Along this axis the Dakota sandstone and the "Red Beds" form three long narrow anticlines separated by down-warped saddles. To the south, about a half mile north of Little Thompson Creek, the basal Dakota sandstone, which caps the anticline in this region, plunges to the south. If projected in this direction, the axis would show some offset to the east relative to the Rabbit Mountain anticline. The possibility that these two structures were formed along the same axis, and were offset by the Little Thompson Fault was not studied, but suggests interesting speculation. To the north, in section 14, the Dakota anticline plunges with a low dip to the north, and is finally cut by two faults trending northwest-southeast. The effect of these two faults is to raise the north side of the anticline very abruptly, and from section 11, the "Red Beds" form the anticline. About three miles farther north, in section 23, south of Cottonwood Creek, the structure again plunges rather rapidly into a saddle, and re-emerges and continues for a short distance north of Cottonwood Creek. The axis represented by these anticlines is about eight miles long.

In general this long anticline is symmetrical, except where affected by faulting, and dips rather steeply both to the east and west. In the Dakota portion of the structure, east dips range from 45 to 80 degrees, and to the west the dips range from 30 to 60 degrees. In the part of the structure shown in the "Red Beds" the dips along the flanks range from 30 to 40 degrees west, and from 25 to 40 degrees east. However, in the "Red Beds", erosion has cut deep along the axis, and has exposed the lower part of the Fountain formation. In these beds, close to the axis of the structure, the dips are noticeably steeper than they are higher in the structure, and in general are steeper to the west than to the east. West dips vary from 60 to 70 degrees, and east dips average about 50 degrees. This gives the structure the appearance of a parallel fold, and if such is its nature, it dies out downward. These dips along the axis may also be explained by a fault in the underlying crystalline rocks.

Associated with this anticlinal axis are two high angle thrust faults. The smaller of these is roughly parallel to the anticlinal axis, and a short distance to the east of it. The east side of this fault has been upthrown a little over a hundred feet. The fault dies out to the south near the anticlinal axis, and to the north in a minor, badly fractured and distorted anticline. Farther east a similar fault has duplicated the entire Dakota section, and part of the Morrison. The maximum throw, just north of the road in section 13, is about 700 feet. To the south, in section 24, this fault dies out, and can be traced into a small anticline in the upper Dakota sandstone. To the north it is cut by the northwest-southeast faults described below, and on the north side of the latter, is lost in the Lykins shale. Here the Lykins formation has a total thickness of 1137 feet, nearly 400 feet more than normal, and indicates duplication of part of the Lykins section by the fault.

The larger of the faults just described, and the anticlinal axis are cut by one or both of two closely spaced northwest-southeast trending faults. The south one of these is reflected in small echelon folds in the Niobrara and upper Dakota ridges, but where the fault cuts the basal Dakota this formation is badly fractured, and is offset about 600 feet. Continuing to the northwest, the upper Dakota, which has been duplicated by the strike fault described above, terminates abruptly against the south side of the fault. Still farther to the northwest the basal Dakota on the west side of the anticline is also offset, and shows a very marked change in dip. On the south side of the fault the Dakota section dips from 15 to 25 degrees to the southwest, and on the north side the same beds dip 70 degrees southwest. The movement along this fault is probably not entirely vertical since the offset on the south side of the fault is down dip on one side of the anticline, and up dip on the opposite flank.



A second and parallel fault occurs between the Dakota and Lyons beds along the southwest side of the "Red Beds" anticline. The trace of this fault is in the Lykins shale, and the movement was probably largely vertical with the north side rising relative to the south side. Here the Lykins formation has been very definitely thinned by the faulting. At one place the Lyons-Dakota interval is only 410 feet, at least 700 feet of the Lykins and Morrison having been eliminated. In both directions this fault is lost in the Lykins shale. The effect of these two faults is to elevate the anticlinal axis on the north about 2000 feet, and to produce a west offset of this axis on the upthrown side of about 1000 feet.

Northeast of Flatiron Mountain a fault cuts the crystalline rocks. A projection of this fault to the southeast would have less than half a mile offset north of the two faults described above, East and south of Flatiron Mountain are a small anticline and syncline in the "Red Beds" which may represent an adjustment in the sedimentary

Plate 6.

A. Squeezing of shale between sandstones near crest of sharp, broken fold.

B. Shattered basal Dakota sandstone in fault zone.

C. Jointing on upper Dakota Dip Slope.

beds to these separated fault zones.

