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CONTENTS.

ILLUSTRATIONS.

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY, 1915.

THE COMPOSITION OF MUDS FROM COLUMBUS MARSH, NEVADA.

By W. B. Hicks.

INTRODUCTION.

The investigation of the dry lake of Columbus Marsh, in Nevada, which had for its economic motive the discovery of potash, was continued by the United States Geological Survey during the summer of 1913 under the supervision of Hoyt S. Gale. The work done included the drilling of a shallow well near the old well 400 and the collection of a set of surface samples of muds from the marsh. This exploration, together with the chemical investigation of the samples thus collected, has furnished further data concerning the character of the mud flat and thrown additional light on the conditions there.

The writer was associated with Mr. Gale during his study of this region and the field observations here recorded were made jointly and are results of mutual discussion. The accompanying map (fig. 1) is based on a plane-table survey made by Mr. Gale, and for this and other assistance the writer wishes to express due acknowledgment.

LOCATION.

Columbus Marsh is situated on or near the line between Esmeralda and Mineral counties, Nev.[1] Coaldale is a railroad station at the southeast corner of the marsh, and the Tonopah & Goldfield Railroad skirts the eastern margin of the mud flat itself. The marsh covers an area of 35 to 40 square miles and is roughly elliptical in outline, being about 9 miles from north to south and 6 miles or more in width. It is a broad mud plain with a rough, lumpy surface—a typical playa, the lowest part of the basin of a distinct drainage system, a physiographic feature characteristic of the Great Basin region. Little salt shows on the mud surface except about the margins of the plain, where several borax-producing plants were located in the earlier days of the borax industry. An accurate representation of this basin is given on figure 1.

PREVIOUS EXPLORATIONS FOR POTASH IN COLUMBUS MARSH.

EXPLORATIONS BY THE UNITED STATES GEOLOGICAL SURVEY.

LOCATION OF WELLS AND METHOD OF EXPLORATION.

In searching for potash during 1912 six shallow wells were put down by the United States Geological Survey in Columbus Marsh to depths ranging from 32 to 50 feet. Later two other wells were sunk to a depth of about 80 feet. These wells were located as follows:

Well No. 100, sec. 13, T. 2 N., R. 36 E.
200, sec. 12, T. 2 N., R. 36 E.
300, sec. 35, T. 3 N., R. 36 E.
400, sec. 8, T. 2 N., R. 36 E.
500, sec. 31, T. 3 N., R. 36 E.
600, sec. 15, T. 3 N., R. 36 E.
700, sec. 9, T. 2 N., R. 36 E.
800, sec. 5, T. 2 N., R. 36 E.

[1] Gale, H. S., Potash tests at Columbus Marsh, Nev.: U. S. Geol. Survey Bull. 540, p. 422, 1914.

The location of the wells is shown accurately on figure 1, which gives a clear conception of the area and extent of the mud flat as well as the distribution of the wells. The drilling

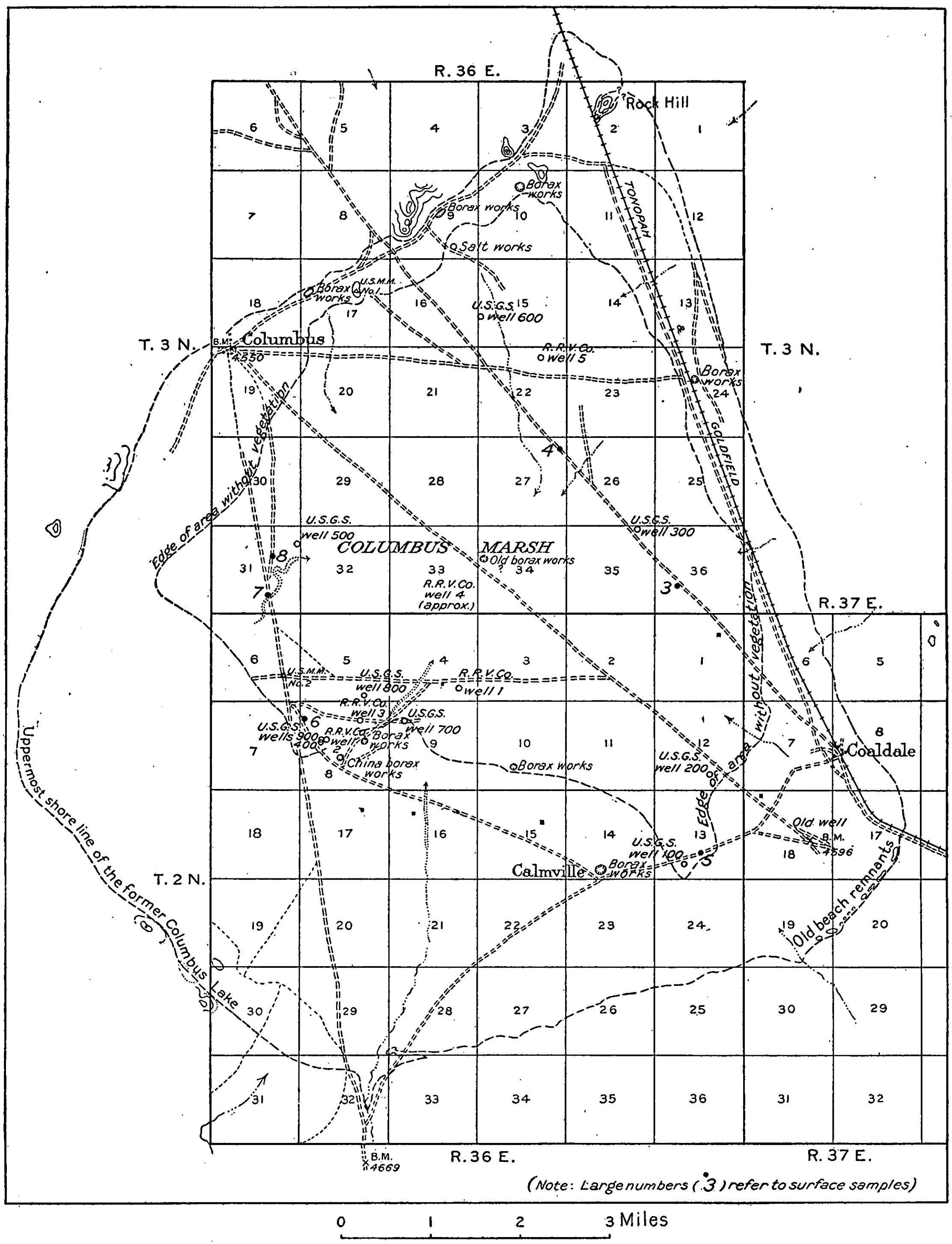


FIGURE. 1.—Map of Columbus Marsh, Nev.

and sampling were done by Charles E. Watson under the direction of Mr. Gale. The samples when received at the laboratory were air-dried. They were powdered without making a mineralogic study and preserved for analysis.

METHOD OF ANALYSIS.

The analysis of the samples from Columbus Marsh was concerned primarily with the estimation of the total soluble salts and the potassium. On extracting the muds with water, suspensions of a colloidal nature were obtained which would settle only after long standing, if at all. For practical analytical purposes in the estimation of the water-soluble salts it became necessary to clarify these suspensions by artificial means. For this purpose ammonium chloride was used, because of its volatility. The method was as follows:

The mud was digested on the steam bath for half an hour with 25 cubic centimeters of water and 0.25 gram of ammonium chloride for each gram of sample taken, this quantity of ammonium chloride being necessary in most cases for the clarification of the solution. The extract was either filtered and the residue washed with water, or made up to definite volume, filtered, and aliquots taken for analysis. In either case the filtrate which represented the extract from 2 to 4 grams of material was evaporated in a tarred porcelain dish (porcelain being used because of the lack of platinum), ignited to dull redness to drive off all ammonium salts, cooled, and weighed, the result being reported as total soluble salts. The ignited residue was dissolved in dilute hydrochloric acid and filtered, and the potassium was determined in the filtrate by what has been called the modified chlorplatinate method.[1]

Although it was presumed that the above-outlined procedure for the estimation of total salts would give somewhat high results, the method was thought to be sufficiently accurate for the work in hand. Being found rapid and practical, it was used in the earlier work on the muds that were of such a nature as to require artificial clarification of their extracts.

SUMMARY AND DISCUSSION.

The analytical data obtained in connection with the exploration of Columbus Marsh for potash during 1912 are summarized in the following table:[2]

Summary of previous analyses of muds from Columbus Marsh, Nev.

[W. B. Hicks, analyst.]

Well No.	Depth of well (feet).	Soluble salts (per cent of sample).			Soluble potash as K.					
					Per cent of sample.			Per cent of total salts.		
		Maximum.	Minimum.	Average.	Maximum.	Minimum.	Average.	Maximum.	Minimum.	Average.
100.......	25	3.62	1.67	2.12	....	....	....	....	....	....
200.......	49	22.30	4.67	9.73	0.68	0.06	0.54	8.46	0.34	5.52
300.......	50	26.91	14.10	18.27	1.01	.43	.65	4.69	2.40	3.58
400.......	38	17.30	5.17	8.66	1.31	.22	.84	20.90	1.67	9.75
400 [a]......	38	6.30	5.17	5.96	1.31	.85	1.02	20.90	13.69	17.07
500.......	48	15.50	11.10	12.84	.84	.35	.55	6.69	2.38	4.30
600.......	46	19.12	10.51	13.46	.86	.26	.57	5.94	1.37	4.23
Average..	....	....	....	12.59	....	....	.70	....	....	5.46

[a] Part below depth of 18 feet.

NOTE.—The complete data relative to wells 700 and 800 have not been published and so are not included here.

These data, exclusive of those for well 100, which was shallow and located at the extreme edge of the flat, show that well 300 has the highest and well 400 the lowest percentage of soluble salts. The reverse is true of their potash content. Wells 200, 500, and 600 show intermediate

[1] Hicks, W. B., A rapid modified chlorplatinate method for the estimation of potassium: Jour. Ind. and Eng. Chem., vol. 5, p. 650, 1913.
[2] See Gale, H. S., op. cit., pp. 423-424.

values in regard to both determinations. In all cases, however, high percentages of soluble salts correspond to low percentages of potassium in the salts. Accordingly, the average content of soluble potash is approximately constant for all the wells except well 400, in which it is unusually high. The percentage of soluble salts in the section from 18 to 38 feet of well 400 is low, but the percentage of potassium in these salts is exceptionally high. The maximum and minimum percentages of soluble salts from wells 300, 500, and 600 vary much less than the percentages from the other wells. This is true to a less degree in regard to the potash content. Although the muds from some of the wells average nearly 20 per cent in soluble salts, no salt beds or distinct saline horizons were found.

Only one sample of water was collected and analyzed from each of wells 300, 500, and 600. These samples were strong brines containing from 18 to 25 per cent of salts, of which 4 to 1.5 per cent was potassium. Six water samples were analyzed from well 400. These averaged 0.73 per cent of salts, of which 3.90 per cent was potassium. Four of these waters, two representing strong flows, came from the section between 18 and 38 feet, in which the salts extracted from the muds showed surprisingly high values in the percentage of potash. These waters were very dilute and nearly uniform in composition, containing on an average 0.47 per cent of salts, of which only 4.31 per cent was potassium. These low figures are at variance with the results obtained for the muds from the same horizon. The low concentration in salts might be explained by assuming that the waters came from strong flows and had not remained in contact with the muds long enough to extract large amounts of the salts. This would require the further assumption, in order to explain the low values for potash, that the potash in the muds was present in a relatively less soluble condition than the other salts. In any event discrepancies in the analytical results obtained for the muds and waters from the same horizon in well 400 are evident.

EXPLORATIONS BY THE RAILROAD VALLEY CO.

Subsequent to the investigations by the United States Geological Survey, described above, the Railroad Valley Co., of Tonopah, Nev., in its search for potash put down five holes in Columbus Marsh. These were shallow holes comparable to the wells of the Survey already described and were located as indicated on the accompanying map (fig. 1). So far as the writer is aware the results obtained by the Railroad Valley Co. in exploring Columbus Marsh have not been published.

UNITED STATES GEOLOGICAL SURVEY WELL 900.

LOCATION AND DETAILS OF DRILLING.

In order to discover the cause of the discrepancies mentioned above and to obtain more information concerning the character of the muds in Columbus Marsh, well 900 was put down in August, 1913, under the direction of Mr. Gale. This well was located in sec. 8, T. 2 N., R. 36 E., about 100 feet east of well 400, and was drilled to a depth of 67 feet. The drilling was done by Charles E. Watson, who used a small modified Empire core drill, the casing always following within a few feet or even going ahead of the bit. In a general way the muds encountered to the depth of 26 feet consisted of alternate layers of sand and clay; below this depth material much more consolidated was also encountered. Several water flows, some of which appeared to be rather strong, were observed as the drilling progressed. Only one, however—that struck at a depth of 3 feet—could be considered a brine, all the others being very dilute. A superficial examination of the muds as they came from the well was made by the writer, but no distinct saline horizons could be detected, the muds apparently being thoroughly washed with water and containing very little soluble matter. The sampling was also done by the writer, care being taken to obtain the most representative set of samples possible under the conditions attendant on the drilling. The muds were collected by averaging all the material representing a distinct layer as it came from the well. These were preserved in tin cans and shipped with the water samples to Washington for analysis.

RECORD OF THE WELL.

A detailed record of the well is given below. It agrees with that of well 400.

Record of United States Geological Survey well 900, Columbus Marsh, Nev.

Muds.

	Thickness.	Depth.
	Feet.	*Feet.*
Surface, crystallized salt and sand	0.2	0.2
Sand with small amount of clay, greenish yellow	4.0	4.0
Clay, light gray and black, wet	.5	4.5
Sand, black with foul odor, very wet	5.0	9.5
Clay, black, sticky	.5	10.0
Sand and gravel, dark gray, moist	7.0	17.0
Sand with a small amount of clay, light gray, moist	2.5	19.5
Clay, with a small amount of sand, light gray	.5	20.0
Sand, fine, light gray, very moist	3.5	23.5
Hardpan, clay and consolidated material	2.5	26.0
Sand, nearly black, wet, without saline taste	3.0	29.0
Clay, greenish gray, smooth	.5	29.5
Sand, black, very moist	1.0	30.5
Hardpan, alternating layers of clay and more consolidated material	6.5	37.0
Clay, alternating layers of light gray and black	2.5	39.5
Hardpan, alternating layers of clay and more consolidated material	5.5	45.0
Sand, coarse, nearly black	3.0	48.0
Clay, black, sticky, soft	4.0	52.0
Hardpan	1.0	53.0
Sand, quicksand, nearly black, foul odor	1.5	54.5
Clay, light gray, soft, sticky	7.0	61.5
Sand, quicksand, nearly black	.5	62.0
Clay, light gray, very sticky	.5	62.5
Sand, mostly quicksand, with some fine gravel	4.5	67.0

Water encountered.

Sample No.		Temperature.	Depth.
		°C.	*Feet.*
1	Strong brine	21.7	2.5
2	Water, nearly fresh, strong flow, rising within 1.5 feet of surface	14.0	15.0
3	Water, nearly fresh, moderate flow	16.0	23.0
4	Water, nearly fresh, strong flow, rising within 2 feet of surface	16.5	27.0
5	Water, nearly fresh, weak flow	17.0	37.0
6	Water, nearly fresh, strong flow, rising within 1 foot of surface, foul odor	14.0	42.0
7	Water, nearly fresh, weak flow	(?)	47.0
8	Water, nearly fresh, strong flow, rising within 16 feet of surface, foul odor	15.0	54.0
9 [a]	Water, nearly fresh, weak flow	(?)	61.0
9	do	17.0	66.0

[a] Not sampled.

CHEMICAL DATA.

CLARIFICATION OF THE MUD EXTRACTS BY THE USE OF AMMONIUM CHLORIDE.

In the chemical investigations relating to Columbus Marsh and more particularly to well 900, the samples have been analyzed for soluble salts and potash, first by the method described above, in which ammonium chloride was used to clarify the solution, and then by a method in which the clarification was effected by filtration through Pasteur-Chamberland clay filters, the potash in all cases being determined by the modified chlorplatinate method already mentioned. In addition more complete analyses of some of the samples have been made, and the total potash in a number of them has been determined. The results of the analyses in which ammonium chloride was used as the clarifying agent are given on page 6. With the exception of the moisture determination the percentages in this paper refer to the material dried at 100° C.

Results of analyses of muds from well 900 with ammonium chloride as the clarifying agent.

[W. B. Hicks, analyst.]

Sample No.	Depth (feet).	Character of material.	Soluble salts (per cent of sample).	Potash as K.		Moisture (per cent).
				Per cent of sample.	Per cent of soluble salts.	
1	0.5	Surface	21.02	0.27	1.27	13.46
2	4.0	Sand	8.20	.28	3.45	18.60
3	4.5	Clay	12.07	.57	4.77	20.60
4	9.5	Sand	7.74	.34	4.34	18.75
5	10.0	Clay	8.63	.45	5.17	25.65
6	17.5	Sand	3.61	.55	15.10	4.91
7	19.5	do	5.50	.86	15.65	18.30
8	20.0	Clay	6.75	1.04	15.33	23.70
9	23.5	Sand	3.35	.91	17.00	16.44
10	26.0	Consolidated material	6.22	.92	14.77	19.27
11	29.5	Clay	6.15	.93	15.13	21.85
12	30.5	Sand	6.65	1.21	18.25	23.10
13	37.0	Consolidated material	6.71	1.29	19.22	25.90
14	39.5	Clay	7.86	1.46	18.60	29.30
15	45.0	Consolidated material	4.15	.45	10.68	16.65
16	52.0	Clay	5.65	.55	9.65	26.20
17	58.5	do	5.80	.41	7.05	41.70
18	62.0	Quicksand	2.28	.15	6.67	27.80
19	67.0	do	2.70	.36	13.12	24.90
Average			6.90	.68	11.33	

These results are in complete agreement with those obtained from well 400. Except in the surface material the percentage of soluble salts is low and nearly constant, while that of potassium is comparatively high, increasing at first with increasing depth to unusually high values in the section between 17 and 39 feet, and then falling off again. The samples for the whole well average 6.90 per cent in soluble salts and 11.33 per cent in potassium, against 8.66 and 9.75 per cent, respectively, for well 400; while in the section between 17 and 39 feet the muds from well 900 average 5.87 per cent in soluble salts and 16.12 per cent in potassium, against 5.96 and 17.02 per cent, respectively, for the muds from the corresponding section of well 400. In fact, the analytical data concerning the two wells are concordant in every particular. The unusually high percentage of potassium in well 400 is found at corresponding depths in well 900. Contrary to expectations, the percentages of both soluble salts and potash decline with increasing depth below 40 feet.

The muds from well 900 vary greatly, being composed of sand, clay, or material much more consolidated, or of mixtures of these, and a most surprising fact is that the analytical data give no indication whatever of such differences in the character of the material represented by the samples.

CLARIFICATION BY FILTRATION THROUGH PASTEUR-CHAMBERLAND FILTERS.

In searching for a method for the clarification of the extracts that would yield a clear solution containing without question only that material which water alone would dissolve from the muds, filtration through porcelain filters suggested itself. Experiments carried out by the writer[1] have shown that only slight changes result to moderately concentrated solutions on passing through Pasteur-Chamberland clay filters and that the alkalies from very dilute alkaline solutions are more or less absorbed by such treatment; therefore mud extracts that are alkaline and very dilute are likely to show appreciable changes in composition after being subjected to this method of clarification. As the mud extracts from the Columbus Marsh

[1] Jour. Ind. Eng. Chem., vol. 6, pp. 829-831, 1914.

samples were not excessively dilute, were composed largely of chlorides and sulphates, and were only slightly alkaline, it is believed that the values for the water-extractable material obtained by this method of clarification are nearly correct, some of them probably being a little low.

The following procedure was used: A 20-gram sample of the mud which had been dried and powdered was heated with occasional stirring for 1 hour on the steam bath with 400 cubic centimeters of water. It was then transferred to a measuring flask, cooled, and made up to 500 cubic centimeters, and 10 cubic centimeters of water was added to correct for the volume occupied by the mud. After mixing and allowing to settle the extract was filtered through a Pasteur-Chamberland clay filter using strong suction. After discarding the first 100 cubic centimeters of the filtrate, aliquots of 100 to 200 cubic centimeters were taken for analysis. The results are given below.

Analytical results obtained from mud samples of well 900 after clarification of the water extract by filtration through Pasteur-Chamberland clay filters.

[W. B. Hicks, analyst.]

Sample No.	Depth (feet).	Soluble salts (per cent of sample).	Soluble potash as K.		Ratio of values obtained by use of ammonium chloride to values obtained by use of Pasteur-Chamberland filters.		
			Per cent of sample.	Per cent of soluble salts.	Soluble salts.	Soluble potash.	
						In sample.	In soluble salts.
1	0.5	18.26	0.11	0.58	1.16	2.45	2.19
2	4.0	4.96	.09	1.83	1.65	3.11	1.88
3	4.5	7.03	.15	2.13	1.72	3.80	2.24
4	9.5	4.80	.11	2.29	1.61	3.09	1.46
5	10.0	3.77	.12	3.16	2.29	3.75	1.64
6	17.5	.56	.04	6.62	6.45	13.75	2.26
7	19.5	.49	.04	5.70	11.22	21.50	2.09
8	20.0	.61	.04	6.50	11.05	26.00	2.36
9	23.5	.74	.03	4.64	7.23	30.33	3.66
10	26.0	.54	.03	5.32	11.50	30.66	2.68
11	29.5	.75	.04	4.72	8.20	23.25	3.21
12	30.5	.79	.04	5.11	8.42	30.25	3.57
13	37.5	.76	.03	5.56	8.83	43.00	3.46
14	39.5	.94	.04	3.78	8.36	36.50	4.92
15	45.0	.52	.03	8.66	7.98	15.00	1.23
16	52.0	1.30	.07	5.45	4.35	7.86	1.77
17	58.5	1.36	.12	9.52	4.27	3.42	.74
18	62.0	.52	.03	6.59	4.38	5.00	1.01
19	67.0	.39	.03	10.15	6.93	12.00	1.29
Average		2.84	.06	5.17			

According to these data the amount of material extracted by water alone from the mud samples in well 900, exclusive of the surface material, is small, amounting on an average to only 2.84 per cent. The average content of potassium is 0.06 per cent of the sample, or 5.17 per cent of the soluble salts. The results from the section of the well between 17 and 39 feet, which yielded unusually high values for potassium by the other method of analysis, are even more striking. Here the average content of soluble matter is 0.69 per cent and that of potassium 0.04 per cent of the sample, or 5.32 per cent of the soluble salts. These figures are exceptionally low compared with those obtained by the use of ammonium chloride—a fact that becomes more evident by an examination of the columns of ratios in the table. Here it is seen that by the method in which ammonium chloride was used for clarification, from 1 to 10 times as much soluble matter and from 2 to 40 times as much potassium is dissolved from the muds as by the method in which the samples are extracted by pure water and clarified by filtration through clay filters. It is also evident that the ratio of the potassium extracted is in general from 2 to 4 times that of the soluble salts. In other words, the soluble salts extracted from the muds by the use of ammonium chloride contain a much higher percentage of potash than the pure water extract. The variation in the results obtained by the two methods is greatest in the case of the muds that contain the least amount of soluble salts. No appreciable changes corresponding to differences in the character of the material appear in the results of the analysis, or in the variations by the two methods.