The critical area where the north-south and northwest-southeast faults intersect is badly covered with soil, and the traces of the faults themselves are in soil filled valleys. Consequently few direct observations on these faults were possible. The location of the faults was made largely by plotting the closest outcrops of the involved sedimentary rocks. That both sets of faults were caused by thrusting forces is indicated by their association with steeply folded anticlines, and by the great amount of mashing, brecciation and slickensiding in the fault zones. Since the trace of the faults on the surface is very little affected by the topography, it was concluded that the fault planes dip steeply; and the fact that the northwest-southeast fault is not offset where it crosses the north-south fault is the only indication of the relative ages of the two systems.

Competency of Beds.

The lower section of "Red Beds" are competent to the extent of lifting their own weight, and the overlying Lykins shales in anticlinal folding. This is seen in the north-south trending anticline in sections 5 and 2. Here the Fountain, Ingleside and Lyons formations are involved in an anticline in which the folding seems to be of the concentric, or parallel type. Along the flank of the anticline, in the Lyons formation the dips average 28 to 38 degrees east, and 28 to 35 degrees west. Erosion has cut a deep valley along the axis of this anticline, in the bottom of which, near the axis, the dips average 65 degrees west and 40 to 50 degrees east. This steepening of the dip along the axis in the deeper strata indicates concentric folding and a dying out of the structure at a shallow depth. It appears that the folding here took place above the granite, and the granite itself may show very little deformation. The conclusion is that this basal section of "Red Beds", under compressional forces, slid over the granite and arched, uplifting its own mass and the overlying Lykins shale. The Morrison and Dakota formations were probably competent to fold under the load of overlying Cretacean beds. The Morrison formation is thick amd massive, and probably forms one of the most competent formations in the region. Even a minor degree of competency in this bed would give the more brittle overlying Dakota formation a tendency to arch upward rather than to break at once into a fault. These two beds, the massive Morrison below supporting the Dakota formation, constitute the most competent series of the area. The stresses transmitted by these competent beds are absorbed by the intervening Lykins shales and overlying Benton, Niobrara and Pierre shales by flow, and minor fracturing and folding.

Plate 7.

A. View northwest along two fault valleys. Steep dipping Dakota forms the long northwest ridge, and faults occupy the valleys on both sides. Lyons forms slope on extreme right background. Note jointing in upper Dakota in lft foreground.

B. View southeast along the south valley of above photograph. Fault runs from middle foreground to the notch in ridge on horizon. Note abrupt termination of hogbacks south of fault.

ANALYSIS OF FRONT RANGE STRUCTURE

Any attempt to go beyond the description of observable features of structures and to explain the origin of these structures must draw largely from inference. This is especially true when the conclusions cannot be put to the test of direct observation. We cannot observe the process of formation of mountain structures, nor can we have any direct evidence of the structural nature of the deformed rocks before orogenic forces became active. Inference is useful only as its conclusions are retained as tentative explanations awaiting further evidence to substantiate or disprove them, and as it suggests other lines of investigation and unsuspected relationship. To be of such use, inference should be made only after all pertinent, discoverable facts have been assembled. The writer, in view of his scanty knowledge of the great number of facts, and with the realization of his lack of experience in interpretation, therefore hesitates to enter this field of structural geology. And it is only for the purpose of outlining some of the factors that may have influenced the development of Front Range structures that this section is written.

General Concepts

Deformation of the earth's crust requires the application of forces great enough to overcome the resistence of the rocks. As the forces are applied the rocks are first placed in a condition of strain, and later, when the applied forces are great enough to overcome the resistence of the rocks--cohesion, adhesion, friction--yielding takes place by flowage, folding and faulting. Rocks may exist for long periods of time under increasing strain before such relief is effected. The location of points of yielding and the nature of the structures developed depend on several factors. Of these, the nature and direction of application of the forces and structural conditions of the rocks which may aid or prevent yielding seem most important. It is first necessary to have some conception of the origin of mountain making forces, of their probable direction of application and depth of effectiveness in the region, and of the nature of the rocks affected.

It is beyond the scope of this paper to discuss the various theories of the origin of mountain-making forces. Several theories are current which depend on volcanic action, shifting of continents, and gravity to furnish the necessary forces. The theory assumed in this discussion holds that these forces are set up through the attempts of a rigid outer shell of the earth to conform to a shrinking interior. The effect is to set up forces acting tangentially to the earth's surface in the rigid shell. In the yielding of the crust, this tangential force may be resolved into various horizontal or vertical forces. Since the contraction of the earth's interior takes place slowly and continuously, these forces gradually increase in intensity, and the outer shell is placed in an increasing condition of strain. Relief of this strain by deformation of the rigid shell takes place when the accumulating forces become strong enough to overcome the resistance of the outer shell to such deformation. The adjustment takes place by folding, faulting and fracturing near the surface, and by flow below the zone of fracture. There is a gradual change between these two zones. In different locations the depth to which the folds and faults visible on the surface extend, that is, the depth through which these forces become active and accomplish relief of strain in the rigid shell, may vary. Some mountains seem to have involved only a shallow portion of the crest below the place where they now exist as topographic features. Other mountain structures have deep "roots". The Front Range seems to be of the latter type. (Chamberlin, R. T., 1919)

Most of the sedimentary formations outcropping along the east border of the Front Range have equivalents in intermountain parks to the west, and on the western slope of the Colorado Rockies. It is not certain that the "Red Beds" series was continuous over the mountains before their uplift. The Dakota formation may possibly have been continuous. The later Cretaceous sediments show little change in character across these gaps which suggests that they were deposited at considerable distance from shore. The conclusion that possibly the Dakota formation, and certainly the Benton and higher formations were continuous across the present mountain area seems reasonable. If so, erosion has removed at least the

Cretaceous series from the area along the crest of the present Front Range.

Longs Peak, on the continental divide, has an elevation of 14,255 feet above sea level. On the plains where the sediments are nearly horizontal the Dakota formation is reached at a depth of from 3000 feet (Darton,1905, plate 49) to 6000 feet (Anthes Well). The Dakota formation here is at an elevation of from sea level to 2000 feet. The uplift of the mountain area accordingly was at least 13000 feet with respect to the plains. That is, the forces which built the Front Range acted through a depth of at least 13000 feet below the sedimentary rocks, and probably much more. This is in accord with Chamberlin (1919, page 42) who for the Lyons area concluded that the deformed zone is about 13 miles deep.

Above a certain depth, depending on temperature and pressure conditions and the mineralogical composition of the rocks, relief of stress takes place by fracturing, folding, or faulting. The deeper zones may yield by flow. According to Daly, (1914, page 181) the crust is rigid enough and retains enough strength to preserve cavities and cracks to a depth of 17.2 to 20.9 miles below the surface. Willis (1929, page 463) gives the depth of the zone of fracture as 30 miles. It cannot be safely assumed that this total thickness will transmit tangential forces equally. There is a gradual increase downward in the ability to transmit tangential forces due to the effect of the load, and along the Front Range by the location of stronger crystalline rocks at depth. Then still deeper the ability of the rock to transmit tangential pressures is decreased by pressure and temperature conditions favoring flow. So probably the depth at which the maximum transmission of stresses occurs is at much less depth than the 20 miles or 30 miles. In this region we may conclude safely that this depth is more than 10000 feet since sediments which were at this depth at the initiation of mountain making movements show no metamorphism, and the depth of maximum transmission of force was possibly well within the crystalline rock zone.

According to Willis (1891-'92, page 238), massive rocks are immovable in relation to a force that folds stratified rocks. Sedimentary rocks yield more readily by folding and later faulting because of their greater flexibility and "flexibility is a direct function of lamination" (Willis, 1891-'92, page 244). It seems possible, then that at the inauguration of movements, the surface rocks (sedimentary) being less rigid, in better position to yield by vertical movement, and more flexible because of their bedding would be the first to yield; and so partially compensate the part of the tangential force active in this zone. The deeper, more rigid and brittle crystalline rocks would still be in a condition of strain. As the forces increased in intensity the crystalline rocks also would yield--first by moderate bending, then by fracture and faulting, and in the end faulting would predominate in such rocks immediately below the sedimentary rocks. Such movements in the crystalline rocks would also be reflected in the sedimentary rocks above in a second set of structures which could also give relief to any strain remaining in the latter after their initial movement. Such difference in the time of yielding of the crystalline rocks and sedimentary rocks would, of course, necessitate differential movement between the two. In general there is little evidence for such movements along the Front Range. This indicates that conditions were favorable for movement in both zones simultaneously, or that movement was inaugurated in the crystalline zone. Locally, however, the sedimentary rocks may have yielded to a minor degree first.

Since the sedimentary rocks of the Front Range region were deposited previous to the Laramide revolution and later than any known previous orogenic movement it is almost certain that at the time of the Laramide revolution these rocks possessed no major structural features which would affect or direct the formation of new structures except those contingent on conditions of deposition. Consequently, if the forces in the Laramide revolution were simple compressional forces, the folds and faults formed should trend at right angles to the direction of compression. If the forces were rotational, the structures should show the relationships to the rotational couple demanded by the direction and relative intensity of those forces.