A consideration of these data shows conclusively that the high figures obtained for potash in the samples from wells 400 and 900 have resulted from the method of clarifying the mud extracts with ammonium chloride. It further furnishes an explanation of the discrepancies observed above in the analyses of muds and waters from the same horizon.

TOTAL POTASH IN THE MUDS.

The total potash in a number of muds from well 900 was determined by the J. Lawrence Smith method.[1] The samples were selected from those showing high percentages of potassium in the ammonium chloride extract and represent the various kinds of material found in the well. The results are given in the subjoined table, which include also those for one sample from well 200, for comparison.

Total potash in muds from well 900 and percentage extracted with ammonium chloride and with water.

[W. B. Hicks, analyst.]

Sample No.	Depth (feet).	Character of material.	Total potash as K (per cent of sample).	Per cent of total potash extracted by—	
				Ammonium chloride solution.	Water.
200+9	29		3.55	19.20	
900+2	4	Sand	2.84	9.88	2.82
900+3	4.5	Clay	2.96	19.25	5.07
900+9	23	Sand	3.26	27.90	.92
900+12	30	do	3.30	36.70	1.21
900+13	37	Consolidated material	3.46	37.30	.87
900+14	39	Clay	3.72	39.20	1.08
900+16	52	do	2.64	20.80	2.65
900+19	67	Sand	2.84	12.68	1.07

According to these data the potash content of the muds is roughly constant without regard to the character of the material. Although only a small percentage of the total potash was extracted by water, from 10 to 40 per cent was carried into solution by ammonium chloride, the high values again being shown by the muds which came from the section of the well between 17 and 39 feet.

ANALYSES OF WATERS.

Incomplete analyses of the waters from well 900 were made. The results, which are set forth on page 9, are sufficient to give a fair idea of the character of these waters and to show the close similarity in composition of their dissolved salts.

[1] Treadwell, F. P., Analytical chemistry, 3d ed., vol. 2, p. 496, John Wiley & Sons, 1911.

Analyses of waters from well 900.

[W. B. Hicks, analyst.]

	1	2	3	4	5	6	7	8	9
Depth (feet)	2.5	15	23	27	37	42	47	54	66
Cl	55.18	54.90	53.36	53.00	51.00	52.48	48.62	49.40	49.28
SO_4	6.19	4.29	6.70	6.83	9.48	6.19	8.30	6.85	9.63
B_4O_7	.39	1.03	1.12	1.30	1.44	1.61	1.22	3.28	1.56
CO_3		.44	.44	.66	.48	.63	.36	2.38	1.02
K	1.91	3.45	3.53	3.65	3.04	3.59	3.00	3.36	3.73
Na, Ca (by difference)	35.89	36.33	34.85	34.56	34.56	35.45	38.50	34.73	34.78
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Total salts	20.52	.62	.59	.50	.66	.38	.87	.31	.47

All the samples contained a small amount of calcium. No test was made for Mg or SiO_2.

With the exception of sample No. 1, which is a strong brine, the waters from well 900 are very dilute and of the same order of concentration. Their soluble salts are very similar in composition, consisting largely of sodium chloride with moderate amounts of sulphates, and containing borates, carbonates, and salts of potassium and calcium. Apparently the percentage of sulphates and borates tends to increase with depth. The potash is not unusually high and is approximately constant for all the waters.

ABSORPTION OF POTASH BY MUDS.

From the preceding data it is evident that the muds from well 900 contain a high percentage of potash. It is also known that only a small quantity of this potash is found in the water extract after filtration through porcelain filters, while a large amount is dissolved by solutions of ammonium chloride. Many investigators [1] have shown that rock-forming minerals are dissolved to a slight degree by water and to a larger extent by salt solutions. The magnitude of such solubility, however, is small.

From a consideration of these facts it is believed that a large percentage of the potash in the muds of Columbus Marsh is held in a loosely combined form, though the exact manner of retention is not known.[2] It is probable, however, that a large portion of this potash has been absorbed from solution and is held by colloids either mechanically or in a weak chemical combination. At the same time it is certain that a small amount of the soluble potash shown in the analyses has resulted from the solvent action of an ammonium chloride solution on the minerals present. This conclusion is emphasized by the fact that both the sands and the clays from well 900 contain approximately the same quantities of potash and give up similar amounts to solutions of ammonium chloride. However, the sand as well as the clay samples which gave the high potash values contain considerable colloidal matter. Furthermore, the muds from Columbus Marsh are still capable of absorbing considerable quantities of potash. Two grams of clay sample 200+9, from well 200, absorbed 0.0287 gram of potassium from a 0.5 per cent potassium chloride solution. This corresponds to an absorption of 1.43 per cent of the mud, an amount greater than that extracted by solutions of ammonium chloride from any of the samples from well 900 except No. 14.

Considering all the facts at hand, it is believed that large amounts of potash with small quantities of other salts have been absorbed from surrounding or percolating solutions and are held in a loosely combined form by the muds of Columbus Marsh, and perhaps by the muds of the desert basins in general. Such a conclusion is in accord with the fact, which has been long recognized, that clays selectively absorb potash, and perhaps it offers the best explana-

[1] For a bibliography on the solubility of rock-forming minerals see Clarke, F. W., The data of geochemistry, 2d ed.: U. S. Geol. Survey Bull. 491, p. 454, 1911.

[2] For bibliographies on the absorption of salts by clays see Van Bemmelen, J. M., Die Absorption, 1910; Clarke, F. W., op. cit., p. 477; Blanck, E., Landw. Zeitung (Fühling's), vol. 62, p. 560, 1913.

tion of the apparent disappearance of considerable quantities of the potassium salts from natural solutions or from the salts associated with the desert-basin saline deposits. Attention [1] has been repeatedly directed, through the analysis of many brines, saline incrustations, and muds, to the low content of potassium in comparison to that of sodium in these deposits. It is possible that in the desert basins the potash has been gradually absorbed from solutions by the muds, while the other salts, being less completely absorbed, have been gradually concentrated through evaporation, this process yielding the natural brines and salt incrustations with low potash content found in these regions at the present time.

CONCLUSIONS.

The data relating to wells 400 and 900 agree very closely. Water, as a rule, removes from the muds of well 900 only small amounts of soluble matter, but solutions of ammonium chloride extract larger quantities. The high percentages of potash found in the soluble salts from the muds of well 400, as well as the discrepancies between the results shown by the waters and muds from the same horizon, were a result of the method of analysis, in which the clarification was effected by ammonium chloride. High percentages of soluble salts in the muds usually correspond to low percentages of potassium in the salts. In such cases the variations in the water and ammonium chloride extracts are not so great.

The muds of Columbus Marsh are capable of absorbing more potash. It is believed that a large part of the potassium in the muds has been absorbed from surrounding or percolating solutions and is held in a loosely combined form, probably by colloids. Such a conclusion offers an explanation of the apparent disappearance of the potassium from the brines and saline deposits of the desert-basin regions.

SURFACE MUDS FROM COLUMBUS MARSH.

SAMPLES.

In order to determine the variations in composition of muds from different localities in Columbus Marsh, a number of samples of the surface material were collected in 1913. It was also thought that some relation between the composition of the muds and the "self-rising ground" of the marsh might be found. The samples represent the surface material to a depth of about 6 inches. They were collected by the writer and preserved in tin cans. The samples were taken at the plane-table stations established in mapping the flat and therefore represent for the most part the edge of the marsh. The localities from which these samples came are described below and are also indicated accurately on figure 1.

Localities from which surface samples were collected.

Sample No.	Location.	Character of surface material.
900+1	Sec. 8, T. 2 N., R. 36 E., at well 900	Sand and clay, moist. Surface smooth, moderately compact, and covered with thin layers of crystalline salts.
3	Sec. 36, T. 3 N., R. 36 E.	Clay and sand, brownish, moist, sticky, containing salt crystals. Surface covered with film of crystalline salts.
	Sec. 27, T. 3. N., R. 36 E.	Sand with some clay, brownish, loose, containing salt crystals. Surface dried to a rough, nearly white, crust.
5	Sec. 13, T. 2 N., R. 36 E.	Sand, brown, moist. Surface smooth, loose, and contains no crystalline salts. Many fragmentary volcanic rocks scattered over surface. Area formerly worked for borax.
6	Sec. 8, T. 2 N., R. 36 E.	Sand, brownish gray. Area covered with salt grass and formerly worked for borax. Sample taken from smooth surface between the ridges.
7	Sec. 31, T. 3 N., R. 36 E.	Sand and clay, brownish. Surface smooth, compact, and covered with film of crystalline salts.
8	do	Sand and clay, brownish yellow. Surface rough and very loose, like freshly plowed ground, and covered with a thin film of crystalline salts.

[1] See Clarke, F. W., op. cit., pp. 142-247; Dole, R. B., Explorations of salines in Silver Peak Marsh, Nev.: U. S. Geol. Survey Bull. 530, pp. 330-345, 1913; Gale, H. S., Prospecting for potash in Death Valley, Cal.; and Salt, borax, and potash in Saline Valley, Inyo County, Cal.: U. S. Geol. Survey Bull. 540, pp. 407-421, 1914.

ANALYSES.

Only partial analyses of the surface samples from Columbus Marsh were made, but the data are complete enough to show the composition of water-soluble matter in these muds. The results of the analyses, made on the material dried at 100° C., are tabulated below.

Analyses of surface muds from Columbus Marsh.

[W. B. Hicks, analyst.]

	900+1	3	4	5	6	7	8
Cl	40.30	53.30	48.15	49.20	34.15	53.20	45.40
SO_4	21.30	2.31	4.15	5.78	4.44	3.45	2.92
B_4O_7	1.14	2.21	1.45	6.21	25.88	3.30	3.01
CO_3	None.	None.	4.67	.75	.92	None.	4.93
SiO_3	.23	3.20	2.60	.43	1.53	1.30	4.80
K	.58	.50	.47	.51	1.91	2.08	.67
Ca	5.89	None.	None.	.37	2.72	.29	None.
Na (by difference)	30.56	38.48	38.51	36.75	28.45	36.38	38.27
Mg	None.	Trace.	Trace.	None.	None.	None.	None.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Soluble salts	18.26	11.27	20.00	11.75	6.53	7.24	10.96

DISCUSSION AND CONCLUSION.

From these results it will be seen that the soluble salts in the surface muds of Columbus Marsh, while containing a large amount of sodium chloride, vary widely in composition. All contain small quantities of potash and silica and varying amounts of sulphates and borates. Sample 900 + 1 shows exceptionally high sulphates, sample 6 high borates, and samples 4 and 8 considerable carbonates. According to the composition of the soluble salts, the mud samples may be classified as follows:

Samples 3 and 7, consisting largely of chlorides.
Sample 900+1 consisting largely of chlorides and sulphates.
Samples 4 and 8, consisting largely of chlorides and carbonates.
Samples 5 and 6, consisting largely of chlorides and borates.

Samples 3, 7, and 900 + 1 came from smooth, rather compact areas; samples 5 and 6 from localities formerly worked for borax, in which the surface material is more or less loose and covered in salt grass; and samples 4 and 8 from rough, very loose surfaces known as "self-rising ground." These facts indicate that the presence of carbonates in the surface material is a factor in causing the "self-rising ground," and that borates and perhaps alkalies in general tend to produce similar effects. The data, however, are not conclusive, because too few samples have been examined.

EOCENE GLACIAL DEPOSITS IN SOUTHWESTERN COLORADO.

By Wallace W. Atwood.

INTRODUCTION.

At the northwest base of the San Juan Mountains, not far from the village of Ridgway, Colo., there is a series of exposures that include a remarkable section of glacial till, which is overlain by formations of early Tertiary age. These exposures were found in September, 1913, while I was conducting an areal geologic survey of the southwest quarter of the Montrose quadrangle. The areal work was being done with a class of advanced students from the University of Chicago, and credit for collecting many of the data presented in this report is due to these able and enthusiastic young men. The party consisted of Messrs. F. B. Plummer, Frank Selfridge, W. J. Coleman, H. R. Bennett, M. M. Leighton, Walter R. Miller, L. E. Wells, Lloyd Le Duc, and V. L. Wooten. Messrs. Bennett and Miller first located what is now referred to as the type section, and they, with Mr. Le Duc, were with me when the material was first recognized to be of glacial origin and to be buried beneath Tertiary formations. Mr. Kirtley F. Mather, who is assisting me in the physiographic survey of the San Juan district, also aided in working out the characteristics and age of these glacial deposits.

After the completion of the work with the student party physiographic studies were continued in this area under the auspices of the United States Geological Survey, and at the close of the season Mr. Whitman Cross joined me and critically examined several of the best sections. I feel especially indebted to Mr. Cross for his very careful analysis of the available field data and for his judgment that the overlying Tertiary formations, with which he is so familiar, have been correctly recognized.

PHYSICAL GEOGRAPHY.

The area within which these early Tertiary glacial deposits have been found is in the foothill belt at the northwest base of the mountains, in the same region where three distinct stages of Pleistocene glaciation among the mountains were demonstrated in 1912.[1]

At the south margin of this area are the precipitous slopes of the high mountains. Many of the summits rise to altitudes of over 13,000 feet, and Sneffels Peak, the highest peak in this mountain front, attains 14,148 feet. At the north is a bold escarpment, bounding the southern face of the Uncompahgre Plateau. To the west are Hastings Mesa and Howard Flats, both of which are broad, flat-topped areas somewhat below the level of the Uncompahgre Plateau, and far below the mountain summits to the south. The valley of Dallas Creek and its tributaries occupies the central portion of the area, and the dissection of this area by these streams has developed a topography of late maturity and uncovered many of the exposures to be described in detail in this paper. The conspicuous topographic features in the central portion of the area, between the mountains and the plateau escarpment, are West Baldy, South Baldy, and Miller Mesa. West Baldy rises somewhat boldly above the generally even surface of Howard Flats. South Baldy is a dome-shaped mountain in the upper portion of the Dallas Valley. Miller Mesa is at the eastern margin of the area and adjoins the valley of Uncompahgre River. In many of the escarpments of this mesa the Eocene till is exposed.

Dallas Creek drains eastward into Uncompahgre River, which is the master stream on the northwest slope of the range. The Uncompahgre rises far south of the region under

[1] Atwood, W. W., and Mather, K. F., Evidence of three distinct glacial epochs in the Pleistocene history of the San Juan Mountains of Colorado: Jour. Geology, vol. 20, pp. 385-409, 1913.

consideration among high mountains, and flows northward, skirting the east base of Miller Mesa and the Uncompahgre Plateau. The western portion of the area is drained by Leopard Creek and its tributaries, and Leopard Creek joins the Dolores. All the streams of this area are tributary to Colorado River.

DESCRIPTIVE GEOLOGY.

MESOZOIC SECTION.

The Mesozoic section here exposed includes, from the top downward, the Mancos shale, the Dakota sandstone, and the series of sandstones and shales belonging to the McElmo formation. These formations decline northward with very gentle dips, but are broken by a great east-west fault a short distance north of Ridgway. The block north of this fault line has been elevated relative to that at the south, and the elevated block is a portion of the Uncompahgre Plateau. The Mancos shale is preserved below the capping of the glacial drift in Horsefly Peak, near the southern margin of that plateau, but most of the surface of the great table-land is formed by the Dakota sandstone, and the slope of the surface corresponds very closely to the inclination of the sandstone. In the escarpment bordering the plateau, below the Dakota sandstone, the McElmo formation is exposed. South of the fault escarpment, in the valley of Dallas Creek, the dominant formation is the Mancos shale, which also forms the basal portion of Miller Mesa. To the west the Dakota sandstone forms the surface of much of Howard Flats and of portions of Hastings Mesa, but there are remnants of Mancos shale upon these upland surfaces, and in each locality where any of the earliest of the Pleistocene glacial deposits are present small areas of the shale are preserved beneath those glacial deposits.

CENOZOIC SECTION.

TERTIARY ROCKS.

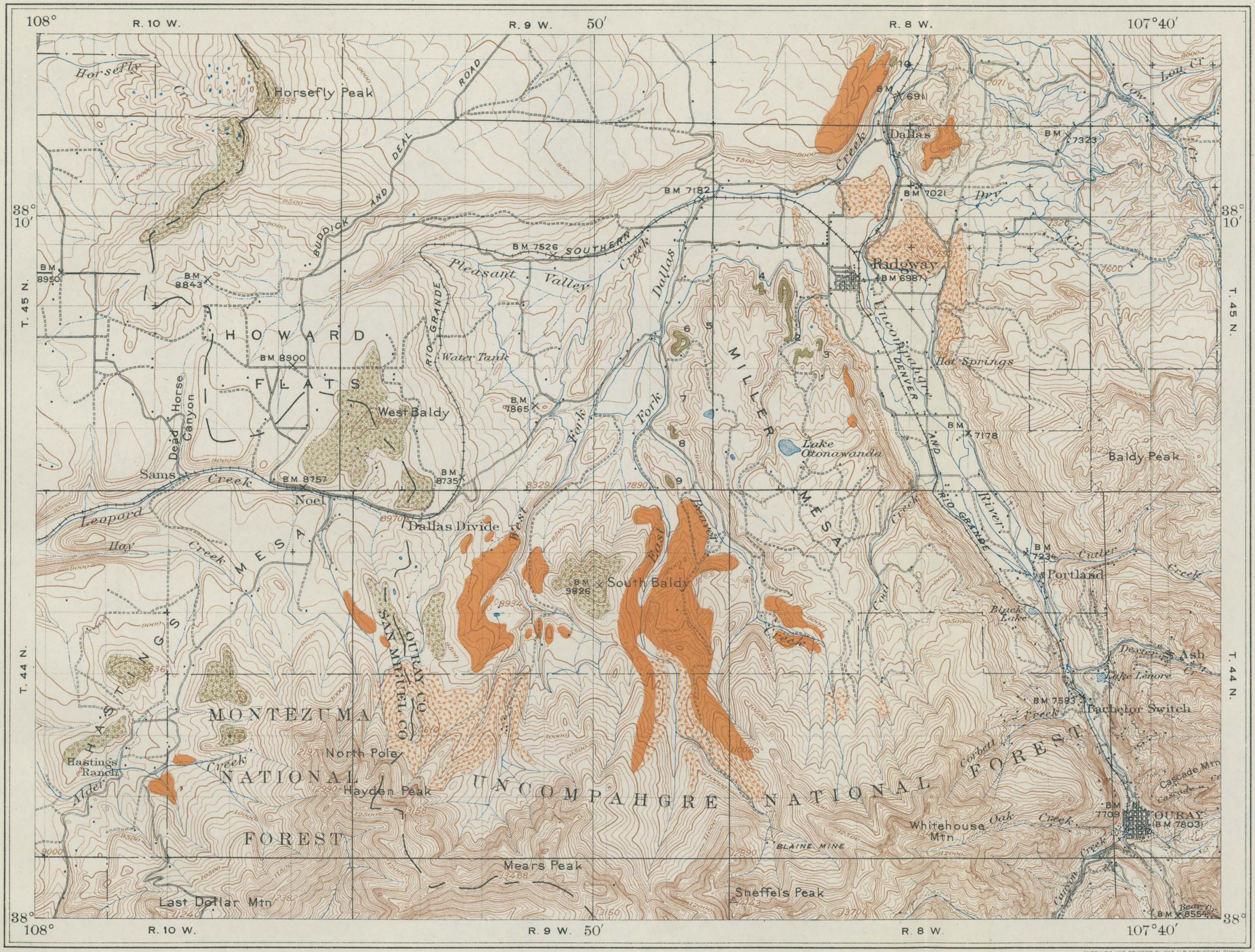
Above the Mesozoic section the geologic succession differs from place to place within the area. The Eocene till, where found, rests unconformably upon the Mancos shale. The till is usually overlain unconformably by the Telluride conglomerate, which, in turn, is overlain unconformably by the San Juan tuff. Locally the Telluride conglomerate or the San Juan tuff rests upon the Mancos shale. At the south margin of the area the San Juan tuff is buried by great thicknesses of later Tertiary volcanic rocks of the Silverton and Potosi volcanic series.

The Telluride conglomerate and the basal portion of the San Juan tuff extend northward over Miller Mesa, to which the tuff forms a resistant capping. The upper volcanic series probably extended much farther northward, but they have since been removed by erosion.

PLEISTOCENE FORMATIONS.

The three distinct Pleistocene drift sheets which have been recognized in the San Juan region must be frequently referred to in this paper and in all subsequent reports on the glacial studies of these mountains. For convenience in description the following names have been selected:

The oldest known Pleistocene drift sheet in this region will be called the Cerro till. The name Cerro is selected from Cerro Summit, near the north margin of the Montrose quadrangle, at which there are heavy glacial deposits of this earliest Pleistocene stage. The Pleistocene glacial deposits of the intermediate stage will be called the Durango till. A little northeast of Durango, a city on the south slope of the range in the valley of Animas River, there are heavy morainic deposits of this intermediate stage. These deposits rest on a high rock bench. They retain a distinct morainic topography and are associated with extensive outwash deposits of the same age. They are readily distinguished from the later glacial deposits which rest upon the valley floor several miles upstream. In the Montrose quadrangle deposits of Durango till occur on the hilltops east and west of the village of Dallas, which is about 3 miles north of Ridgway, also near the headwaters of Dallas Creek, and a short distance to the southeast of Dallas Divide. The most recent Pleistocene glacial deposits in the region will be referred to



LEGEND

Pleistocene — QUATERNARY

Wisconsin till
(Latest glacial drift)

Durango till
(Glacial drift of an intermediate Pleistocene stage)

Cerro till
(Oldest Pleistocene glacial drift in this region)

Eocene — TERTIARY

Ridgway till
(Upper member is pebble till, lower member is bowlder till)

Base from Montrose topographic atlas sheet

ENGRAVED AND PRINTED BY THE U.S. GEOLOGICAL SURVEY

MAP OF SOUTHWESTERN PART OF MONTROSE QUADRANGLE, COLORADO

Showing distribution of Eocene and Pleistocene glacial deposits

Geology by Wallace W. Atwood

Scale $\frac{1}{125000}$

1 ½ 0 1 2 3 4 5 Miles

1 ½ 0 1 2 3 4 5 Kilometers

Contour interval 100 feet.