But we cannot be so certain regarding the conditions in the basement rocks before their latest deformation. These rocks are pre-Cambrian in age, and in their high degree of metamorphism show evidence of disturbance in pre-Cambrian times. The "Red Beds" indicate additional elevation and at least local mountain-making in early Pennsylvanian times. Consequently, we cannot safely disregard the possibility that these rocks already possessed structural lines at the time of the Laramide revolution.

There are still two possibilities. The first that any such structures were "healed", or that they were not so located as to afford relief to forces in the Laramide period of movement; and, second, that such structures were so located and in condition to move again at this time, and new structures would develop in the crystalline rocks only when such development were easier than movement along these old lines.

Only very general conclusions are possible, but they may be stated as follows:-

1. That in the Front Range region the depth of deformation by faulting and folding was great enough to include a thickness of crystalline rocks at least as thick, and probably several times as thick as the sedimentary cover.

2. That the tangential forces were active in the crystalline rocks with an intensity equal to or greater than the similar forces active in the sedimentary rocks.

3. That movement was inaugurated in the crystalline rocks or started in both crystalline rocks and sedimentary rocks

simultaneously, but that local conditions may have favored movement in the sedimentary rocks before any movement took place in the basement rocks.

4. That the sedimentary rocks at the time of the Laramide revolution possessed no major structures other than bedding and differences in thickness.

5. That the crystalline rocks probably possessed structures inherited from previous orogenic movements which may or may not have been located in a position which would afford relief during the Laramide revolution.

Development of Front Range Structure

With the above general concepts in mind we may now consider in more detail the various conditions that may have contributed to the formation of the structures of the Front Range. The facts which must form the basis for further inference, and which in turn must also be explained, may be summarized as follows.

1. North-south trend of the Front Range

2. Normal east dipping, north striking monocline in the sedimentary rocks.

3. Presence of minor north-south trending folds and thrust faults.

4. Certain of the above folds are of the parallel type, indicating a relative shallow depth of folding.

5. Northwest-southeast trending thrust faults and

echelon folds in which the deformation is greatest toward the northwest.

6. North-south folds and faults older than the north-west-southeast trending structures.

First it can be assumed that these two structural trends were developed during two different periods of movement in which the forces were of different nature. If the forces were compressional in an approximately horizontal plane the anticlines and faults developed in adjustment would trend at right angles to the compression. If the forces were rotational, the structures developed would be inclined to the direction of greatest compression as demanded by mathematical analysis of rotational forces. In this explanation the rocks involved are assumed to offer equal resistance to these forces, not possessing characteristics that would tend to localize, give direction to, or determine in any way the nature of the structures developed. The differences in competency of various rock layers to transmit the forces, the depth of deformation, and the depth of maximum transmission of forces need not be taken into consideration. According to this mathematical analysis the two sets of structures may be explained by an initial compressional force acting in an east-west direction developing the north-south trending structures, and giving the north-south trend to the Front Range. A second period of deformation due to rotational forces, either horizontal or vertical rotation, will explain the northwest trending structures. We may consider this rotation as being due to a couple. An east-west force coupled with a small north-south force or coupled with a vertically acting force. The fact that this idea assumes equal resistance and uniform yielding in the affected rocks stands as its greatest objection. As usually stated, it does not consider all the factors in the problem.

A second explanation assumes identical forces through the entire period of deformation, and explains the development of various structures as having been determined by some pre-existing structural condition in the deformed zone. There are again two possibilities regarding the nature of the forces--rotational forces, or simple compressional forces. The assumption that the forces causing the Front Range deformation were simple compressional acting in an east-west direction adequately explains the north trend of the Front Range and the north-south trending folds and faults. But, a north-south or vertical component must be introduced to account for the northwest-southeast trending structures.

It has been suggested that the difference in the competency of the rocks to transmit the compressional forces gave rise to local rotational forces. In this connection the persistence of the direction and parallelism of the latter structures seems signigicant. In a random arrangement of competency to transmit forces such parallelism is difficult to explain, and would require that the ability of the rocks to transmit forces become constantly greater, or less along a north-south line. It seems rather, that the great variations in competency of rocks would produce rotational forces in one direction in one locality, and in another direction in a second locality.

A second possibility, on the assumption of original compressional forces, is that inherited structures in the crystalline rocks were responsible for the location and development of enechelon folds and faults.

There is so far no definite evidence of old structural lines in the basement rocks. But, as pointed out above, in view of the evidence for several periods of disturbance previous to the Laramide revolution, the possibility must be considered. The latest of these movements built a series of mountain ranges which have been placed by various writers in various regions in Central and Western Colorado. One of the most recent maps (Melton, 1925, pages 84-89) locates one range in the position of the present Front Range, and a second range, trending northwest-southeast from the northwest corner of Colorado to South Central Colorado. If the main structures in these ancestral mountains roughly parallel their main trend, on the basis of these maps the most recent faults existing at the time of the Laramide revolution would trend northwest-southeast.

What would be the effect of simple compressional forces acting on a series of sedimentary rocks overlying granite which had old fault lines trending northwest-southeast? First, the general effect would be to build up a mountain range trending north-south, probably located in the area underlain by rocks weakened by previous movements. The northwest-southeast fault lines would be well located to give relief to the compression. In general, movement would start in the crystalline rocks, and in some places would be along these old fault planes. Any movement in the crystalline rocks would be reflected in the sedimentary cover, and would give direction to the developing structures. In other localities where preliminary movement took place in the sedimentary rocks before any movement took place along deeper fault lines the early structures in the sedimentary cover would be north-south trending folds and faults. Such structures would be of rather shallow depth, would not involve the crystalline rocks below, and some degree of differential movement between the two rock zones would be necessary. Later, when movement started in the deeper crystaline rocks, the development of these north-south structures would probably come to an end, and new adjustments would be made along lines determined by the deeper faults. A second set of structures would develop trending northwest-southeast. Perhaps in places the strain in the sedimentary rocks had been entirely relieved before much movement took place in the deeper rocks. In such an event the later faulting in the crystalline rocks would still be reflected in the overlying sedimentary rocks as upward diminishing folds.

The above theory is adequate to explain the north-south trend of the Range, the older north-southanticlines and thrusts, and the younger northwest-southeast structures. In addition it suggests a reason for the dying out of en echelon folds upward in shales, and the increase in their displacement lower in the stratigraphic section toward the crystalline rocks, frequently being replaced by faults.

Since the presence of old structural lines in a northwest-southeast direction in the crystalline rocks is assumed, no definite conclusions can be drawn regarding this explanation of the development of Front Range structures. Further research along the following lines is suggested.

1. A study of the "Red Beds" for the purpose of locating more definitely the Ancestral Rocky Mountains.

2. A study of the Metamorphic series to locate any structural trends in these rocks.

3. A study of the faults which pass from sedimentary to crystalline rocks; especially in the crystalline rock area, to discover any evidence of movement before Cretaceous time.

4. A study of the mineralized veins and dikes of the crystalline rock area to determine the number of movements along these planes.

The possibility that the forces building up the Rocky Mountains were rotational in character must be considered next. By rotational is meant a condition of unbalanced opposing forces, the greater force from the east directed toward the north end of the deformed zone, and the greater force from the west directed toward the south end of the deformed zone, or visa versa. The same effect would be accomplished by a rigid mass on the east moving southwestward squeezing the rocks against a rigid mass on the west side of the deformed area.

If there were no structural features present in the rocks to influence the development of new structures, such movements would have a greater effect on the general trend of the Front Range. Instead of trending north-south, it would be skewed around to the west, and the sedimentary rocks along the flanks would show a greater echelon arrangement. The normal monocline would be broken into numerous enechelon folds. Furthermore, this idea does not explain the earlier north-south anticlines and thrust faults.

The experiments of Bailey Willis on Appalachian Structures indicates that folding may be localized in a series of sedimentary rocks by a change in the initial dip of the sediments. This may have some significance in the problem here considered. The Cretaceous rocks are noticably thicker in North Central and Western Colorado than in the regions to the east. The changes from east to west in the "Red Beds" have not been studied. Whether or not a greater accumulation of weak sedimentary rocks here was sufficient to localize the relief of mountain making forces cannot be known, but if so we have an adequate explanation for the structures of this region. Rotational forces, whose major effect was to cause compression in an east-west direction, were brought to bear on this portion of the earth's crust. The major movements were localized by the greater thickness of sedimentary rocks (change in initial dip) and the resulting structures were given a north-south trend. The component causing rotation found relief in the development of the northwest-southeast trending structures. In further examination of this theory it is suggested that a more detailed study of the "Red Beds" especially, and of the Mesozoic series be made to determine the places of accumulation of greatest thickness of sediments.

Summary

The Carter Lake area shows two sets of structures--one set is represented by folds and high angle thrust faults trending north-south, and probably of relatively shallow depth; and a second set of later development is represented by high angle faults trending approximately northwest-southeast. The origin of these structures and their relationship may be explained in the following ways:-

1. Two separate periods of movement:- The first, a simple east-west compressional force, developed the north-south structures; a second period of rotational stress formed the northwest-southeast structures. The differences in competency of various beds, the differences in ability to transmit force, the depth of deformation, the depth

of maximum transmission of force, and the possibility of control by older structures are not considered.