Datum is mean sea level.

1915

as the Wisconsin till, in accordance with a usage already established in describing the latest of the till sheets in the Rocky Mountains. The correlation of the deposits of the last glaciers in the Rocky Mountains with those of the last great continental ice sheet has been established in the study of the deposits at the east base of the Rocky Mountains near the Glacier National Park,[1] but the correlation of the deposits of the pre-Wisconsin glaciers in the Rocky Mountains with the pre-Wisconsin drift sheets of the Central States is uncertain, and hence the local names Cerro and Durango are introduced.

The Pleistocene glacial deposits within this area are at the surface and must not be confused with the buried glacial deposits to be herein described. The remnants of the Cerro till, or oldest known Pleistocene glacial deposits of this region, are at widely separated localities, on the higher portions of the lowland country. Thus, West Baldy and South Baldy are both capped with the Cerro till. Certain of the higher hills rising above Hastings Mesa are also so capped, and Horsefly Peak, a prominent feature on the Uncompahgre Plateau, rising to an elevation of 10,338 feet above the sea level, or about 2,500 feet above the bordering plateau surface, is also capped with Cerro till. The moraines of the Durango or intermediate Pleistocene glacial stage occur in association with the modern valleys or canyons just north of the San Juan range. They are distinctly below the level on which the Cerro till was left, and yet farther down the valleys than the deposits left by the ice of the last or Wisconsin glacial stage. The accompanying map (Pl. I) furnishes the essential data on the distribution of these Pleistocene glacial deposits within the area under consideration.

The Cerro morainic deposits, now preserved in scattered remnants on certain hilltops, exhibit many characteristics of great age. They rest upon an erosion surface, most of which has been carried away by streams since the ice of this earliest Pleistocene stage melted. The wide distribution of these remnants and the vast stretches of country which have been deeply dissected since these deposits were made point most impressively to the great age of these moraines. Furthermore, these deposits within the area under consideration are composed very largely of volcanic rocks, which once capped the mountain summits to the south but which are now almost entirely missing from the range. It is clear that the basins in which the Cerro glaciers formed have been obliterated by subsequent erosion. The distribution of these glacial deposits is furthermore suggestive of a valley system quite different from that of the present day. The present remnants of Cerro till are not opposite the mouths of the modern canyons. Many of them are opposite the mountain spurs, at localities that ice coming from the mountain canyons of to-day could not reach. This relationship also points to the great antiquity of these deposits. Furthermore, these oldest Pleistocene moraines do not contain an abundance of bowlders from the older formations which have been uncovered as the dissection of the range has gone on. By this means it is possible to distinguish the Cerro moraines from those of the Durango and Wisconsin stages. The oldest Pleistocene deposits are much weathered, and stream erosion has nearly obliterated all signs of morainic topography in them.

The moraines of the two later Pleistocene stages (Durango and Wisconsin) are associated with the modern canyons, and some of them extend but a few miles down the valleys from the great amphitheatral basins where the glaciers formed. In the valley of Uncompahgre River, at the east margin of this area, the terminal moraines of the Durango and Wisconsin stages have been recognized a short distance down the valley from the village of Ridgway. In the smaller valleys west of Miller Mesa the later glaciers were but a few miles in length. They failed to reach the broad lowland area of the Dallas Valley.

RECENT DEPOSITS.

Since the last Pleistocene glaciers melted away the streams have distributed vast quantities of sand and gravel over their flood plains, and these lowlands stretch far off to the northwest, beyond the margin of the range. Locally there has been some land sliding, and a number of torrential fans have been developed.

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[1] Alden, W. C., Pre-Wisconsin glacial drift in the region of Glacier National Park, Mont.: Geol. Soc. America Bull., vol. 23, pp. 687-708, 1912. Calhoun, F. H. H., The Montana lobe of the Keewatin ice sheet: U. S. Geol. Survey Prof. Paper 50, 1906.

EOCENE TILL.

TYPE SECTION.

GENERAL FEATURES.

The section 1 mile west of Ridgway, at the locality where the Eocene till was discovered, has been selected as the type section. The locality is marked as No. 1 on Plate I. It is within plain view from the Ridgway station platform, and the term Ridgway till has therefore been adopted for this formation. The cliff in which the till is exposed (see Pl. II) contains the Mancos shale (*a*) at the base. Overlying the shale unconformably is a section (*b*) 80 to 100 feet thick which exhibits all the usual characteristics of glacial till. This section appears from a distance as a distinct yellow band. Above the yellow band, resting upon an uneven erosion surface, is a dark slate-colored stratum (*c*), which, on careful examination, has also been found to be a glacial till. The upper till sheet is overlain by a layer of the Telluride conglomerate (*d*), which varies in thickness from 70 feet at the south (left-hand) end of the section shown in Plate II to 10 or 15 feet at the north end of the section. Above the Telluride conglomerate, also upon an erosion surface, is a remnant of San Juan tuff (*e*) having a thickness of at least 30 feet.

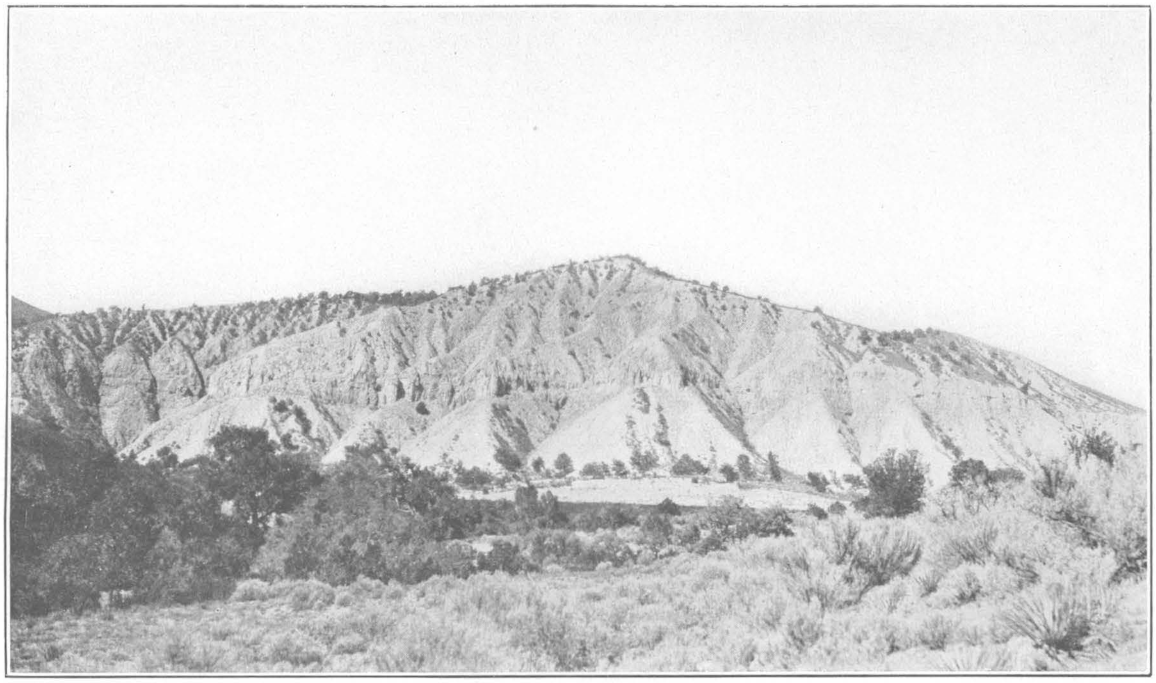
The spur in which this type section is exposed is so nearly separated from the main part of Miller Mesa that the section above described may be traced around the north end and on the west side, so that it is perfectly clear that the formations extend through this spur. The section thus described continues, with some variations in the thickness of the different formations, southward along the face of the Miller Mesa escarpment for fully a mile. At the southernmost exposure (locality No. 2), which, however, may not be the southern limit of these formations in the mesa, the section is somewhat different from that at the type locality and is described on page 18.

RIDGWAY TILL.

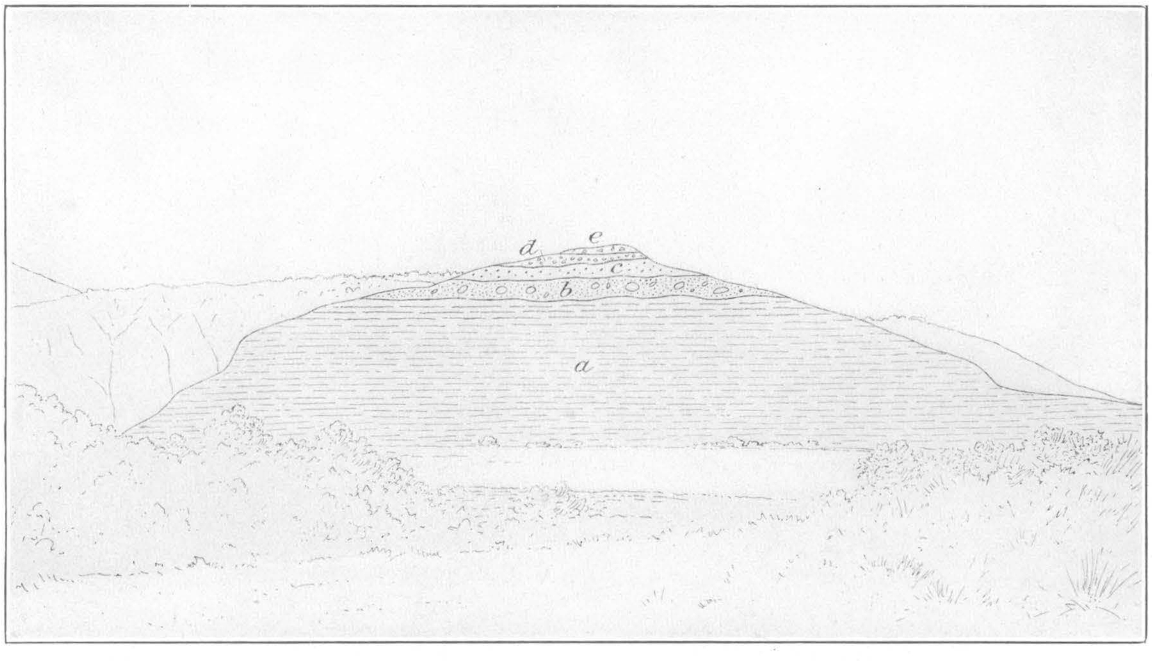
Lower or bowlder member.—The lower till sheet at the type locality contains an abundance of stones which range in size from tiny pebbles to bowlders 15 feet in diameter. These stones vary in composition, like the rock formations in the core of the San Juan Mountains, beneath the great volcanic cap which was added to the mountain area in Tertiary time. They include many varieties of porphyries, granites, some volcanic tuff, quartzites, sandstones, limestones, and conglomerates. The harder, crystalline bowlders, the pink and purple quartzites, and the volcanic rocks came from the core of the range, but the softer sandstones, limestones, light-colored quartzites, and conglomerates were plucked by the ice from the upturned sedimentary strata at the north base of the range. These stones have been derived from formations which range in age from the pre-Cambrian to and including the Upper Cretaceous. The bowlders of tuff came from a volcanic series older than any of those which form the present great mass of the San Juan Mountains. The San Juan tuff overlies the Telluride conglomerate, which in turn overlies the glacial deposits.

The tuff deposits that contributed material to the Ridgway till seem to have belonged to an early and rather local extrusion. These tuffs were largely removed by erosion before the Telluride conglomerate was laid down, for such material is rarer in the conglomerate, all through the western San Juan Mountains, than it is in the known exposures of Ridgway till. The San Juan tuff, which reaches a thickness of 3,000 feet near Ouray, is composed mainly of transported material similar in petrographic character to the fragments of tuff in the till. But the source of the San Juan tuff was a great volcanic mass erupted, soon after the Telluride conglomerate was laid down, in the area which supplies the Telluride materials. These facts fix the general time relations of the Ridgway glacial epoch to the volcanic history of the San Juan Mountains.

The pink and purple quartzites came from the pre-Cambrian Uncompahgre formation, now well exposed near Ouray and up the canyon of Uncompahgre River. Most of the limestones were derived from the Devonian or Carboniferous formations which are also now exposed near Ouray. A vast quantity of red sandstone and conglomerate was gathered by the ice from the Cutler (late Carboniferous) and Dolores (Triassic) formations. These formations must



A.



B.

RIDGWAY TILL AT THE TYPE LOCALITY, 1 MILE WEST OF RIDGWAY, COLO.

For explanation of diagram see p. 16.

have been exposed but a few miles south of the localities where the Eocene drift is now located. They are well exposed to-day in the Uncompahgre Valley, between Ridgway and Ouray. The white quartzites are from the Dakota sandstone, which is locally a distinct quartzite.

A great many of these stones show distinct signs of ice action. Small striated stones are abundant (see Pl. III, *B*) and subangular forms are conspicuously common. Many of the huge bowlders are distinctly striated, and in certain of the great masses of red conglomerate from the Cutler formation, the exposed surfaces of the limestone pebbles carry striæ. The abundance of striated stones found on the exposed surface of this till may seem somewhat surprising, and it should be explained that as the underlying Mancos shale is rapidly washed away, the glacial drift is continually falling, and therefore, at this locality, continuously presenting a fresh exposure. The discovery of other striated stones in this till may be safely expected for many years to come.

The matrix of this lower or yellow till is sand and clay, and it is quite probable that most of the clay was derived from the underlying Mancos shale. The sand may have come from various formations. The conspicuous yellow color of this lower layer of glacial till is characteristic of every exposure of this member throughout the area. The yellow coloring is not confined to the surface, but evidently continues throughout the section. It appears to be due to the oxidation of the iron minerals associated with the matrix of this till. If this oxidation proceeded from the top throughout the mass, which has a thickness of at least 90 feet, it would seem to indicate that this member was at the surface during an exceedingly long period of time. Possibly the material as gathered by the ice had this extreme yellow color.

In texture this drift is exceedingly firm. It stands with a slope so steep that it is difficult to work around the hill on foot at that horizon. In places the large stones, or bowlders, have acted as preserving caps, and the rain erosion has developed great earth pillars 6 to 8 feet in height, each with its bowlder cap. Certain of these earth pillars are shown in Plate III, *A*. Throughout the finer matrix of this till there is an abundance of small stones, many of which have been beautifully polished and striated.

Upper or pebble member.—The upper member of the Ridgway till is strikingly different from the lower member. When first examined, it was thought to be a layer of clay without stones or pebbles. In color it so closely resembles the Mancos shale that it was suggested in the field that it might be a part of that formation. This hypothesis was, however, very promptly abandoned, for it was somewhat unreasonable to think that there was a glacial epoch in southwestern Colorado during a period of marine invasion. Again a lacustrine origin was considered, but it is quite certain that this material is unstratified. I was for some time in great doubt as to what its true origin might be. The absence of large stones, such as characterized the drift sheet just below, seemed to exclude the idea of another glacial deposit. That the same ice which brought the bowlder till could have contained or carried this upper sheet of material seemed improbable. It also seemed unlikely, if ice had brought the upper material, that it could have had the same source as the ice which deposited the bowlder till. It was certainly strange that ice could have moved over the bowlder till without gathering some large stones. However, on very careful search, several small but distinctly striated pebbles were procured from this upper sheet. When a mass of this material could be broken out and carefully examined, it was found that the distribution of the tiny stones and pebbles was similar to that in the typical deposit of glacial till, the only difference being that the stones were much smaller. These characteristics have been found to persist in the several exposures of this upper member, and it is quite clear now that the material is a glacial deposit, and the term "pebble till" is suggested as appropriately descriptive of it. This upper member is not so deeply weathered as the lower member, but the upper 6 or 8 feet seems to be somewhat leached, as if that portion had been exposed to the air for some time and affected by the usual processes of weathering.

The stones in the pebble till are so small that no attempt has yet been made to identify them and determine their source, but further studies of these deposits may make it possible to procure collections that will help to determine the source of the drift. As the examination of the several exposures progressed a few larger stones, the largest 2 or 3 inches in diameter and one stone 6 inches in diameter, were found in the pebble till. The striking characteristics, however, of this upper member are an absence of large stones, a firm clay matrix, an unstratified condition, and striated pebbles.

FORMATIONS OVERLYING THE EOCENE TILL.

Telluride conglomerate.—The Telluride conglomerate, which overlies the upper till member at the type locality, contains many pebbles 4 inches or less in diameter and a few stones as much as 10 inches in diameter. The matrix is sandy, with some fine gravel. The formation is cemented and stands with a nearly vertical face. It has a general pink color and closely resembles other exposures of this well-known formation of the San Juan Mountains. It was, however, a notable surprise to find distinctly striated stones in this conglomerate. It is of course clear that the formation is of later age than the underlying glacial deposits, and the streams which laid down the Telluride conglomerate must have drawn in part upon glacial deposits for their materials. Possibly some of the stones in the conglomerate were not carried far, and that would account for the preservation of glacial striæ on stones transported by water.

San Juan tuff.—The San Juan tuff overlies the Telluride conglomerate at the Ridgway type section and forms the capping of the spur in which the section occurs. The material is quite evidently of volcanic origin, and most of the fragments are angular. They vary from dust to blocks 8 feet in diameter. It is possible to detect distinct lines of bedding in this exposure of the tuff. It has a gray, slate-colored appearance, is much broken from weathering, and seems at places to have settled irregularly since it was deposited. There is very little rounded material in this exposure of the tuff, but otherwise it resembles the San Juan tuff which has been fully described by Cross in the geologic folios on the San Juan district.

OTHER SECTIONS.

The other exposures about the rim of the mesa may now be described somewhat briefly, for the different formations retain their marked characteristics, but at most of the several localities one or another of the formations included in the type section is missing. The numbers used in the descriptions represent corresponding numbers on Plate I.

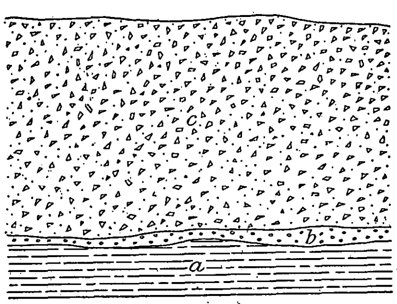


FIGURE 2.—Geologic section at locality No. 2 near Ridgway, Colo. *a*, Mancos shale; *b*, pebble member of Ridgway till, 6 feet; *c*, San Juan tuff.

Locality No. 2 is at the extreme south end of the exposure which contains the type section, but it is fully a mile distant from the type section. It is on the west wall of Pleasant Valley. At this point the Mancos shale is exposed at the base. (See fig. 2.) Above it is about 6 feet of the upper or pebble till, in which a number of striated stones were found. Overlying the pebble till is the San Juan tuff fully 200 feet thick. The missing members in this section are the bowlder till and the Telluride conglomerate. The Telluride conglomerate was not recognized, although there was a narrow band of pinkish material at the base of the San Juan tuff, which suggested that possibly a little of the Telluride was left there. The pebble till thickens toward the north and within a few rods in that direction it is underlain by bowlder till.

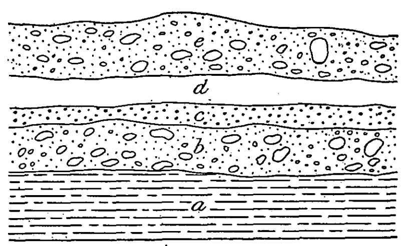
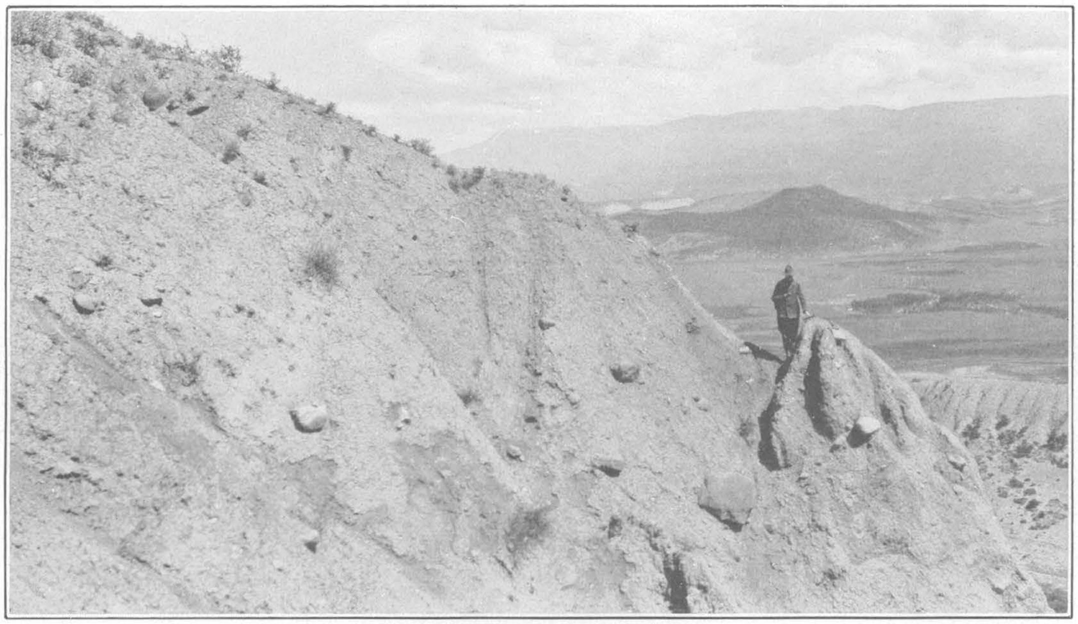


FIGURE 3.—Geologic section at locality No. 3 near Ridgway, Colo. *a*, Mancos shale; *b*, bowlder member of Ridgway till, 40 feet; *c*, pebble member of Ridgway till, 15 feet; *d*, obscured, 15–20 feet; *e*, Pleistocene glacial till of Durango stage.