2. One period of movement, or several periods of movement caused by similar forces acting through a deep section of sedimentary and crystalline rocks.

   A. Simple compressional forces: This explains the origin of all north-south structures. The northwest-southeast structures may be explained by an auxilliary theory.

      1) Difference in competency of sedimentary rocks to transmit forces developed the rotation which formed the northwest-southeast structures. This does not explain the parallelism of these structures, nor absence of southwest-northeast structures.

      2) Older structures in the basement rocks trending northwest-southeast moved during Laramide revolution to relieve compressional forces, and in this movement southeast structures in sedimentary as well as crystalline rocks were developed.

         a. Local conditions at Carter Lake permitted folding in sedimentary rocks before movement took place in the basement rocks, and the shallow north-south structures were formed.

         b. Later yielding in the crystalline rocks formed the northwest-southeast structures which were reflected in the sedimentary beds above as faults and enechelon folds.

c. In regions where north-south structures are absent, movement was inaugurated in deeper crystalline rocks.

d. In regions where no echelon folds and faults occur, movement was inaugurated in crystalline rocks, but no structures existed in the latter favorably located for new movement.

B. Rotational forces explain echelon folds and faults, but does not explain the north-south trend of the Front Range, the north-south monocline, or other minor north-south structures, unless a second structural condition is postulated. This may have been a change in initial dip in the sedimentary rocks along a north-south axis.

BIBLIOGRAPHY

Andrews, E. C.
1923 Contributions to the Hypotheses of Mountain Formation.
Geological Society of America Bulletin, Vol34 pages 381-399

Bronson, E. B.
1930 Jurassic-Triassic Contact in Western Wyoming (Abstract)
Geological Society of America Bulletin Vol. 41 page 120

Butters, R. M.
1913 "Permian or "Permo-Carboniferous" of the Eastern Foothills of the Rocky Mountains of Colorado."
Colorado Geological Survey, Bulletin 5, part 2.

Cross, Whitman (and Emmons S. F.)
1894 "Pikes Peak Folio","U. S. Geological Survey, Geological Atlas of the U. S., Folio no. 7.

Cross, Whitman, and Howe, Ernest
1905 Red Beds of Southwestern Colorado and their Correlation.
Geologic Society of America Bulletin. Vol. 16 pages 447-498

Chamberlin, R. T.
1919 "Building of the Colorado Rockies."
Journal of Geology vol 27 pages 145-164, 225-251
1922 The Wedge Theory of Diastrophism
Journal of Geology vol33 pages 755-792

Daly, R. A.
1914 "Igneous Rocks and their Origin."

Darton, N. H.
1901 "Comparison of the Stratigraphy of the Black Hills with that of the Front Range of the Rocky Mountains." Abstract.
Geologic Society of America Bulletin.
Vol 12, page 478
1905"Geology and Underground Water Resources of the Central Great Plains."
United States Geological Survey. Professional Paper no. 32

Eldridge, G, H,
Emmons, S. T.
Cross, Whitman
1896 "Geology of the Denver Basin
United States Geology Survey Monograph 27

Fenneman, N. M.
1905 "Geology of the Boulder District, Colorado."
United States Geological Survey . Bulletin 265

Finlay, George I.
1907 "The Gleneyrie Formation and its Bearing on the Age of the Fountain Formation in the Manitau Region."
Journal of Geology. Vol 25, pages 586-589

Flint, R. F.
1921 A Brief Review of Rocky Mountain Structures.
Journal of Geology Vol. 32, pages 410-432

George, R. D.
1915 Geologic Map of Colorado
Colorado Geological Survey. Scale 1/500000

Hubbs, W. H.
1923 The Mechanics of the Formation of Arcuate Mountains
Geologic Society of America. Bulletin.
Vol.34 pages 243-252

Henderson, Junius
1908 "The Red Beds of Northern Colorado
Journal of Geology" Vol 25. pages 491-492
1920 "The Foothills Formations of North-Central Colorado"
Colorado Geological Survey Bulletin, 19
pages 59-96

Knight, S. H.
1917 "Age and Correlations of the Red Beds of Southeastern Wyoming" Abstract.
Geologic Society of America Bulletin
Vol. 28, pages 168.
1933-Correlation of the pink-gray massive sandstone between the Morrison and Lykins formations in northern Colorado.
Personal communication

Lee, Willis T.
1913 "Type Section of the Morrison Formation."
American Journal of Science, 4th. series, vol.49
pages 183-188

Lee, Willis T.
1917 "Relation of the Morrison and Sundance Formations" Washington Academy Society Bulletin. vol. 7 page 431
1923 Building of the Southern Rocky Mountains Geologic Society of America Bulletin. vol 34 pages 285-308
1927 "Correlation of Geologic Formations Between East-Central Colorado, Central Wyoming, and Southern Montana."