Locality No. 3 is nearly east of No. 2, about three-quarters of a mile south of Ridgway, on the west side of the Uncompahgre Valley. Here a thickness of 40 feet of the yellow bowlder till overlies the Mancos shale and is in turn overlain by 15 feet of the pebble till. (See fig. 3.) The immediate covering of the pebble till is obscured. Possibly some San Juan tuff is present at that horizon, but there are no satisfactory outcrops. The surface of the hill or ridge is mantled with Pleistocene till of the Durango stage.



A. DETAILED VIEW OF THE BOWLDER MEMBER OF THE RIDGWAY TILL AT THE TYPE LOCALITY, 1 MILE WEST OF RIDGWAY, COLO.

B. STRIATED STONES FROM THE RIDGWAY TILL AND TELLURIDE CONGLOMERATE.

The second stone from the right came from the Telluride conglomerate.

Locality No. 4 is about half a mile west of No. 1. The Mancos shale is exposed at the base. (See fig. 4.) No bowlder till is present, but there remains at least 30 feet of the pebble till, with its usual characteristics. Telluride conglomerate is lacking, and the pebble till is overlain by the San Juan tuff, which reaches to the surface of the mesa.

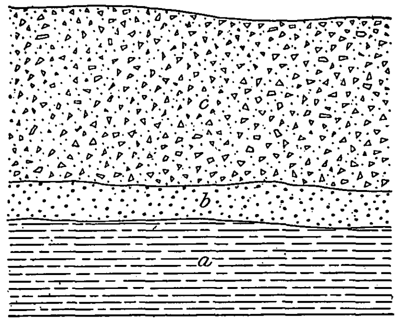


FIGURE 4.—Geologic section at locality No. 4 near Ridgway, Colo. *a*, Mancos shale; *b*, pebble member of Ridgway till, 30 feet; *c*, San Juan tuff, 90 feet.

Locality No. 5 is on the west side of Miller Mesa, southwest of No. 4. At this point the Mancos shale is overlain immediately by Telluride conglomerate, and that in turn by San Juan tuff. (See fig. 5.) The section does not contain the glacial formations, but their absence at this point is significant and will be discussed elsewhere (p. 23). The Telluride conglomerate at this locality contains striated stones.

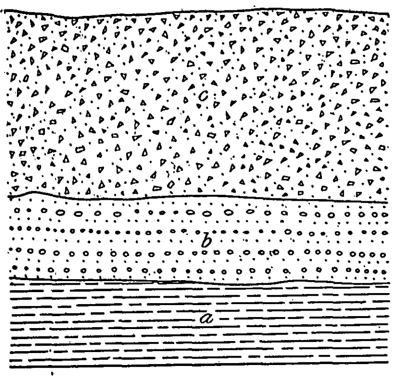


FIGURE 5.—Geologic section at locality No. 5 near Ridgway, Colo. *a*, Mancos shale; *b*, Telluride conglomerate, containing striated pebbles; *c*, San Juan tuff.

Locality No. 6 is on the west side of Miller Mesa, due west of No. 2 and just across a small valley from No. 5. It is in a small outlier from the main part of the mesa. Here the type section is repeated, with the exception of the upper capping of San Juan tuff. (See fig. 6.) The Mancos shale is at the base and is succeeded by 30 feet of bowlder till overlain by 20 feet of pebble till, and this in turn by 40 feet of the Telluride conglomerate. At this locality the bowlder till contains a great deal of waterworn material. It is quite possible that the deposit represents a local pocket in the older of these Eocene till sheets, where water had much to do with the deposition of the material. At this locality no striated stones have yet been found in this lower member. In the overlying pebble till striated stones have been found, and a few such stones have also been found in the Telluride conglomerate, which overlies the glacial deposits.

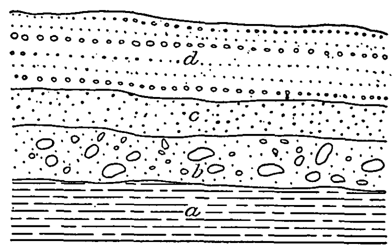


FIGURE 6.—Geologic section at locality No. 6 near Ridgway, Colo. *a*, Mancos shale; *b*, bowlder member of Ridgway till, 30 feet; *c*, pebble member of Ridgway till, 20 feet; *d*, Telluride conglomerate, with striated pebbles, 40 feet.

At locality No. 7, at the rim of the mesa, there is an excellent exposure of the San Juan tuff, and below that fully 300 feet of Telluride conglomerate, in which striated stones have been found. Below the Telluride is the Mancos shale. (See fig. 7.) This section, therefore, resembles that at locality No. 5. It is without glacial formations, but very near to the localities where the glacial material remains.

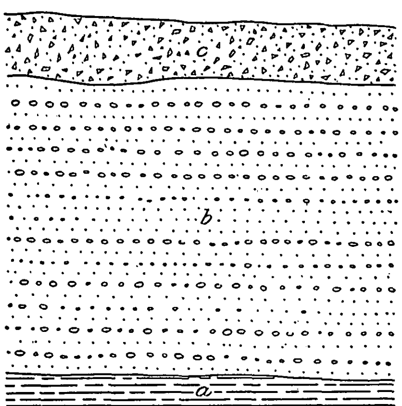


FIGURE 7.—Geologic section at locality No. 7 near Ridgway, Colo. *a*, Mancos shale; *b*, Telluride conglomerate, with striated pebbles; *c*, San Juan tuff.

Locality No. 8 is about a mile south of No. 7, just south of an east-west dike, which causes the road to make a distinct bend toward the west at that point. At this locality the entire type section is repeated. (See fig. 8.) The Mancos shale is exposed at the base, followed by the bowlder till with its usual characteristics, the pebble till, the Telluride conglomerate, and the San Juan tuff.

Locality No. 9 is about a mile south of No. 8, in a prominent hill a short distance west of Beaver Creek. This hill is not to-day a part of Miller Mesa, and the glacial material forms its capping. (See fig. 9.) In this respect this locality differs from all others, for the deposit which is interpreted to be Eocene till is not buried. Its physical and lithologic characteristics are, however, identical with those of the bowlder till in the lower part and the pebble till in the upper part. It is with confidence interpreted as a remnant of the Eocene till, from which the covering of Telluride conglomerate and San Juan tuff has somewhat recently been removed. It might be asserted that this particular hill may have been overridden by the earliest of the Pleistocene glaciers, but in reply it may be urged that the composition of this till and the fact that it has two distinct members make it quite distinct from the deposits of the Cerro stage. The absence of the great latite bowlders which characterize the glacial deposits of the Cerro stage would seem to put it in another geologic epoch. If the interpretation is correct, the latite flows which contributed so largely to the Pleistocene glaciers were not present in the San Juan Mountains at the time the Eocene till was gathered. The intermediate and latest Pleistocene glaciers did not reach the summit of this hill.

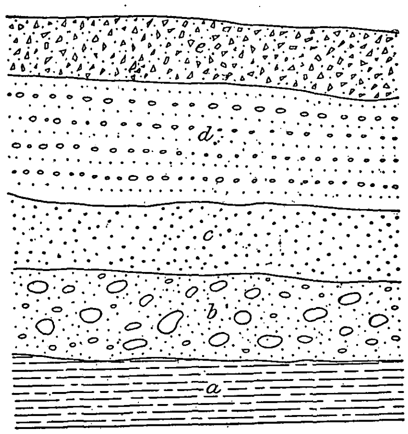


FIGURE 8.—Geologic section at locality No. 8 near Ridgway, Colo. *a*, Mancos shale; *b*, bowlder member of Ridgway till; *c*, pebble member of Ridgway till; *d*, Telluride conglomerate; *e*, San Juan tuff.

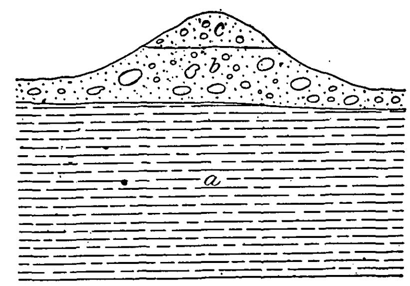


FIGURE 9.—Geologic section at locality No. 9 near Ridgway, Colo. *a*, Mancos shale; *b*, bowlder member of Ridgway till; *c*, pebble member of Ridgway till.

Locality No. 10 is about 4 miles northeast of No. 1. It is on the southeastern rim of Log Hill Mesa, a portion of the great Uncompahgre Plateau. The exposure is on the face of the cliff bordering the Uncompahgre Valley, about a mile north of the Dallas railway station. Upon the surface of Log Hill Mesa in this vicinity is a thin mantle of glacial drift which was deposited during the Durango stage of the Pleistocene epoch. The formation is in a small hill or knob on the mesa (see fig. 10 and Pl. IV), and the section exposed there includes, from the top downward, the following formations:

Section at locality No. 10.

	Feet.
San Juan tuff	80–90
Telluride conglomerate	4–10
Bowlder member of Ridgway till	40
Mancos shale	70–80
Dakota sandstone.	
McElmo formation.	

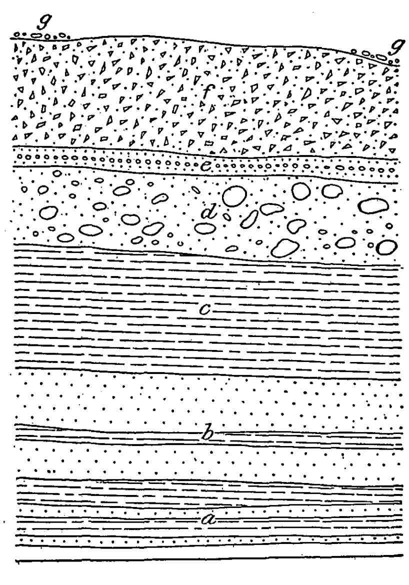
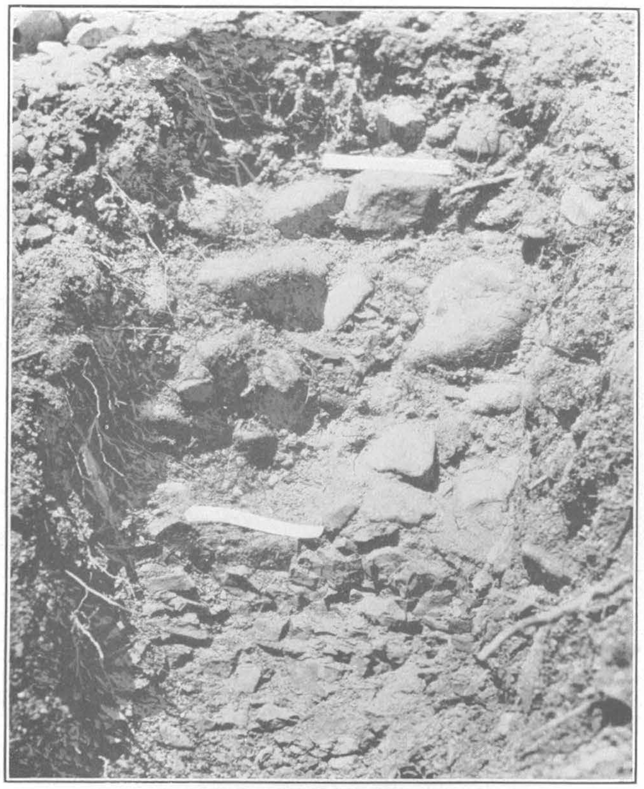


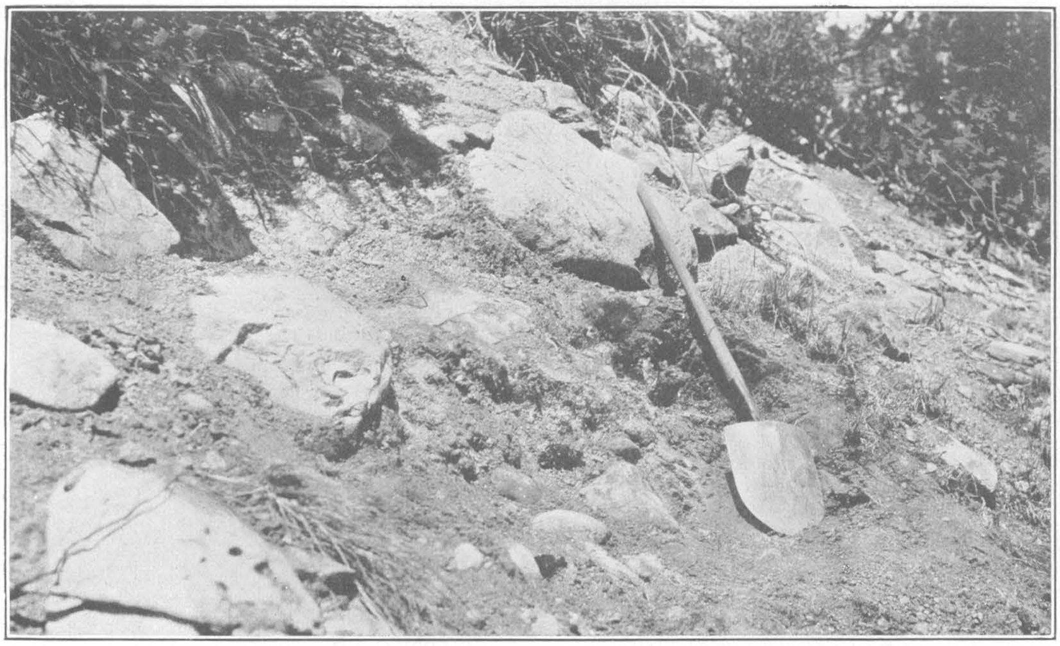
FIGURE 10.—Geologic section at locality No. 10 near Ridgway, Colo. *a*, McElmo formation; *b*, Dakota sandstone; *c*, Mancos shale; *d*, bowlder member of Ridgway till; *e*, Telluride conglomerate; *f*, San Juan tuff; *g*, glacial bowlders of the Pleistocene Durango till.

This exposure is of special interest, for it is the most northern locality at which the Ridgway till has been found and is the one locality not immediately associated with Miller Mesa where this older glacial drift is known to occur. The preservation of the older drift at this place is readily accounted for by the heavy mantle of San Juan tuff and Telluride conglomerate. The exposures on the cliff were not altogether satisfactory, and it was found necessary to clear away with pick and shovel the loose material throughout the section described, so as to prove beyond doubt the presence of a layer of till beneath the Telluride conglomerate at this locality. The Ridgway till here, as at many



A. SECTION IN BOWLDER MEMBER OF RIDGWAY TILL AT LOCALITY NO. 10 NEAR RIDGWAY, COLO.

The till immediately underlies the Telluride conglomerate. Distance between white marks is about 8 feet.



B. SECTION IN BOWLDER MEMBER OF RIDGWAY TILL AT LOCALITY NO. 10 NEAR RIDGWAY, COLO.

All loose material was removed and glaciated bowlders exposed.

other localities, differs from the Pleistocene drift of the region in not including any material contributed from the later Tertiary volcanic rocks of the San Juan Mountains. It contains representatives from the earlier volcanic rocks and an abundance of bowlders from the sedimentary beds. The section where the loose surface material was cleared away did not show any of the pebble till

SOURCES OF THE RIDGWAY TILL.

Lower or bowlder member.—The composition of the lower or bowlder till member makes it perfectly clear that this material was gathered in the San Juan Mountains, south and southeast of the locality where it is now exposed. The stones in the drift are just such as are exposed in the core of the range. The large tuff bowlders resemble the tuff bowlders in the San Juan tuff, but it is apparent that they came from a volcanic formation which was much earlier than the San Juan tuff and which yielded many of the bowlders contained in that formation. It is evident from other studies carried on by Cross that there was a period of volcanism earlier than that which began with the formation of the San Juan tuff.

Upper or pebble member.—The source of the upper or pebble till member is not so clear. If it came from the San Juan Mountains, it is very strange that it does not also contain large bowlders, or at least an abundance of stony material. If the ice which brought the pebble till moved far over a surface mantled by the bowlder till, it would seem that it should have gathered a great deal of stony material. The source of the pebble till, as exposed in these localities, seems to have been chiefly the Mancos shale. The area in which the Mancos shale was exposed at the surface during Eocene time was to the north or northeast of Ridgway, in the direction of Vernal Mesa and the West Elk Mountains. If ice had come from that direction to the vicinity of Ridgway, it would have traveled the last 30 or 40 miles of its course over a surface of Mancos shale, and as most of the glacial drift of any one locality is usually of local origin, that would account for the character of the material in the pebble till. The contrast between the bowlder till and the pebble till suggests distinct glaciers, either from a single center at distinct times in the history of glaciation or from distinct centers. It appears most likely that the earliest Eocene ice which invaded the Ridgway territory must have come from the south, and that later, after that ice had retreated, and perhaps disappeared, and after a long period of weathering and erosion had elapsed, other ice invaded this same region from another direction. Possibly this other direction was the northeast, the ice coming from the region of the West Elk Mountains.

AGE OF THE RIDGWAY TILL.

The position of the Ridgway till upon the Mancos shale makes it evident that it is late Cretaceous or younger, but the Mesaverde formation overlay the Mancos shale at the time of the first uplifting of this mountain area, at the close of the Cretaceous period. The Ridgway till was therefore not deposited until after the close of Cretaceous time, and not until the Mesaverde formation had been entirely eroded from the vicinity of Ridgway.

The Telluride conglomerate, which rests upon the Ridgway till at several localities, has been referred by Cross [1] to the Eocene. It therefore appears that the Ridgway till is of early or mid-Eocene age.

EOCENE GLACIERS.

The facts thus far presented lead to the inference that the earlier Eocene ice may have been of an alpine type and descended from an early generation of San Juan Mountains, bringing vast quantities of coarse, stony material to the foothills of a range of mountains that has long ago disappeared. If the pebble till was brought by ice from the north and northeast, and if that ice formed in mountains, it must have come a distance of fully 40 miles and, in early Eocene time, probably moved over a surface of slight relief. Such ice could not have been a true mountain or alpine glacier. It would suggest the presence of a piedmont glacier, or possibly a local ice sheet, in Colorado in early Tertiary time.

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[1] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Telluride folio (No. 57), 1899.

PROBABLE FURTHER EXTENSION OF THE EOCENE TILL.

The distribution of these Eocene glacial deposits at the northwest base of the San Juan Mountains suggests the possibility that other remnants of the Ridgway till may be found at other localities about the base of the range. Furthermore, if the mountains which existed in early Tertiary time in the San Juan region contained glaciers, it is more than likely that other mountain areas of early Tertiary time, in Colorado and throughout the Cordilleran province of North America, also contained glaciers. If the suggestion of a somewhat distant origin for the ice which deposited the pebble till is correct, it would seem that the Eocene glaciers in the Cordilleran province may have been more extensive than the Pleistocene glaciers of that region and possibly had dimensions commensurate with those of local ice sheets. Certainly many of the early Tertiary conglomerates of the western portion of the continent should be examined to determine whether they may not be of glacial origin, and the discovery of glacial deposits of Eocene age in the western mountain areas may henceforth be expected. It seems reasonable to suggest that if there were such extensive glaciers in the Cordilleran province of North America in early Eocene time, there may have been glaciers on lower lands within the continent at the same time, the conditions thus simulating those of the Pleistocene epoch.

SUMMARY OF AVAILABLE FACTS PERTAINING TO THE RIDGWAY TILL.

It is appropriate now to sum up the characteristics of the Eocene glacial deposit as they have been determined from the various localities described and to present a brief statement of the available facts pertaining to this formation.

1. The Ridgway till is divisible into two members.
2. The lower member is distinctly a bowlder till.
3. This lower member appears to have been deeply weathered, perhaps weathered throughout its maximum known thickness of 90 feet.
4. The lower member contains an abundance of striated stones.
5. Wherever it has been found this lower member rests upon Mancos shale.
6. The stones in the lower or bowlder till have certainly come from the San Juan Mountain area to the south.
7. The upper member is appropriately described as a pebble till.
8. It appears to have been subject to a much shorter period of surface weathering.
9. Most of the upper till sheet is clay, which was probably derived from areas where the Mancos shale was exposed at the surface.
10. At certain localities the lower member, or bowlder till, is missing and the pebble till is present.
11. There was probably an erosion period after the deposition of the bowlder till and before the deposition of the pebble till.
12. At certain localities the pebble till is missing and the bowlder till is present.
13. At most localities the Telluride conglomerate overlies these glacial deposits, but in places it is absent and the overlying formation is the San Juan tuff.
14. At one locality (No. 9) the bowlder and pebble till sheets are present, but not the Telluride conglomerate nor the San Juan tuff. At this locality the pebble till is at the summit of the hill.
15. Striated stones have been found in the pebble till.
16. Striated stones, presumably from the Ridgway till, have been found in the overlying Telluride conglomerate at several localities.
17. At some localities within the area bounded by the exposures of the Ridgway till the Telluride conglomerate rests upon the Mancos shale. At these localities the Telluride conglomerate has been found to contain striated stones.
18. The exposures described are within an area 8 miles long in a northeasterly direction and 2½ miles wide in a northwesterly direction. The areal extent of the region within which the deposits have thus far been found is about 20 square miles.
19. All but one of the exposures are about the margin of the Miller Mesa, and it is quite probable that there may be somewhat extensive remnants of the Ridgway till buried within the mesa.
20. The surface of the Mancos shale beneath the till is too loose and soft to have received or retained glacial striæ.

GEOGRAPHIC HISTORY SINCE THE CLOSE OF THE MESOZOIC ERA.

With the discovery of evidence of early Eocene glaciation in the San Juan district, it is of some interest to review the geographic history of this region.

At the close of the Mesozoic era and the opening of the Cenozoic era there were mountain-making movements which affected the entire Rocky Mountain province of North America, and the great dome which was then formed in the San Juan area was at once subjected to vigorous erosion. As the mountain mass rose erosion began, and as the great dome was more and more deeply dissected a mountain topography must have been produced, and those mountains may be thought of as the first generation of the San Juan range. (See fig. 11.) During the period of mountain growth there was some volcanism. Many porphyritic intrusions and the deposition of the great volcanic tuffs which made contributions to the Ridgway till date back to this period. The Eocene till indicates that during the dissection of these early San Juan Mountains ice formed in the range and descended to the bordering lowlands. Possibly ice formed in neighboring ranges and approached the San Juan Mountains, and possibly there were distinct glacial epochs in that period of glaciation.

After the retreat and disappearance of the early Tertiary ice, stream erosion continued, and the western portion of the San Juan Mountain area was reduced to a surface of slight relief which may be thought of as a peneplain.[1] This peneplain bordered on the west a higher area of mountainous character, which supplied the material for the Telluride conglomerate. The deposition of gravels upon this peneplain surface was probably due to some uplift and rejuvenation of the streams in the eastern portion of the range. After the deposition of the Telluride conglomerate there was further erosion in the range, and then came the three great epochs of volcanism, the San Juan, the Silverton, and the Potosi. During these epochs of volcanism a great volcanic plateau was developed. By this time the Miocene epoch had been reached and possibly passed, and with the quieting down of volcanic activity began the erosion and dissection of the volcanic plateau. During this period of dissection another generation of San Juan Mountains were carved, this time out of volcanic débris and great lava flows. (See fig. 11.)

Recent physiographic studies of the range have led to the recognition of a summit peneplain in the San Juan region (see fig. 11), so it would appear that the first dissection stopped at a plain which is now represented by many of the summit areas within the region. The San Juan Mountains that were first carved out of this great volcanic plateau should then be thought of as surmounting those of to-day. Perhaps, if replaced, they would rise 3,000 or 4,000 feet above the present summits. (See fig. 11.)

With the redoming of the area, which involved the warping or doming of the summit peneplain, another cycle of erosion was begun. Valleys were again formed, and in these valleys snows collected which in time formed glaciers that advanced to the lowlands bordering the range. These earliest Pleistocene glaciers retreated and disappeared. The range continued to be uplifted, and the streams were so rejuvenated that they cut great canyons below the broad troughs occupied by the Cerro glaciers. Again climatic changes favored the formation of ice among the summits, and that ice (the Durango glaciers) descended through the main canyons to the foothills and later retreated and disappeared. The canyons were still more deeply cut into the mountain mass, and then climatic conditions favorable for glaciation once more returned and the Wisconsin or third series of Pleistocene glaciers formed and descended through the great canyons, nearly as far as those of the Durango stage. These glaciers have now disappeared, and there

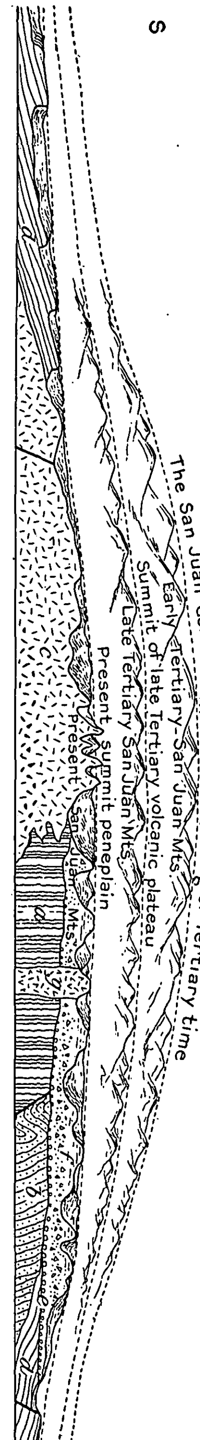

FIGURE 11.—Diagrammatic cross section showing the physiographic evolution of the San Juan region since the beginning of Tertiary time. *a*, Pre-Cambrian schist and gneiss; *b*, Algonkian quartzites; *c*, Pre-Cambrian granitic intrusion; *d*, Paleozoic and Mesozoic rocks; *e*, Ridgway till and Telluride conglomerate; *f*, middle and late Tertiary volcanics; *g*, Tertiary intrusives.

[1] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Silverton folio (No. 120), 1905.

is no true glacier ice remaining in the region to-day, but the streams are vigorously dissecting the mountain mass to still greater depths. The vigor of that work is illustrated in many a sharp, V-shaped notch cut below the depth of ice action. The débris taken from the mountain area is being distributed along the great valleys leading away from the range.

The ice gouging in the three successive Pleistocene stages and the vigorous stream work during the interglacial intervals and since the last melting away of the ice suggest somewhat continuous mountain growth in this region during late geologic time.

OTHER GLACIAL EVIDENCE.

Before closing this report it may be appropriate to refer briefly to other glacial deposits made at different times in the history of the earth. The accompanying table presents some data as to these deposits and indicates that glacial conditions have existed at many times and at very many places on the earth. The records of pre-Cambrian glaciation are found in Norway and Canada and perhaps indicate early Huronian or Proterozoic age, though probably not exactly the same age in the two countries. The glacial deposits recorded from China are known to be either Lower Cambrian or pre-Cambrian, for Cambrian strata immediately overlie the glacial till. There is some reason for believing that the early deposits of Australia may be pre-Cambrian. Some doubtful evidence of glaciation is afforded by the Devonian of England, but the records of Devonian glaciers in South Africa are more certain. The record of late Carboniferous (Permian) glaciation comes from South Africa, Australia, Tasmania, South America, India, the East Falkland Islands, England, Germany, and the Boston Basin in Massachusetts. In New Zealand there is evidence of glacial ice action during Triassic time. Doubtful indications of Cretaceous and Eocene glaciation come from Italy, and the record herein reported is derived from a study of the Eocene till in southwestern Colorado. The Icelandic glacial records are of Miocene age, and there are Miocene deposits in Italy which may be of glacial origin. The Pleistocene record is found in all the high mountains of the world, in great lowland areas in North America and Europe, and in the Arctic and Antarctic regions. Since Pleistocene time glacial conditions have continued in many parts of the world and are still present at high altitudes and in high latitudes.

An inspection of the table should also bring out with some emphasis the occurrence of glacial epochs at the opening of each of the great eras of geologic time. Possibly the pre-Cambrian records are separated by periods of time as long as the Paleozoic or Mesozoic eras, which intervened between later records of ice action. This distribution of glacial records in the history of the earth appears to have some real significance and recalls the profound studies of T. C. Chamberlin on the causes of glacial climates. Each great geologic era was closed by a great physical revolution, which brought vast areas above the sea and therefore subjected those areas to the processes of weathering and erosion. By such revolutions the areal extent of the seas was reduced and the distribution of lands and seas changed. These changes have undoubtedly been great factors in determining the climates of the earth. They have affected the movements of ocean currents and the distribution of precipitation and of different temperatures. Possibly these great physical changes have had so profound an influence upon the climates of the different portions of the earth that they have been fundamental causes of the great glacial epochs. The lesser glacial epochs may have been associated with periods in which lofty mountains were being made. The glacial records surely suggest a field of most significant research.

Geologic and geographic distribution of reported evidence of glacial deposits.

Geologic time scale.			Geographic distribution.
Cenozoic.	Quaternary.	Recent.	High latitudes. High altitudes.
		Pleistocene.	Northern North America. Northwestern Europe. High latitudes. High altitudes.
	Tertiary.	Pliocene.	
		Miocene.	Iceland.[a] Italy.[b] Italy.[c]
		Oligocene.	
		Eocene.	Southwestern Colorado.[d] Italy.[b]
Mesozoic.	Cretaceous.		Italy.[b]
	Jurassic.		
	Triassic.		New Zealand.[e]
Paleozoic.	Carboniferous.	Permian.	South Africa.[f] South Australia.[g] West Australia.[h] Tasmania.[i] South America.[j] India.[k] East Falkland Islands.[l] Boston Basin, Mass.[m] Germany.[n] England.[o]
		Pennsylvanian.	
		"Mid-Carboniferous."	Oklahoma.[p]
		Mississippian.	
	Devonian.		Doubtful evidence from England.[q] South Africa.[r] Canada.[s]
	Silurian.		
	Ordovician.		
	Cambrian.		China.[t] Australia.[u]
Proterozoic.			Canada.[v] Norway.[w]

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Footnotes on page 26.

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RELATION OF THE CRETACEOUS FORMATIONS TO THE ROCKY MOUNTAINS IN COLORADO AND NEW MEXICO.

By Willis T. Lee.

PURPOSE OF THIS PAPER.

Some time ago, while working on a problem that involved the question of the presence or absence of islands near the close of the Cretaceous period in the region now occupied by the southern part of the Rocky Mountains, I was forced to the conclusion that no land masses or islands of any considerable size persisted there throughout the Cretaceous period, for I found no sedimentary rocks that were clearly derived from such islands. This result led to a reexamination of available information to see what evidence the sedimentary rocks in other areas near the present mountains could furnish, and I found rather unexpected confirmation of my conclusion. In the course of this study it became evident that there is apparent conflict of testimony between different classes of fossils and that the physical evidence, including lithology, structure, and sequence of beds, is at variance with some of the commonly accepted correlations. In this state of uncertainty I tried to apply physiographic principles to see if they would throw any light on the interrelations of the Cretaceous formations of the Rocky Mountain region and on the events that opened and closed the period. This led me to a conclusion similar to that reached by the paleontologist C. A. White[1] many years ago, namely, that the Upper Cretaceous formations up to and including the Laramie extended across the site of the mountains.

I believe that the principles of physiography, as well as those of lithology, paleontology, and structure, may be used to good advantage in the correlation of sedimentary formations, and that they may prove effective in some problems where the others fail. I propose to attempt an application of these principles to some phases of the stratigraphy of the Rocky Mountain region of Colorado and New Mexico, although I recognize that to do this adequately much more information must be gained, especially in areas that are now very imperfectly known. The most that can be accomplished at the present time is to point out some of the relations that seem to exist, in the hope that observation may thus be stimulated.

A study of this kind naturally leads into many byways, and the paper might be expanded indefinitely. I propose, however, at this time to confine the discussion to such facts as may have a direct bearing on the correlation of some of the Cretaceous formations in the Rocky Mountain region and to such facts as will throw some light on the physical conditions of this region at the close of the Cretaceous. The significance of the unconformity separating the Cretaceous and Tertiary systems in this region—that is, the post-Laramie, post-Vermejo unconformity—is very largely dependent on the question whether any considerable parts of the Rocky Mountain area remained above sea level throughout Cretaceous time.

The sections used in this paper were measured independently, most of them for the purpose of showing the stratigraphic relations of the coal-bearing rocks. Hence the coal-bearing formations have been described more fully than others. The measurements and descriptions were made by different men, and the personal equation must be considered; also due allowance must be made in the interpretation of results.

[1] U. S. Geol. and Geog. Survey Twelfth Ann. Rept., p. 50, 1883.

REASON FOR THE INVESTIGATION.

COAL BEDS AT MANY HORIZONS WITHIN THE CRETACEOUS.

During the investigations of the Rocky Mountain coal fields coal beds have been found at so many horizons within the Cretaceous that it seems probable that conditions favorable to their accumulation existed over extensive areas in one place or another from Dakota to Laramie time. There seems to be a tendency on the part of some geologists to explain these numerous coal beds on the assumption that the land underwent repeated oscillations which carried it sometimes above and sometimes below sea level, whereas it seems equally possible to account for them on the assumption that sedimentation was going on contemporaneously with the advance of the sea, due either to subsidence of the basin or to rise of sea level, and that the apparent withdrawal of the sea at a given locality as shown by brackish or fresh water sediments was due to the relatively rapid accumulation of sediments in that portion of the basin which was thereby filled to the existing sea level. The relation of marine to nonmarine beds would thus depend on the rate of sedimentation relative to the rate of subsidence. For example, in some parts of western New Mexico and eastern Arizona no Cretaceous rocks younger than Colorado have been found. This has been attributed to the "emergence" of these parts, whereas it may as rationally be interpreted to mean that during Colorado time, without any oscillation of the land, these parts of the basin received alternately brackish-water and marine deposits, and that during later time sediments were carried seaward over these deposits to parts of the basin not yet filled, just as the Mississippi is now filling the Gulf of Mexico without materially building up the surface of its delta.

In the region with which this paper deals the evidence seems to point to an intermittent downward movement of the surface (or an intermittent upward movement of the sea level) during early Cretaceous time and practical stability during later Cretaceous time rather than to oscillations that produced so-called islands in the region of the present Rocky Mountains. (The term Rocky Mountains in this paper refers to the ranges of central Colorado extending southward into New Mexico and northward into Wyoming.)

In correlating the sedimentary formations of the several localities which are now more or less disconnected because of erosion there is a tendency to correlate rocks that are lithologically similar and to neglect the obvious fact that a coal-bearing sandstone may have been in process of formation at one locality at the same time that marine beds were being formed at another locality.

CORRELATIONS: LITHOLOGY VERSUS PALEONTOLOGY.

There is a tacit understanding among geologists, more or less precise according to the individual, that a formation name implies a definite age relation. The application of a formation name, however, is dependent on correlation and is subject to all the uncertainties attendant on correlation. For example, coal-bearing sandstones of middle Upper Cretaceous age at several of the localities described in the following pages have been called Mesaverde. There are reasons for believing that the so-called Mesaverde of the several localities may occupy very different places in the time scale, ranging from upper Colorado to a position well toward the top of the Montana group. A sedimentary formation is usually defined as a lithologic unit, but this definition is not closely adhered to in practice, and in reality formational boundaries are often drawn on fossil rather than on lithologic evidence. Moreover, it is not possible to adhere to this definition in all cases, inasmuch as beds formed at the same time may change laterally from sandstone of fresh-water origin, through brackish-water beds, to shale or limestone of marine origin. If the rocks can be traced through these transitions, a fresh-water sandstone and a marine shale may be proved to be of the same age; but if for any reason connection can not be established by actual tracing and the correlation must depend on lithology and sequence or on paleontology, it seems to be practically impossible to determine whether certain fresh-water, brackish-water, and marine beds are of the same age or are more or less widely separated in time.

NEAR-SHORE VERSUS OFFSHORE DEPOSITS.

It is obvious that in a basin which is being filled with sediment the finer material is likely to be carried far out and the coarser material to accumulate near shore and that swamp conditions favorable to the formation of coal are likely to prevail along the coast. As the shore migrates, either because of the accumulation of sediments or because of a change in sea level, the conditions of sedimentation are likely to remain constant with respect to the shore but to vary with respect to given localities. It is possible that in a filling sea like the interior Cretaceous sea of North America brackish-water and fresh-water conditions favorable to the accumulation of coal persisted near shore throughout the life of the sea, while marine conditions existed continuously in the center of the basin. It is conceivable, therefore, that a coal-bearing sandstone, were its continuity unbroken by erosion, might be traceable without interruption through the Cretaceous beds and yet vary in age from place to place, as is illustrated in figure 12. For example, the basal sandstone at A may be the homogenetic equivalent of the basal sandstone at B, but it is not the time equivalent.

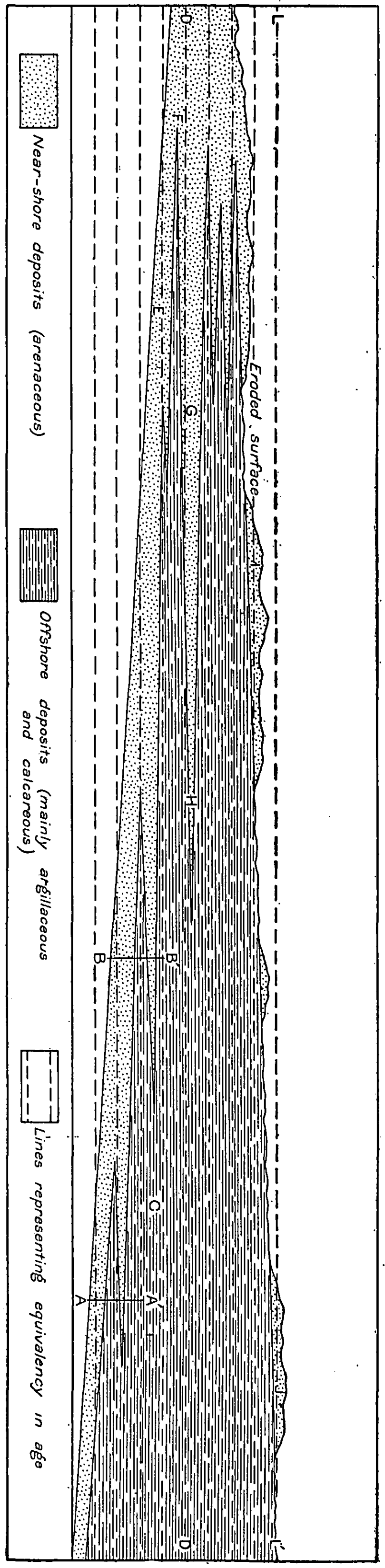

FIGURE 12.—Sketch section to illustrate the distinction between homogenetic equivalency and time equivalency.

This illustration is intended to represent some of the possible relations of the sedimentary rocks formed in a sea that advanced from the right, spreading over a land mass toward the left. A basal sandstone is formed at A and is soon covered with marine shale as the sea advances. The same thing then takes place at B. Later a retreat of the sea, a temporary halt in advance, or an increase in the amount of sediment causes a second sandstone to form at A′ and a little later at B′. If now the rocks are exposed at A and at B and the intervening rocks are eroded away or covered, the sections A-A′ and B-B′ appear alike in that each shows a sandstone separated by a marine shale from a basal sandstone. The sections may be so near each other that correlation by lithology would seem to be admissible, and such fossils as happen to have been found may not be adequate to show difference in age. There is little doubt that under these conditions the formations of the two sections would be erroneously regarded as time equivalents, whereas they are only homogenetically equivalent and really differ in age.

Sediments accumulating near shore may contain fossil plants, fresh-water or brackish-water invertebrates, or certain kinds of marine invertebrates, according to local conditions at the time of sedimentation. But the fossils in the sandstone at B′ are likely to be so different from the open-sea forms at C that there is little possibility of recognizing them as being of the same age.

If the diagram is taken to represent the Cretaceous rocks of the southern Rocky Mountain region, the line D-D the separation in time between the Colorado and Montana groups, and the line L-L′ the beginning of Laramie time, then the sandstone A-B may represent the Dakota; the sandstone at A′, the coal-bearing rocks at Engle, N. Mex.; the sandstone at B′, the coal-bearing rocks at Carthage and Zuni, N. Mex.; the sandstone at E, the coal-bearing rocks at Pinedale and elsewhere in Arizona; the sandstone at F, the coal measures of Colob Plateau, in Utah; the sandstone extending from G to H, the Mancos and Mesaverde from the Datil Mountains, N. Mex., to Durango, Colo.; the sandstone at I, the coal-bearing "Laramie" formation of the San Juan Basin; and the sandstone at J (projected across the spaces where it has been removed by erosion), the youngest coal-bearing rocks of Cretaceous age in northern Colorado and southern Wyoming—that is, the Laramie formation of the Denver Basin and the formations of corresponding age in northwestern Colorado and southern Wyoming.

It is quite impossible to make a diagram that will illustrate a general principle and at the same time adequately represent local details. Three qualifications seem desirable in the application just made. First, as the diagram stands, it might be interpreted to mean that the offshore and near-shore deposits accumulated at the same rate. If rate of sedimentation alone were to be illustrated the lines representing equivalency in age should bend downward toward the right, for, as is well known, the great bulk of sediments accumulate near shore, and a thick near-shore deposit is likely to be the time equivalent of a much thinner offshore deposit. Second, the representation of formation boundaries in the diagram by straight lines drawn at an angle with the lines representing equivalency in age is generalized and should not be interpreted as indicating abrupt changes in conditions of sedimentation. There is more likely to be an irregular transitional zone in which the offshore and near-shore deposits meet and interfinger. In this process of interfingering marine conditions will sometimes extend well up toward the source of the sediments and at other times brackish or fresh-water conditions will extend far out into the basin. Third, inasmuch as the basin fills most rapidly near shore a bed of given thickness, character, and stratigraphic position near the periphery of the basin is likely to be older than a bed of the same thickness, character, and stratigraphic position near its center. As portions of the basin near its periphery are built up to the limit of deposition the fresh sediments are transported toward the center over those previously deposited. This process, of course, is further complicated by oscillations both of the land and of the sea level.

PHYSIOGRAPHIC BASIS OF CORRELATION.

In view of some of the foregoing considerations it would seem wise to emphasize the physiographic conditions, in so far as they can be ascertained, that existed during the formation of beds whose correlation is attempted. A large volume of exact information is necessary in order to use such data to the best advantage, but it is my belief that enough is known about the Cretaceous and older Tertiary formations of the Rocky Mountain region to use the physiographic data in connection with structure, lithology, and paleontology to a greater extent than they have been used heretofore in making correlations.

ATTITUDE OF THE CRETACEOUS FORMATIONS TOWARD THE ROCKY MOUNTAINS.

Some of the most significant facts bearing on the use of physiography in correlating the Upper Cretaceous formations of the southern Rocky Mountain region are found in the relation of these formations to the mountains. It was the belief of early observers that highlands of considerable extent existed in the Rocky Mountain region throughout Upper Cretaceous time. Although for years there has been a growing tendency on the part of some investigators to regard this belief as unfounded, no one has taken the trouble heretofore to combat it, and it has persisted with characteristic tenacity. Whatever may have been its influence on the establishment of the time scale for the Upper Cretaceous formations of the Rocky Mountain region, the fact remains that a stratigraphic column has been established for areas east of the mountains which differs radically from that established for areas west of the mountains. If, however, there were in the mountain region during Upper Cretaceous time no highlands capable of contributing any considerable amount of sediment or of forming a barrier to the distribution of sediments derived from the continental land masses on either side of the interior sea, the two columns should not be so discordant as they seem to be, and it may be well to reexamine the principles on which they were established.