Leith, C.K.
1923 Structural Geology Revised Edition, Henry Holt and Co. New York.

Link, Theodore A.
1928 "En Echelon Folds and Arcuate Mountains." Journal of Geology, vol. 36, pages 526-538

Marvine, Arch B.
1873 "Report of Arch. B. Marvine, Assistant Geologist Directing the Middle Park Division." United States Geological Survey of the Territories, F. V. Heyden Geologist.

Mead, W. J.
1920 "Notes on the Mechanics of Geological Structures" Journal of Geology, vol. 28, pages 505-523

Melton, F. A.
1925 "The Ancestral Mountains of Colorado and New Mexico" Journal of Geology, vol. 33, pages 84-89

Mook, Charles Craig
1916 Study of the Morrison Formation New York Academy of Science, Annals. vol 27 pages 39-191

Morse, R.
1923 Jointing and the Application of the Strain Ellipsoid Journal of Geology, vol. 31, pages 666-669

Nevin, C. M.
1931 "Principles of Structural Geology" John Wiley and Son.

Quam, Louis O
1932 "Geology of the Rabbit Mountain Area, Colorado." Thesis for M. S. degree, University of Colorado.

Reeside, John B. Jr.
1931 "Supposed Marine Jurassic (Sundance) in Foot hills of Front Range of Colorado." American Association Petroleum Geology. Bulletin 15, pages 1095-1105

Stanton, T. W.
1905 "The Morrison Formation and its Relations with the Comanche Series and the Dakota Formation." Journal of Geology, vol. 13, pages 657-659
1915 "Invertebrate Fauna of the Morrison, Dakota and Sundance Formations." Geologic Society of America Bulletin, vol 26, pages 755-756
1922 "Some Problems Connected with the Dakota Sandstone." Geologic Society of America Bulletin, vol. 33, pages 265-272

Schuchert, C.
1918 Correlations of the Morrison and Sundance Formations. Geologic Society of America Bulletin, vol, 29, page 256

Thompson, Warren O
1933 Relationship of Fountain, Ingleside and Lyons Formations Personal communication

Tiejie, A. J.
1923 "A Study in Sedimentation of the Red Beds of the Front Range in Colorado." Journal of Geology, vol. 31, pagea 192-207

United States Geological Survey
1908 Topographic Map Loveland Quadrangle. Scale 1/62500

Willis, Bailey
1891-92 "Mechanics of Applachian Structures." United States Geological Survey. 13th Annual Report, part 2

Willis, Robbin and Willis, Bailey
1929 "Geologic Structures," second edition McGraw Hill Book Co., New York and London

Ziegler, Victor
1917 "Foothills Structures in Northern Colorado." Colorado School of Mines Quarterly vol.12, no. 21