One of the principal objects of this paper is to point out some of the reasons for believing that no highlands of any considerable extent existed in the Rocky Mountain region of Colorado

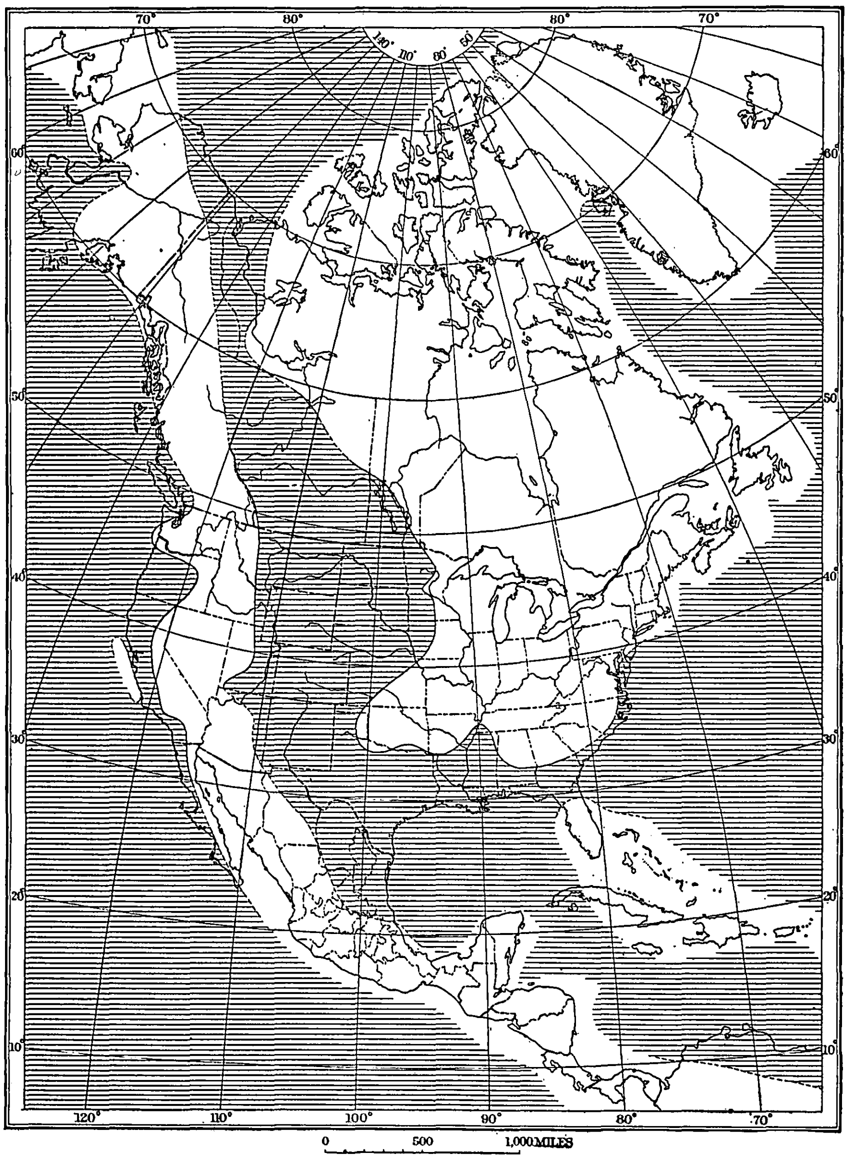

FIGURE 13.—Paleogeographic map of North America showing by shading the part of the continent submerged during the Benton epoch. (After Charles Schuchert.)

and New Mexico during the Upper Cretaceous epoch and that the sedimentary formations of this region were once essentially continuous across the areas now occupied by the mountains, with only such variations in thickness and character as are to be expected in different parts of a single basin. Schuchert[1] anticipated this conclusion in some measure when, in his maps, one of which is reproduced as figure 13, he extended the Cretaceous sea completely over the Rocky Mountain area. However, on page 586 of his text he states that the sea connected the Gulf of

[1] Schuchert, Charles, Paleogeography of North America: Geol. Soc. America Bull., vol. 20, pp. 427-606, 1910.

Mexico and the Arctic Ocean *east* of the Rocky Mountains and that throughout Cretaceous time "the Laramie Range seems to have been in slight upward movement with decided elevation toward the close of the period." This statement recalls Eldridge's description [1] of certain arches near Golden, Colo., which he supposed to have existed during the Cretaceous period, but whose existence Richardson [2] seems to doubt. If this arching were as important as Eldridge and others have maintained, indications of similar mid-Cretaceous movements should be present elsewhere, but they have not been found in the Rocky Mountain region, although evidences of the proximity of land occur all along the border of the continental mass west of the Cretaceous sea, as Stanton has frequently pointed out.

GEOGRAPHIC CONDITIONS PRIOR TO DAKOTA TIME.

There is little evidence of notable crustal movement in the Rocky Mountain region for a long time prior to the beginning of the Upper Cretaceous epoch. The highlands that occupied this region in late Paleozoic and early Mesozoic time had been eroded and the region brought to a condition of low relief, if not practically to base-level. The interior Cretaceous sea seems to have advanced with little interruption over the area now occupied by the southern part of the Rocky Mountains. Without entering into a long discussion of the pre-Cretaceous physiography, I may be permitted to call attention briefly to some of the principal arguments for this postulate of low relief.

JURASSIC EPICONTINENTAL SEA.

In late Jurassic time a shallow epicontinental sea covered the northern and western parts of the Rocky Mountain region.[3] The distribution, thickness, and character of the sediments laid down in this sea are not such as to indicate that the area now occupied by the Rocky Mountains furnished any considerable quantity of coarse material. Moreover, the presence of marine Jurassic fossils in western Texas,[4] although they constitute a later fauna than that of Wyoming, suggests that the southern part of the Rocky Mountain region may not have been much farther above sea level than the northern part.

PHYSIOGRAPHIC CONDITIONS INDICATED BY THE MORRISON FORMATION.

The Morrison formation lies with apparent conformity on the marine Jurassic beds in southern Wyoming. It overlaps the marine Jurassic both east and west of the Rocky Mountains and extends southward into New Mexico with remarkable uniformity in thickness, character, and fossil contents. Certain beds in North Park, South Park, and elsewhere in Colorado, in the midst of the mountainous area, indicate that the areal distribution of the Morrison was essentially the same as that shown later in this paper for the Dakota sandstone.

There are, however, a few places where the Morrison is known to terminate against older rocks, allowing the Dakota sandstone to overlap it. One such locality near Colorado Springs, Colo., is described by Cross,[5] and according to Hayden's atlas of Colorado the Dakota rests in several places on older rocks, the Morrison apparently being absent. However, this atlas has proved to be inaccurate in this respect in several places, and the Morrison has been found to be even more continuous than was formerly supposed. These discoveries led Cross and Larsen [6] to believe that the Morrison and its western equivalent in the Gunnison formation may have been connected across the mountain region.

THE COMANCHE SEA.

The Comanche sea appears to have found little obstruction to its passage as far west as the present Rocky Mountains. The Comanche sediments of eastern Colorado and New Mexico indicate that the sea advanced over a graded plain. It is not known to have invaded western

[1] Eldridge, G. H., Geology of the Denver Basin in Colorado: U. S. Geol. Survey Mon. 27, pp. 82–104, 1896.

[2] Richardson, G. B., Structure of the foothills of the front range, central Colorado: Washington Acad. Sci. Jour., vol. 2, p. 429, 1912.

[3] Logan, W. N., A North American epicontinental sea of Jurassic age: Jour. Geology, vol. 8, pp. 242–273, 1900.

[4] Cragin, F. W., Paleontology of the Malone Jurassic formation of Texas: U. S. Geol. Survey Bull. 266, 1905.

[5] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Pikes Peak folio (No. 7), 1894.

[6] Cross, Whitman, and Larsen, E. S., The stratigraphic break below the Jurassic sandstone in southwestern Colorado: Washington Acad. Sci. Jour., vol. 4, p. 238, 1914; Contributions to the stratigraphy of southwestern Colorado: U. S. Geol. Survey Prof. Paper 90–E (Prof. Paper 90, pp. 39–50), 1914.

Colorado, but, on the other hand, there is no known evidence that the areas immediately west of the present mountains were far above sea level during Comanche time.

The general character of the Comanche sediments is worthy of note in this connection. At their base is a sandstone that is generally conglomeratic in the Rocky Mountain region and consists of coarse sand in other regions. It differs from many sandstones in being singularly free from partings of clay or other fine-grained material. Because of its open texture, due to the absence of fine material, it is one of the most important water-bearing sandstones in the Rocky Mountain region. The pebbles in the conglomeratic parts consist almost wholly of resistant rock, such as chert, quartzite, and argillite. Observations made at many localities throughout the Rocky Mountain region give the general impression that the sandstone is due to a washing and reworking of residual silica distributed over a base-leveled surface. It is conceivable that owing to the shallowness of the sea for considerable distances from shore broad lagoons were formed that prevented free access of marine waters and that in these lagoons the weathered surface material was agitated by the waves sufficiently long to be thoroughly washed and evenly distributed, so that the coarser material was deposited relatively near shore and the finer material eventually came to rest beneath the deeper and quieter water at some distance out. This sandstone is the lower part of the Dakota in the Rocky Mountain region as formerly described. It has only recently been recognized as distinct in age from the true Dakota [1] and mapped as the Purgatoire formation. The reference of the Purgatoire to the Washita epoch of the Lower Cretaceous is in accordance with the classification used by the United States Geological Survey. If, however, the Washita is Upper Cretaceous, as Berry [2] asserts and as Haug [3] and other European geologists believe, then the Purgatoire is also Upper Cretaceous and the Dakota sandstone therefore holds a position somewhat above the base of this series.

Above this basal sandstone occurs a thin layer of clay, carbonaceous in some places, that constitutes the so-called "Dakota fire clay." That it is of Lower Cretaceous age is proved by the presence in it of certain marine invertebrates. If this thin layer of clay and the underlying sandstone are all that in the Rocky Mountain region can represent the great thicknesses of Lower Cretaceous rocks in Texas and Mexico, it is evident either that they represent a long period of time or that they represent only a part of the Lower Cretaceous. It is regarded as a well-established fact, based on both paleontologic and stratigraphic continuity, that the Lower Cretaceous of the Rocky Mountain region represents only the upper part of the Lower Cretaceous series. If, therefore, the Morrison is not Lower Cretaceous in age the greater part of Lower Cretaceous time must be represented by a hiatus at the base of the Purgatoire. Little evidence of such a hiatus has ever been found. If, however, it is granted that the Comanche sea advanced over a graded plain and that there was little warping of this plain prior to the beginning of Upper Cretaceous time, there might be no recognizable unconformity at the base of the Purgatoire formation, although the time break might be great.

From what has been written it is perhaps sufficiently evident that such highlands as may have existed in the Rocky Mountain region had been subjected to degradation through all of Jurassic and all of Lower Cretaceous time; and, furthermore, that so far as is now known these lands supplied very little sediment during these periods. It is quite otherwise in western Colorado and eastern Utah, where the thick sediments of Jurassic age, including in some places probable equivalents of the Morrison, indicate nearness to the continental land mass farther west. In other words, the Rocky Mountain region seems to have been reduced to a condition closely approximating base-level by the close of Lower Cretaceous time. Such areas as had escaped inundation by the Lower Cretaceous sea and had been exposed to the weather through long ages must have contained considerable quantities of siliceous material concentrated at the surface by the removal of the more easily decomposed minerals. This residual silica was available for the formation of the Dakota sandstone.

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[1] Stanton, T. W., The Morrison formation and its relation with the Comanche series and the Dakota formation: Jour. Geology, vol. 13, pp. 657-669, 1905. Stose, G. W., U. S. Geol. Survey Geol. Atlas, Apishapa folio (No. 186), 1912.

[2] Berry, E. W., Correlation of the Potomac formation: Maryland Geol. Survey, Lower Cretaceous, pp. 136-137, 1911.

[3] Haug, Emil, Traité de géologie, pp. 1169, 1293, Paris, 1907.

GEOGRAPHIC CONDITIONS INDICATED BY THE DAKOTA SANDSTONE.

EARLY CRETACEOUS PENEPLAIN.

Probably the best indication of the physiographic conditions prevailing in the Rocky Mountain region at the close of the Lower Cretaceous is given by the Dakota sandstone. This sandstone is essentially continuous both east and west of the Rocky Mountains and is present in many places between the mountain ranges—as, for example, in North, Middle, and South parks, Colo. It is upturned on all sides against the mountains in such a manner as to strengthen the belief that it once extended continuously over the areas now occupied by them.

The distribution of the Dakota sandstone, taken from Hayden's atlas of Colorado and from later maps of certain areas, is shown on figure 14. East of the mountains its altitude ranges from 6,000 to 10,000 feet. West of the mountains it is somewhat higher, attaining such altitudes as 12,600 feet in southwestern Colorado, 11,500 to 13,200 feet in central-western Colorado, and 13,400 feet near Breckenridge, between Middle and South parks. Inasmuch as the highest peaks of the Rocky Mountains are little more than 14,000 feet in altitude, it is reasonable to suppose that the Dakota sandstone may once have extended continuously over this region and that it would now be found on the highest peaks had it not been removed by erosion. This suggestion becomes especially pertinent when it is considered, for example, that in a district like Breckenridge the Dakota, together with the overlying marine Cretaceous, is found at altitudes of more than 13,000 feet, although 45 miles to the east it passes beneath the surface of the Great Plains, and if the thicknesses of the strata overlying the Dakota are correctly reported, it reaches depths below the present sea level, as shown in the sketch section, figure 15. Moreover, this suggestion gains added force from the fact that near Breckenridge, according to Ransome, the Dakota is overlain by remnants of Cretaceous sedimentary rocks estimated as 5,500 feet thick, a thickness comparable with that of the Cretaceous on either side of the mountains. Inasmuch as the highest peaks rise less than 1,000 feet above these remnants, there seems to be little room for doubt that the Cretaceous sedimentary formations, in this part of the range at least, once extended continuously over the area now occupied by the mountains. Also, the Dakota occurs at short intervals from Breckenridge northward and westward to the large areas west of the mountains in which the continuity of this sandstone is unbroken.

In this connection it may be in place to mention the somewhat remarkable uniformity in the altitudes of many of the highest peaks of the Rocky Mountains, a large number of which are close to 14,000 feet above the sea. This uniformity has been noted by many observers,[1] and the suggestion has been made by some that the tops of these peaks mark the approximate position of an ancient peneplain. Others regard this suggestion as visionary. It is conceivable that the flat top of Longs Peak, about 250 feet wide and 600 feet long, may be a remnant of the old peneplain, and the domelike summits of other mountains may possibly be similar remnants in a more advanced state of erosion. The few facts available can not be taken as a basis for definitely postulating an ancient peneplain, but the uniformity in altitude of the high peaks, together with the geologic evidence, seems to indicate that they are best explained as the least degraded portions of the base-leveled surface on which the Dakota sandstone was laid down.

Cross [2] has shown that the post-Cretaceous uplift of the Rocky Mountains was accompanied by the outpouring of large quantities of andesite and that although the andesitic débris forms a large part of the early Tertiary beds, such as the Denver and equivalent formations, no remnant of the flows has survived. This is somewhat remarkable if the andesite rested on the equally resistant crystalline rocks of the present mountains, but if it was outpoured on weak Cretaceous sedimentary beds that once covered the older crystalline rocks, its total removal is more readily understood, for these weak beds would erode easily, undermining the igneous material and thus facilitating its removal.

There are few places where the Dakota sandstone abuts against older rocks in such a manner as to indicate that it terminates against land masses that existed in Dakota time and few places

[1] Davis, W. M., The Colorado Front Range: Assoc. Am. Geog. Annals, vol. 1, pp. 21-87, 1911.

[2] Cross, Whitman, Geology of the Denver Basin, in Colorado: U. S. Geol. Survey Mon. 27, pp. 201-206, 1896.

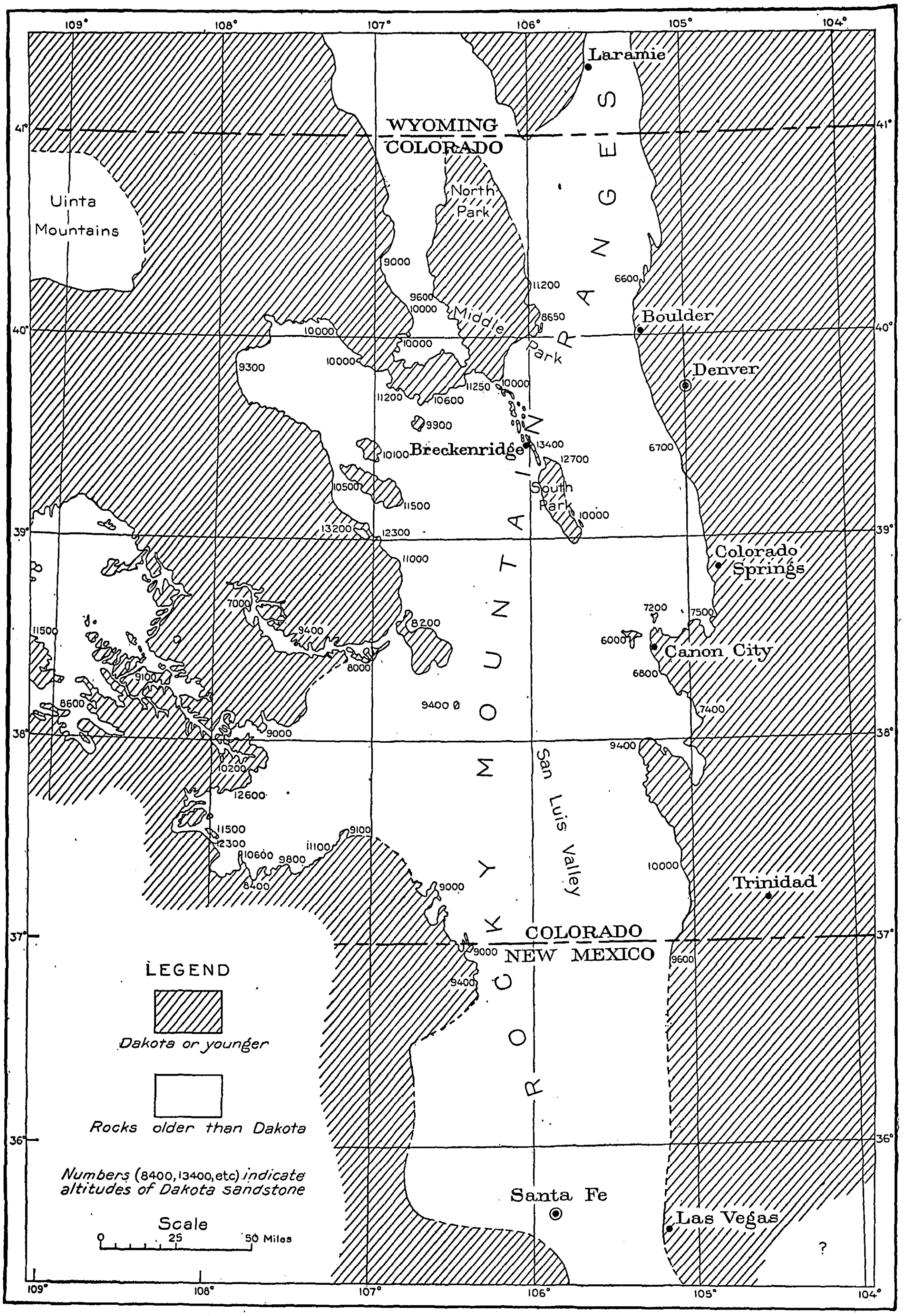


FIGURE 14.—Map of the southern part of the Rocky Mountain region showing altitudes of the Dakota sandstone and the relations of the Dakota to the Rocky Mountain ranges. (Adapted mainly from Hayden's atlas of Colorado.)

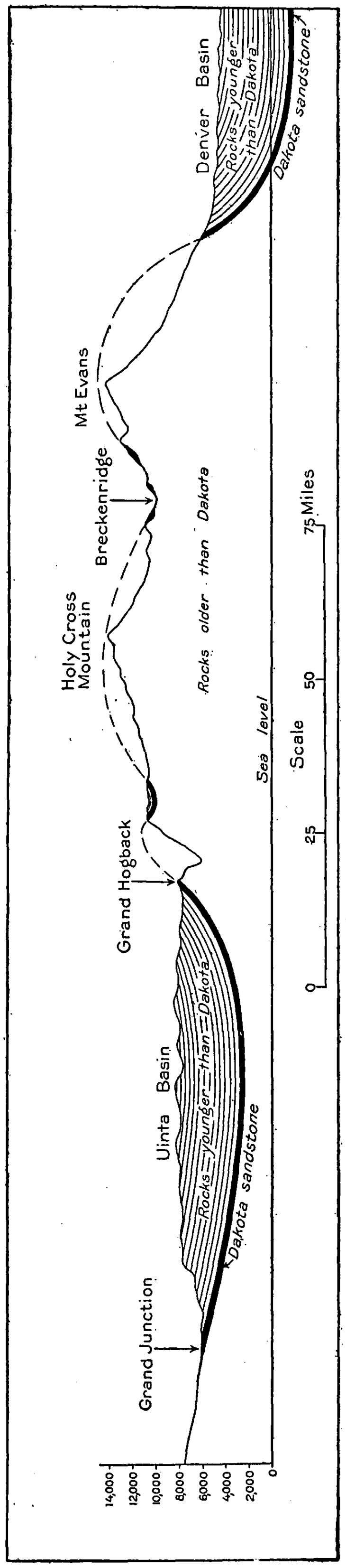


FIGURE 15.—Profile from western Colorado across the Rocky Mountains to the Denver Basin, showing the warped peneplain on which the Dakota sandstone is supposed to have been laid down.

where the succeeding Benton shale overlaps the Dakota and rests on older rocks. Cross[1] has described an apparent overlap of this kind near Pikes Peak, and several are indicated in Hayden's atlas of Colorado. But these supposed overlaps have been proved to be not overlaps in several places mentioned by the early observers, and the query arises whether the observed phenomena were correctly interpreted in other places.

The mapping of the Dakota sandstone in the vicinity of the Rocky Mountains in Hayden's atlas is approximately correct so far as it goes, but more recent observations have proved the presence of the Dakota in many places not shown on Hayden's map. The Dakota and the overlying Mancos, with McElmo beds below them, have been traced by Cross and Larsen[2] up Tomichi Creek, the eastern branch of Gunnison River, to a zone east of Sargent, where all these formations are abruptly upturned. A remnant of the McElmo and Dakota beds resting on granite was found by these same observers near Saguache Creek, 16 miles west of Saguache, a town on the western border of the San Luis Valley. R. D. George, on his map of Colorado, has recently added a number of details, such as the occurrence of the Dakota near Canon City, west of the mountain range through which the Royal Gorge is cut, and also at the crest of the Park Range, in northern Colorado. In brief, recent observations are strengthening the belief that the Dakota was originally continuous over the area occupied by the present mountains.

CHARACTER AND POSSIBLE ORIGIN OF THE DAKOTA SANDSTONE.