Plate 9

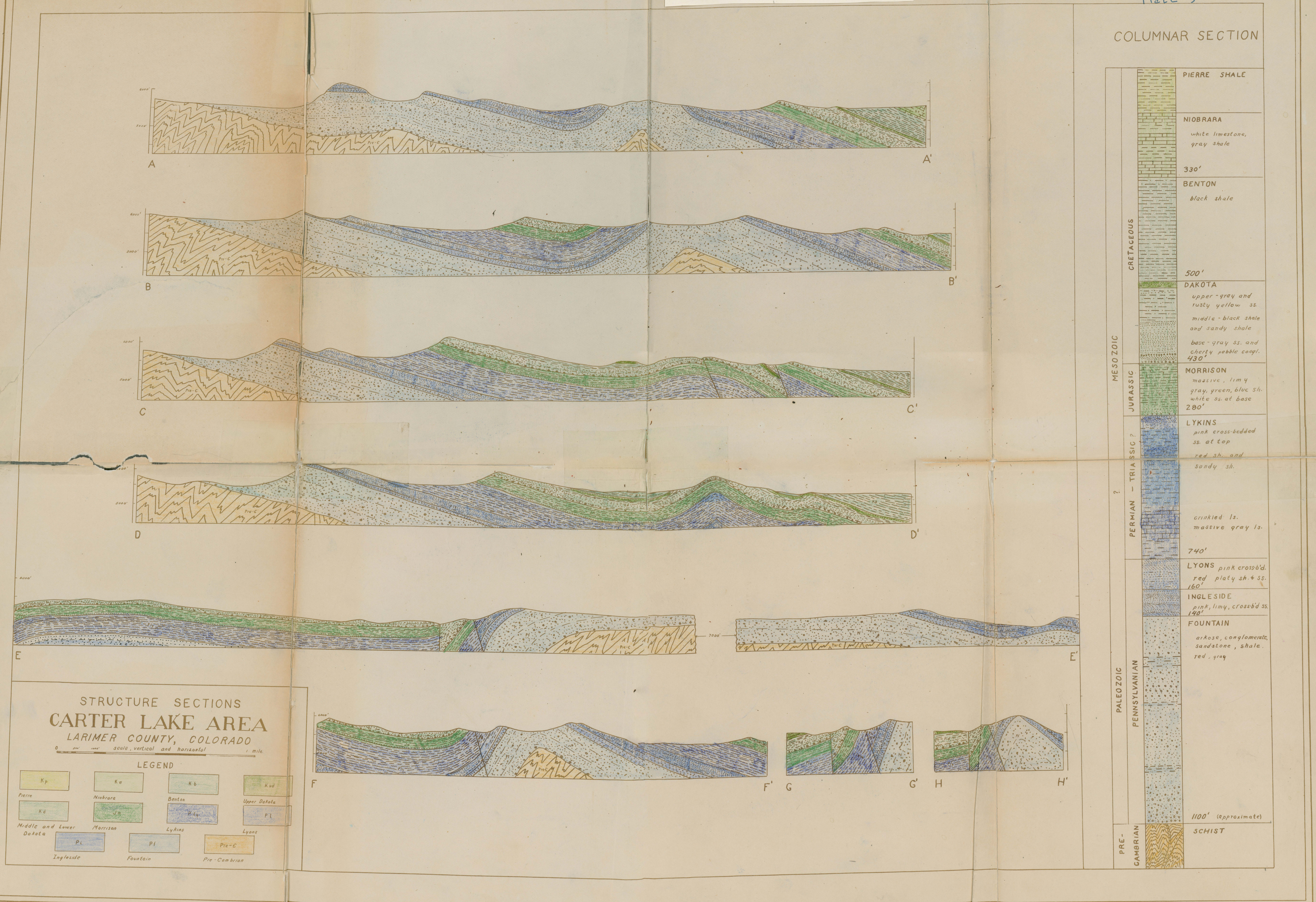

STRUCTURE SECTIONS
CARTER LAKE AREA
LARIMER COUNTY, COLORADO
scale, vertical and horizontal
1 mile
LEGEND
Pierre
Niobrara
Benton
Upper Dakota
Middle and Lower Dakota
Morrison
Lykins
Lyons
Ingleside
Fountain
Pre-Cambrian
A
A'
B
B'
C
C'
D
D'
E
E'
F
F'
G
G'
H
H'
COLUMNAR SECTION
MESOZOIC
CRETACEOUS
JURASSIC
PERMIAN – TRIASSIC ?
PALEOZOIC
PENNSYLVANIAN
PRE-CAMBRIAN
PIERRE SHALE
NIOBRARA
white limestone, gray shale
330'
BENTON
black shale
500'
DAKOTA
upper - gray and rusty yellow ss.
middle - black shale and sandy shale
base - gray ss. and cherty pebble congl.
430'
MORRISON
massive, limy gray, green, blue sh.
white ss. at base
280'
LYKINS
pink cross-bedded ss. at top
red sh. and sandy sh.
crinkled ls.
massive gray ls.
740'
LYONS pink cross-b'd.
red platy sh. & ss.
160'
INGLESIDE
pink, limy, cross-b'd ss.
140'
FOUNTAIN
arkose, conglomerate, sandstone, shale.
red, gray
1100' (approximate)
SCHIST

Plate 8


GEOLOGIC AND TOPOGRAPHIC MAP
CARTER LAKE AREA
LARIMER COUNTY, COLORADO
scale
0
1 mile
contour interval 100'
datum mean sea level
Base-corrected USGS map Loveland Quad.
LEGEND
Kp Pierre
Kn Niobrara
Kb Benton
Kud Upper Dakota
Kd Kmd Kld Middle and Lower Dakota
Jm Morrison
Ply Lykins
Pl Lyons
Pi Ingleside
Pf Fountain
Pre-Є Pre-Cambrian
true north
R. 70 W.
T. 5 N.
T. 4 N.
COTTONWOOD
CREEK
FLATIRON MTN.
CHIMNEY HOLLOW
MEADOW HOLLOW
CARTER LAKE
BM X 5440
BM X 5769
Berthoud-Carter Road
A
A'
B
B'
C
C'
D'
F
F'
G
G'