Dakota is a name that has been used in the past for several different formations. In some of the older reports the Dakota is described as several hundred feet thick, including much more than is assigned to this formation at the present time. The Dakota of the reports published a few years ago includes a sandstone and a shale now known to be of Lower Cretaceous age. Where these can be definitely identified the Dakota sandstone proper has a maximum thickness of little more than 100 feet, and in many places its thickness is 50 feet or less. It is a coarse-grained sandstone, in some places conglomeratic and usually hard and quartzose. There are few places in the Rocky Mountain region where recognizable fossils have been found in it, and there is no certainty that the Dakota of one locality is the exact time equivalent of the Dakota of another locality. It seems to be the custom to assign a sandstone to the Dakota if it occurs immediately below shale known from fossil evidence to be of Benton age. In other words, the Dakota (the term being used now in its restricted sense as meaning the

[1] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Pikes Peak folio (No. 7), 1894.
[2] Personal communication.

sandstone resting on the Purgatoire formation,[1] which was formerly regarded as the lower part of the Dakota) seems to be the basal sandstone of the Upper Cretaceous series—that is, the sandstone formed near shore in the advancing Upper Cretaceous sea.

Doubtless objection will be raised to this restriction of the term on the ground that the Dakota is a sandstone of fresh-water origin. It has been so regarded mainly because of its lack of marine invertebrates in most places where it has been observed, and the presence in it of fossil plants. Apparently because of this assumption that the Dakota is of fresh-water origin, sandstones near the base of the Cretaceous lithologically like the Dakota and once regarded as Dakota have, when marine invertebrates were found in them, been assigned to younger formations. The objection loses some of its force when the gradual slope over which the Cretaceous sea advanced is considered. It seems entirely possible that a basal sandstone formed on such a slope might be essentially of fresh-water character and be followed immediately by beds of marine origin. Thus, as the sea advanced the sandstone deposited one day might the next day be buried underneath marine shale.

According to this hypothesis, it follows that the Dakota of one locality may be the exact equivalent in age of some of the Benton shale of another locality. Paleontology has thus far thrown little light on this question, possibly because the fossils may not have been examined with this point in view, and possibly because fossils may not be adequate to show recognizable stages in so regular a transgression of the sea. It is especially difficult to make close paleontologic correlations between fresh-water beds and marine beds. The Cretaceous sea may have advanced rapidly, because the area that it submerged was nearly level, but there are some facts that cast doubt on this possibility. For example, in southwestern Wyoming the Bear River formation, which, according to report,[2] ranges from 500 to 5,000 feet in thickness, has been supposed to represent the Dakota, inasmuch as it is the oldest Upper Cretaceous formation of that locality and lies beneath shale of lower Colorado age.[3] If the Colorado of the Cretaceous section of southwestern Wyoming is equivalent in age to the Colorado of other localities, as the fossils tend to prove, the sediments of the Bear River must have accumulated in about the same time that it took the 50 to 100 feet of Dakota sandstone of other localities to form. Even though it is granted that the Bear River is a delta deposit, and that its formation was measurably rapid, the accumulation of its thick beds of sediment must have taken a long time. On the other hand, if certain marine fossils found near the base of the Bear River formation indicate Colorado age, as Stanton [4] states, most if not all of that formation must be younger than Dakota.

All things considered, it seems probable that the interior Cretaceous sea advanced from the Gulf of Mexico, and perhaps also from the Arctic Ocean, and completely covered the region now occupied by the Rocky Mountains. (See fig. 13, p. 31.) It is possible that areas which were never submerged by the Cretaceous sea may be found in the Rocky Mountains, as some geologists believe they will, but no such Cretaceous island is known at the present time. West of this region the sea seems to have encountered steeper slopes on the flanks of the old continent, where for some reason as yet unknown the basal sandstone differs considerably from the Dakota sandstone of localities farther east, and in many places at least is recognized as being of Benton age.

EVIDENCE OF COAL-BEARING FORMATIONS.

Throughout this paper the term "near-shore deposits" is used for rocks made up of material more or less coarse, some deposits containing coal beds and land plants, others containing brackish-water or littoral marine faunas. Inasmuch as the coal-bearing rocks prove nearness of land at the time when they were formed, they demand consideration, for they occur at one place or another in the Rocky Mountain region at almost every horizon within the Cretaceous system and at localities far from the rim of the Cretaceous basin. White [5] has pointed out that

[1] Stose, G. W., U. S Geol. Survey Geol. Atlas, Apishapa folio (No. 186), 1912.
[2] Veatch, A. C., Geography and geology of a portion of southwestern Wyoming: U. S. Geol. Survey Prof. Paper 56, p. 50, 1907.
[3] Stanton, T. W., The Colorado formation and its invertebrate fauna: U. S. Geol Survey Bull. 106, p. 45, 1893.
[4] Veatch, A. C., op. cit., p. 63.
[5] White, David, Physiographic conditions attending the formation of coal: U. S. Bur. Mines Bull. 38, pp. 52–84, 1913.

in large measure coal beds indicate accumulation of vegetal matter in coastal swamps. Although these swamps may have been modified in various ways by barriers, fluctuations of land and water level, etc., the accumulation as a rule took place not far from sea level. It is quite true that the presence of sand, littoral faunas, and coal beds [1] indicates deposition near shore, but these features do not indicate the character of the shore, nor do they prove that the sediments were derived from land near by rather than from land at a distance.

The formation of the interior Cretaceous basin falls in the class of great epirogenic movements where uniformity of action is to be expected. On the whole this basin seems to have been due to the downward warping of a base-leveled surface. While variations in the rate of warping probably occurred, it does not seem likely that upward warping of a magnitude sufficient to form land masses of any considerable extent occurred in the middle of the downward-warped area during the time when the general subsidence was going on.

The significance of the coal beds in my reconstruction of the physiography of Upper Cretaceous time may be stated as follows: The Rocky Mountain region reduced to base-level at the close of Lower Cretaceous time was included in the area whose subsidence caused the formation of the interior basin of Upper Cretaceous time. The basin did not attain at once its maximum depth, nor did the sea occupying it attain at once its maximum extent. Sedimentation proceeded contemporaneously with the advance of the sea, which doubtless was intermittent and perhaps even oscillatory. It thus happened that coastal swamps favorable for the accumulation of peat developed sometimes near the periphery of the basin and sometimes far out toward its center. Thus near the ancient western continent the near-shore deposits with their coal beds and other evidences of fresh-water conditions alternating with rocks containing brackish-water and littoral marine faunas are found throughout the Upper Cretaceous series, while farther from this old land mass the near-shore deposits wedge out and merge with offshore or purely marine deposits. Without carrying the discussion to unwarranted lengths I may say that it seems obvious that the occurrence of all the coal-bearing rocks of Upper Cretaceous age in the Rocky Mountain region may readily and rationally be explained without assuming that diastrophism reversed its normal processes and produced upward warping in the middle of an area that on the whole was being warped downward.

DISTRIBUTION OF UPPER CRETACEOUS FORMATIONS.

GENERAL FEATURES.

The general distribution of the Colorado formations in the Rocky Mountain region is too well known to require more than a passing remark in this connection. In most places where the Dakota sandstone occurs the Colorado overlies it with obvious conformity. In a few places, as, for example, near Pikes Peak,[2] the Benton seems to overlap the Dakota and to lie on older rocks.

East of the Rocky Mountains the rocks of Colorado age are lithologically separable from those of Montana age in some places but not in others and are so uniform in thickness that it seems necessary to postulate relatively uniform conditions of sedimentation over extensive areas during Colorado time. Certain supposed unconformities near Golden, Colo., described by Eldridge,[3] do not support this hypothesis. He explained the thinning out of some of the Cretaceous formations as due to the presence of highlands over which these formations did not at any time extend. Doubt has recently been thrown on the existence of these unconformities at Golden by Richardson,[4] who thinks that the observed relations may be due to strike faults. Others who have examined the region with this conception in mind do not accept Richardson's suggestion. It would seem that if these supposed highlands really existed they were of local occurrence. Several years ago I advocated Eldridge's hypothesis in explanation of similar

[1] Stanton, T. W., Boundary between Cretaceous and Tertiary in North America, as indicated by stratigraphy and invertebrate faunas: Geol. Soc. America Bull., vol 25, p. 345, 1914.
[2] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, Pikes Peak folio (No. 7), 1894.
[3] Eldridge, G. H., Geology of the Denver Basin, in Colorado: U. S. Geol. Survey Mon. 27, pp. 82-104, 1896.
[4] Richardson, G. B., Structure of the foothills of the front range, central Colorado: Washington Acad. Sci. Jour., vol. 2, p. 429, 1912.

phenomena near Perry Park, Colo., but I have since come to believe that this explanation is doubtful.

West of the mountains, and also within them where isolated remnants of Cretaceous rocks occur, there is no definite line of separation between the Colorado and Montana groups, although the lower part of the shale overlying the Dakota is known to be of Colorado age and the upper part to be of Montana age. However, the discovery of the same fossils on both sides of the mountains indicates that the sea was continuous either across or around the present mountainous area, and the available data seem to indicate that it was continuous across. This conclusion is reiterated because of certain correlations that will be suggested later.

Where the rocks consist of limestone there could not have been large accessions of sediment such as would be expected from near-by highlands. Arenaceous shales occur in the Colorado group east of the mountains, but the content of sand seems to be no greater near the mountains than far from them, and there is no indication that this sand was derived from lands in the region of the present mountains rather than from lands on either side of the interior sea. In brief, the general lithologic character of the formations of the Colorado group argues against rather than for the presence of land in the mountain region during Colorado time.

The presence of sedimentary rocks of Colorado age in many places within the mountains indicates that at least some parts of the mountainous area were submerged by the sea in Colorado time, but S. F. Emmons and other geologists following him have maintained that islands persisted in that area throughout the Cretaceous period. This contention is not in accord with the evidence that the Dakota was laid down on a practically level floor nor with the fact that in North Park, South Park, and other intermontane localities the marine Cretaceous rocks have essentially the same character and thickness that they have on either side of the mountains.

West of the Rocky Mountains the rocks of Colorado age are, on the whole, more arenaceous and less calcareous than the corresponding rocks east of the mountains. Beds of limestone are thin and few in number, but in some places, especially near the western margin of the Cretaceous area, the sandstones are massive. In this connection it is a significant fact that west and south of the Rocky Mountains the Cretaceous sedimentary rocks are prevailingly argillaceous near the mountains and become progressively more arenaceous away from them, until near the margin of the old continent in New Mexico and Utah they consist mainly of sandstone, some of which is conglomeratic. This lithologic evidence is in harmony with the postulate of an early Cretaceous peneplain covering the Rocky Mountain region and extending far to the west, on which the Dakota sandstone was laid down as the Cretaceous sea advanced over it. If this advance was due to subsidence of the land, the subsidence must have been very regular, for the Colorado formations vary but little in thickness over wide areas. A rise in sea level allowing the water to spread over the surface of a relatively stable land during Colorado time might equally well explain the observed relations.

The sea seems to have transgressed the Rocky Mountain peneplain with relative rapidity, the thin Dakota sandstone being formed along its advancing front. Against the western land mass in central New Mexico, Arizona, and Utah the advance seems to have been halted and an unstable condition of sedimentation established, owing possibly to oscillations of the land but more likely to oscillations of sea level, the accumulations of sediments being built out from shore farther at some stages than at others. The shorter stages are best indicated by the occurrence of alternating layers of sediments of fresh-water, brackish-water, and marine origin. The longer stages are indicated in the sections given in the several figures accompanying this paper.

The formations referred to the Montana group seem to be more irregular in character and thickness than those of the Colorado group. Whether this irregularity is due to oscillations and surface warping in late Upper Cretaceous time or to some other cause has not been satisfactorily determined. It is a fact worthy of consideration in this connection that some of the greatest variations in thickness, as reported, occur in the soft Pierre shale close to the mountains, where duplication by faulting and thickening by lateral thrust would naturally be expected. Where measurements have been obtained from drill records, vertical sections, etc., at sufficient distances from the mountains to make it reasonably sure that original thicknesses were obtained, the rocks of the Montana group have been found fairly uniform in thickness and character. This uniformity is one of the things that I wish to show by the accompanying sections. Another is the probable source of the sediments and the direction in which the formations gradually change in thickness and in character.

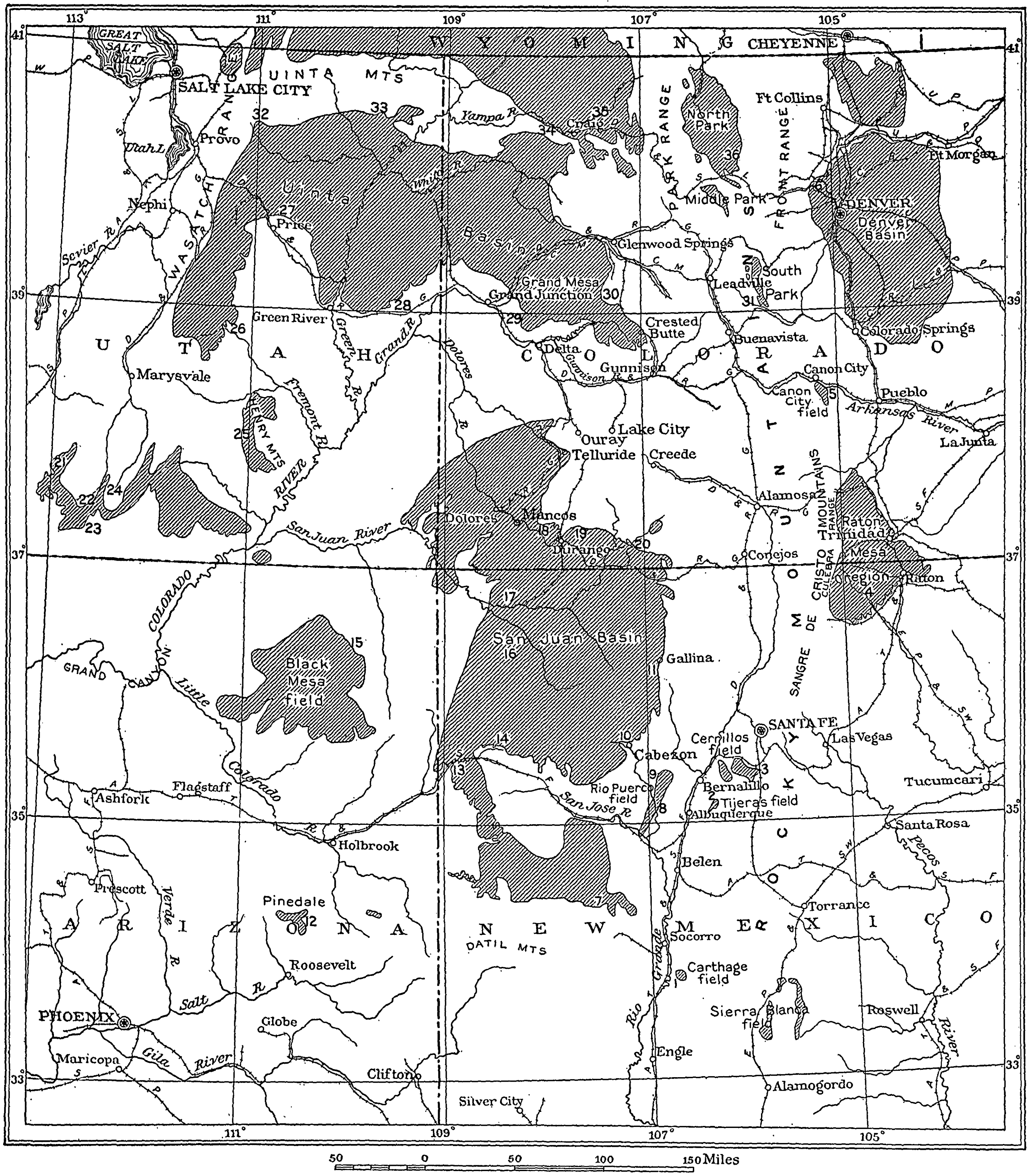
Inasmuch as the following descriptions of sections are somewhat lengthy, it may be appropriate to state here that I desire to emphasize my belief that the Cretaceous sediments came mainly from the continental land mass west of the interior sea, and that they spread eastward over the present site of the Rocky Mountains—in other words, that no mountains or even islands of any considerable size existed there in Cretaceous time. I have already stated that the advance of the sea in Colorado time was halted against the western continent. Whether or not this continent suffered differential uplift at the close of the Colorado epoch, as certain conglomerates and possible unconformities in Utah and elsewhere seem to indicate, there is little question that this or whatever land furnished the sedimentary material must have been relatively high or of great lateral extent in order to supply the enormous masses of sediment that accumulated in the interior Cretaceous sea. On the other hand, sedimentation seems to have been continuous in many places throughout Upper Cretaceous time, and it is not possible to distinguish stratigraphically between the Montana and the Colorado.

Among the conclusions that may be drawn from a study of the sections described below, two stand out rather prominently. First, the area of maximum depth in that part of the basin here described, as indicated by the maximum filling shown in the published sections, is in northern Colorado and southern Wyoming. It is a fair assumption, borne out in a measure by the character of the sediments, that the filling of the basin progressed from the periphery toward this center, and that as time went on the center finally contained the youngest rocks. It may be noted in this connection that the youngest coal-bearing rocks of Cretaceous age—that is, the Laramie of the Denver Basin and formations of corresponding position—occur over a relatively small area in southern Wyoming and northern Colorado, on both sides of the mountains. If these mountains were above sea level during Upper Cretaceous time they must have stood near the center of the basin. Inasmuch as the mid-Cretaceous marine formations occur in full thickness in North Park, Colo., in the center of the area in which these youngest Cretaceous coal-bearing rocks occur, it seems reasonable to assume that there were no mountains there at the time and that the marine formations and perhaps also the overlying coal measures once covered the region.

The second conclusion that may be drawn from the sections is that the sandstone formations near the ancient western continent thin eastward, toward the present Rocky Mountains, and the shale formations are thin to the west but thicken toward the present mountains; also that the shales have about the same thickness and character on either side of the mountains and in the intermontane areas. If, as is postulated in this paper, the main mass of sediments came from the west, the sandstones should thin eastward and finally be replaced by shale, and it is quite natural that the massive mid-Cretaceous sandstones on the west should be replaced farther east by thin, inconspicuous sandy layers and that sands in great quantity should have reached the center of the basin only in late Cretaceous (Fox Hills and Laramie) time, after its peripheral parts had been filled.

THE SECTIONS ILLUSTRATED.

The sections on figures 16 to 22 have been selected with a view to showing comprehensively the distribution of the Cretaceous formations. They have been generalized in order that the features having a bearing on the present study may not be obscured by nonessential details. References are given to published descriptions, but in some of the sections modifications have been made in accordance with information obtained since the time of publication. Two groups of sedimentary rocks are especially emphasized—near-shore deposits, including those of fresh-water and brackish-water origin together with sandstones of marine origin; and offshore deposits, consisting principally of marine shale with some limestone.



MAP OF THE COAL FIELDS IN THE SOUTHERN ROCKY MOUNTAIN REGION, SHOWING THE LOCATION OF THE SECTIONS DESCRIBED.

Adapted from map of the coal fields of North America, by M. R. Campbell.

The lines connecting the sections are intended to show homogenetic equivalents rather than time equivalents. For example, the Vermejo formation of the Canon City field seems to be the homogenetic equivalent of the Laramie of the Denver Basin (section 6), inasmuch as it consists principally of coal-bearing rocks of fresh-water origin, but it seems to be the time equivalent of the Fox Hills sandstone of this basin.

The several sections will be considered in groups with special reference to their relation to the Rocky Mountains. The approximate location of the sections is indicated on Plate V by numbers corresponding to those given in parentheses in the section headings in the text.

CARTHAGE, N. MEX., TO BOULDER, COLO.

The sections of figure 16 are so chosen that a line connecting the localities at which they were measured will pass east of the Rocky Mountains to a point well south of the end of the main range and near the border of the southwestern continental land mass of Upper Cretaceous time. (See fig. 13, p. 31.)

CARTHAGE (1).[1]

Although Carthage is the southernmost locality at which a satisfactory section is available, the sedimentary rocks of Upper Cretaceous age extended at least 70 miles farther south, to the vicinity of Engle, N. Mex., where coal beds of Benton age have been found. The rocks of the Carthage field are badly faulted, but the succession, as shown in the section, seems to be well established.

A sandstone at the base of the section is referred with a query to the Dakota because, like the Dakota (?) of the other sections, it lies below rocks of Benton age. No fossils were found in it, and it may represent the Tres Hermanos sandstone member of the Mancos shale of the Tijeras section, described below. The Dakota (?) is overlain by marine shale with thin layers of sandstone of Colorado age, and these in turn by coal-bearing rocks that contain brackish-water invertebrates which range in age from lower Colorado to Laramie. Because of lithologic similarity Gardner correlated these rocks with the Mesaverde of the San Juan Basin and referred them with a query to the Montana. Later investigations indicate that they are older than Montana. The coal measures are overlain unconformably by Tertiary red beds containing Palæosyops near the base.

The area between Carthage and Tijeras, a distance of about 80 miles, has not been examined in detail, but no rocks of Cretaceous age have been found there.

TIJERAS (2).[2]

At the base of the Tijeras section lies a sandstone that is called Dakota on the evidence of lithology and stratigraphic position. No fossils have been found in it. The overlying shale, the Mancos, consists of a thick shale of marine origin with a sandstone, the Tres Hermanos member, near the base. The principal part of the coal measures is of Montana age and is correlated by lithology and invertebrate fossils with the Mesaverde of the San Juan Basin. Some of the upper part may be younger than Montana, but the few fossils found in it were not sufficient to determine the age.

The Cretaceous rocks of the Tijeras field obviously were connected at one time with those of the Hagan and Cerrillos fields, to the north, and for the purposes of this paper the formations represented in these fields, now separated because of erosion, may be regarded as essentially continuous.

CERRILLOS (3).[3]

At Cerrillos the Galisteo sandstone lies unconformably on the Mesaverde formation and is lithologically similar to the beds of Tertiary age in the San Juan Basin. For these reasons it is regarded as Tertiary, but evidence is not at hand for closer correlation. The coal-bearing

[1] Gardner, J. H., The Carthage coal field, N. Mex.: U. S. Geol. Survey Bull. 381, pp. 452–460, 1910.
[2] Lee, W. T., Stratigraphy of the coal fields of northern central New Mexico: Geol. Soc. America Bull., vol. 23, pp. 629–633, 1912.
[3] Idem, pp. 633–659.

Mesaverde formation has yielded a large number of marine and brackish-water invertebrates and land plants, all of which indicate Montana age. The Mancos consists of a thick shale with marine fossils of Montana age at the top and of Benton age near the base. It contains the

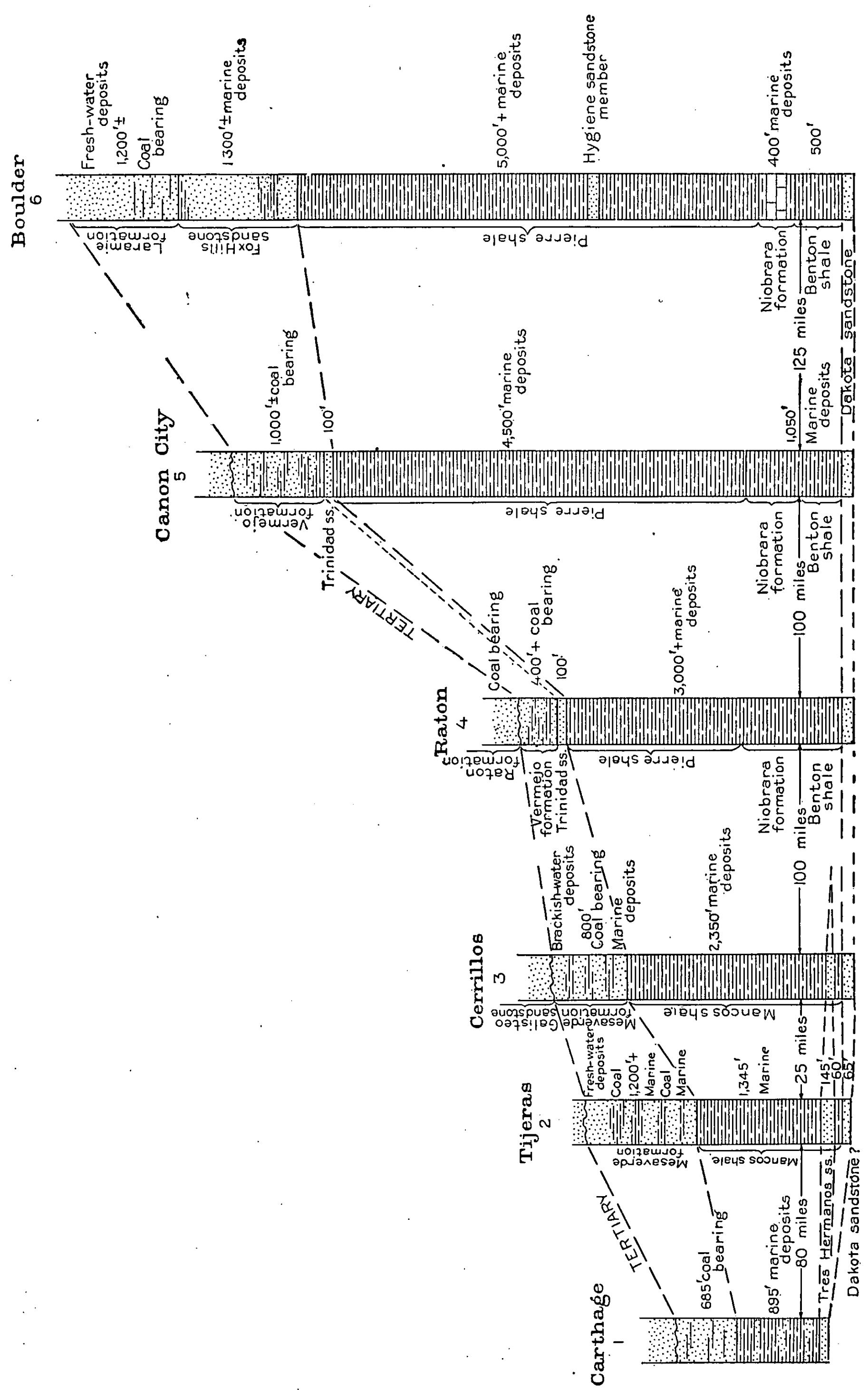


FIGURE 16.—Group of sections from Carthage, N. Mex., to Boulder, Colo. (For location see Pl. V.) The names at the left of each section indicate correlations that have been made. The lines connecting the sections are intended to show homogenetic equivalents rather than time equivalents.

Tres Hermanos sandstone, here a single layer only a few feet thick. The sandstone below the Mancos is referred to the Dakota because of its conglomeratic character and its position between the Mancos shale and the Morrison formation.

No coal-bearing rocks are known to occur between the Cerrillos and Raton fields, but except for about 35 miles east of Cerrillos, where all rocks younger than the "red beds" have been eroded away, the older Cretaceous rocks are continuous. The Mancos of the Cerrillos section is so similar in thickness and character to the Pierre of the Raton section as to suggest that the Mancos was originally continuous with the Pierre across the intervening area.

RATON (4).[1]

The coal measures of the Raton Mesa region consist of the Raton formation, which is Tertiary in age, and the Vermejo formation, which is of Montana age. The Vermejo flora tends to correlate this formation with the Mesaverde of the Cerrillos field and of the San Juan Basin, but the marine invertebrates from the top of the underlying shale suggest that the Vermejo is younger than the Mesaverde. In brief, the Vermejo is recognized as a Montana formation, but it seems to occupy a place in the time scale higher than the Mesaverde. The total thickness of the marine Cretaceous of this section is not known, but a well bored near Raton indicates that it is more than 3,000 feet. The drill did not reach the base of the shale.

Although Raton is about 100 miles from Canon City, as shown on the plate of sections, the coal-bearing formations of the two regions are separated by only about 30 miles and the older Cretaceous rocks are continuous between these coal fields.

CANON CITY (5).[1]

The coal measures of the Canon City field lie unconformably beneath rocks supposed to be of Tertiary age because of their lithologic character and structural relations. The coal measures are correlated by fossil plants with the Vermejo formation of the Raton Mesa region and contain invertebrates that tend to correlate them with the Fox Hills sandstone to the north. The thickness of the Pierre shale in this field is estimated as 4,500 feet. This thickness was obtained from well borings in the trough of a syncline, where it seems probable that, because of crushing, the shale is now thicker than it was when originally deposited. The thickness of the Colorado portion of this section is taken from the Pueblo folio.

Canon City and Boulder are about 125 miles apart, but the coal measures represented in the two sections are separated only by the 40 miles between Canon City and Colorado Springs. From Colorado Springs to northern Colorado the coal measures are nearly continuous.

DENVER BASIN—BOULDER (6).[2]

The Laramie formation of the Denver Basin consists of coal-bearing rocks. Beneath it lie sandstone and sandy shale of Fox Hills age, which are described as 600 feet thick near Colorado Springs[3] and 1,300 feet thick near Boulder. Fenneman states, without explaining how or where the measurement was made, that the Pierre shale near Boulder is more than 5,000 feet thick. For the same shale near Colorado Springs Finlay gives a thickness of 2,500 feet, although Eldridge[4] states that its thickness between these two localities is 7,700 to 7,900 feet. It is partly because of these great variations in reported thickness that I am disposed to question the meaning of the figures and to believe that the maximum thicknesses as measured represent something more than the original or depositional thickness of the shale. For this reason I have used the section giving an intermediate thickness. A relatively thin sandy member known as the Hygiene sandstone occurs 1,000 to 2,700 feet above the base of the Pierre. It has not been definitely recognized outside of the Boulder region, and little is known of its relation to formations of other fields.

SUMMARY.

On considering this series of sections together, it seems obvious that shore conditions favorable to the accumulation of coal and of the sediments normally associated with coal existed in central New Mexico early in Upper Cretaceous time and progressively later toward the north.

[1] Lee, W. T., unpublished manuscript.
[2] Fenneman, N. M., Geology of the Boulder district, Colo.: U. S. Geol. Survey Bull. 265, pp. 28–34, 1905.
[3] Finlay, G. I., U. S. Geol. Survey Geol. Atlas, Colorado Springs, folio (in preparation).
[4] Eldridge, G. H., Geology of the Denver Basin, in Colorado: U. S. Geol. Survey Mon. 27, p. 69, 1896.

In other words, as the sea filled with sediments derived from the land mass to the southwest, the shore along this particular line of sections was pushed gradually farther north. This suggests that had not the Cretaceous rocks connecting the several fields been eroded away there might now be a coal-bearing formation extending from Carthage, N. Mex., northward through Colorado and beyond, that would be of Benton age at one extremity and of Laramie age at the other.

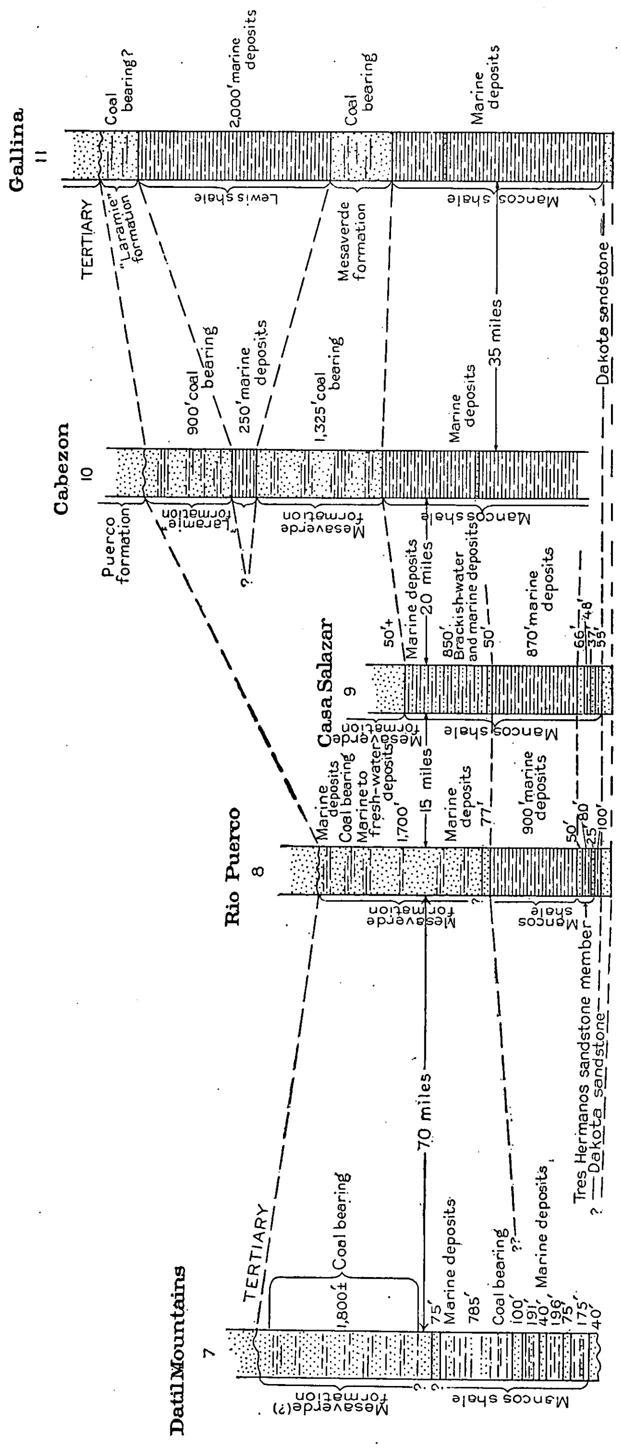


FIGURE 17.—Group of sections from Datil Mountains to Gallina, N. Mex. (For location see Pl. V.) The names at the left of each section indicate correlations that have been made. The lines connecting the sections are intended to show homogenetic equivalents rather than time equivalents.

DATIL MOUNTAINS TO GALLINA, N. MEX.

The series of sections given in figure 17 has been chosen for the purpose of showing the change in character of the Cretaceous formations in a north-northeasterly direction from a point in the Datil Mountains near the western Cretaceous land to the present Rocky Mountains—the Gallina locality.

DATIL MOUNTAINS (7).[1]

The coal-bearing formations west of the Rio Grande are separated by erosion from those to the east, just described, but there are good reasons for believing that they are parts of formations that once extended continuously over western New Mexico. In the Datil Mountains a thin conglomeratic sandstone of irregular occurrence is regarded as the Dakota, and above it are sandstone and shale about 3,700 feet thick. The lower half of these rocks is referred on fossil evidence to the Mancos and the upper half to the Mesaverde. The Mancos, which elsewhere is almost exclusively a marine shale, here consists of sandstone and shale in nearly equal proportion and contains several beds of coal in the upper part. The Mesaverde of this section is similar to the typical Mesaverde, which is essentially a coal-bearing sandstone.

The Cretaceous formations are practically continuous from the Datil Mountains to the Rio Puerco field, but little is known of them in the intervening areas.

RIO PUERCO FIELD (8).[2]

In the Rio Puerco field the Mesaverde formation lies unconformably beneath rocks that are lithologically similar to some of the Tertiary beds of the San Juan Basin. It consists of

[1] Winchester, D. E., unpublished manuscript.

[2] Lee, W. T., Stratigraphy of the coal fields of northern central New Mexico: Geol. Soc. America Bull., vol. 23, pp. 622–629, 1912.

arenaceous rocks of marine, brackish-water, and fresh-water origin alternating with beds of coal. Arenaceous rocks not notably different from those of the coal measures extend nearly 700 feet below the lowest known coal and terminate with the Punta de la Mesa sandstone, a member that can be recognized as far north as Gallina, about 75 miles from Rio Puerco. This sandstone was formerly included in the Mesaverde because of its obvious relation to the sandy beds above it, but is now regarded as a member of the Mancos shale. The name Mancos shale is somewhat misleading for this field. Only the lower part of the formation is shale, and fossils indicative of Benton age occur practically to the top of this part. Near the base of the Mancos occurs the Tres Hermanos sandstone member, which is recognizable from the Datil Mountains to Casa Salazar but which was not found farther north, near Gallina. This sandstone is coal bearing in the Datil Mountains, but in the Rio Puerco field only a single layer of carbonaceous shale was found in it. The sandstone below the Tres Hermanos is called Dakota (?) because it is at the base of such Upper Cretaceous rocks as occur here. No fossils have been found in it.

CASA SALAZAR (9).[1]

The section near Casa Salazar differs from the Rio Puerco section mainly in the character of the rocks above the Punta de la Mesa sandstone member. They consist of shaly sandstone that seems to be transitional between the shale of the upper part of the Mancos at Cabezon and the lower part of the arenaceous beds of the Rio Puerco field. Only the base of the Mesaverde formation is exposed here.

The Mancos shale is exposed continuously between Casa Salazar and Cabezon and the continuity of the Mesaverde is only slightly interrupted.

CABEZON (10).[2]

At Cabezon the Puerco formation lies unconformably on the "Laramie," and the Lewis seems to be the attenuated edge of a shale formation that is very much thicker farther north. The Mesaverde seems to thicken as the Lewis thins and vice versa.

From Cabezon to Gallina the Cretaceous formations are continuous, but for a few miles they are not exposed at the surface because of the Tertiary overlap.

GALLINA (11).[3]

Near Gallina the Tertiary rocks lie unconformably on the "Laramie" formation, which is much thinner than it is near Cabezon. This formation, though regarded by some as of Laramie age, contains fossil plants which indicate that it is Montana. The Mesaverde also is much thinner, but the Lewis has greatly increased in thickness. The Mancos shale is reported as 500 to 1,000 feet thick and has a sandy bed (the Punta de la Mesa (?) sandstone) 275 feet from the top. The Dakota underlies the Mancos, but the Tres Hermanos sandstone, if represented at all, is inconspicuous.

SUMMARY.

The Datil Mountain locality is nearest the western continental land mass of Cretaceous time and the Gallina locality farthest from it. As in the sections farther east, the sandstones shown at the base of the several sections are homogenetically equivalent but may not represent equivalency in time. Near-shore deposits, including coal, began to accumulate in the Datil Mountain region early in Colorado time while marine shale was accumulating farther north. The coal measures of the Datil Mountains, being principally if not wholly of Colorado age, were in process of formation while marine shale was accumulating near Cabezon and Gallina.

During Mesaverde time the strand line seems to have moved northward along this line of sections because of the filling of the sea and perhaps in part because of change of sea level. However, the open sea could not have been far away, for marine invertebrates occur at several horizons in the Mesaverde of the Rio Puerco field. A second notable advance of the sea occurred in Montana time, resulting in the formation of the Lewis shale. Inasmuch as this shale is notably lenticular, according to the reported measurements, there must either have been

[1] Lee, W. T., unpublished manuscript.
[2] Gardner, J. H., The coal field between San Mateo and Cuba, N. Mex.: U. S. Geol. Survey Bull. 381, pp. 461–473, 1908.
[3] Gardner, J. H., The coal field between Gallina and Raton Spring, N. Mex., in the San Juan coal region: U. S. Geol. Survey Bull. 341, pp. 335–351, 1907.

a local downward warping of the basin in which it was deposited or else the advance of the sea was so slow that near-shore sediments now included in the upper part of the Mesaverde and perhaps also in the lower part of the "Laramie" were accumulating near Cabezon while offshore or marine clays were accumulating near Gallina.

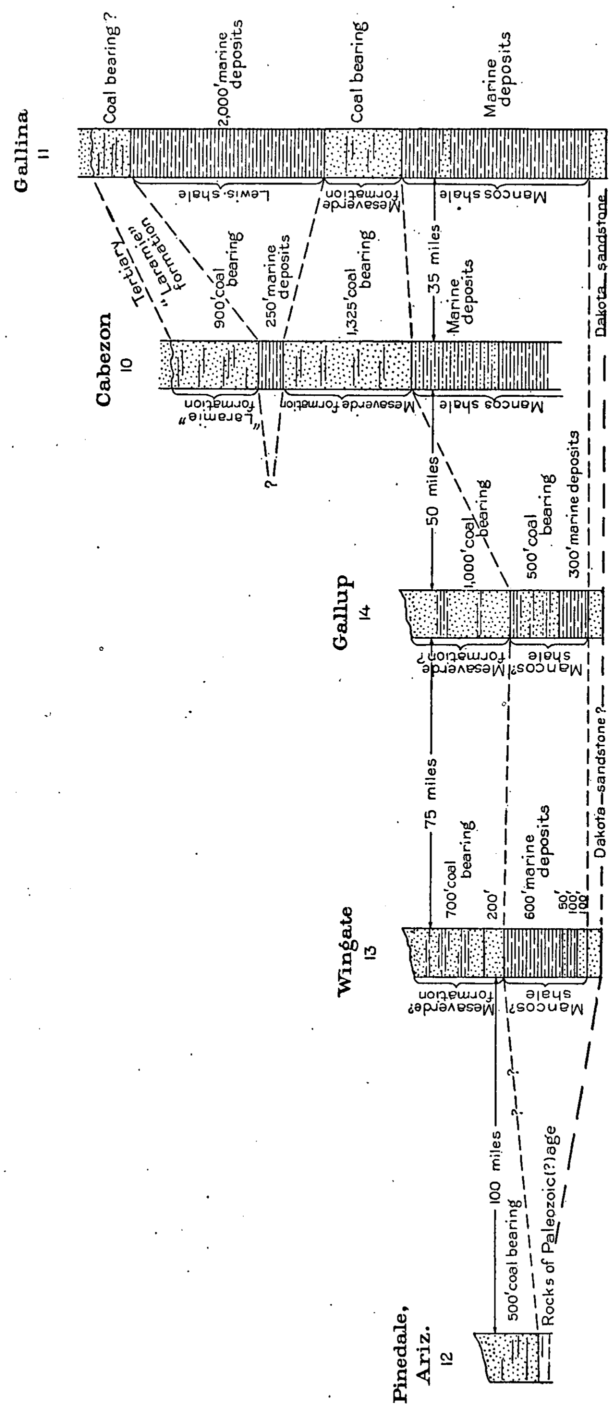


FIGURE 18.—Group of sections from Pinedale, Ariz., to Gallina, N. Mex. (For location see Pl. V.) The names at the left of each section indicate correlations that have been made. The lines connecting the sections are intended to show homogenetic equivalents rather than time equivalents.

Of the five localities included in this series Gallina is nearest to the present highlands of the Rocky Mountains and the Datil Mountain locality is farthest from them. An inspection of the sections of figure 17 shows that the offshore deposits (the Mancos and Lewis shales) increase and the near-shore deposits decrease in thickness toward the Rocky Mountain area. Had this area furnished the sediments this relation would have been reversed.

PINEDALE, ARIZ., TO GALLINA, N. MEX.

The sections shown in figure 18 are chosen to illustrate the change in character of the formations along a line crossing the San Juan Basin from a point in Arizona near the border of the western continental land of Cretaceous time northeastward to the present Rocky Mountains. Because of the absence of other published sections for the eastern part of this basin the Cabezon and Gallina sections are here repeated.

PINEDALE (12).[1]

The coal measures of the Pinedale region occupy a small area south of Holbrook, Ariz., and seem to have been continuous at one time with those of the San Juan Basin, although they are now separated by erosion. They are about 500 feet thick and contain coal near the base. No sandstone referable to the Dakota was found. Just above the beds of coal were found fossils of Benton age that correlate these rocks with the coal measures of southern Utah. The Cretaceous rocks lie unconformably on shaly sandstone of probable Paleozoic age. Two other small areas have been described by Gilbert.[2]

FORT WINGATE (13).[3]

The section at Stinking Spring, 12 miles west of Fort Wingate, N. Mex., was measured long before the present formational nomenclature of this region was adopted. The coal-bearing

[1] Veatch, A. C., Coal deposits near Pinedale, Navajo County, Ariz.: U. S. Geol. Survey Bull. 431, pp. 239–242, 1911.

[2] Gilbert, G. K., Report on the geology of portions of New Mexico and Arizona examined in 1873: U. S. Geog. and Geol. Expl. W. 100th Mer., vol. 3, p. 544, 1875.

[3] Idem, pp. 503–567.

rocks seem to be what are now called Mesaverde by some authors and are referred to the upper part of the Mancos shale by others. They are underlain by a marine shale that is doubtless the Mancos, and certain sandstones near the base of this shale hold a position similar to that of the Tres Hermanos sandstone. The lowest sandstone is called Dakota, but there is nothing aside from stratigraphic position to indicate that it is equivalent in age to the Dakota of other localities.

GALLUP (14).[1]

The coal measures near Gallup are supposed to be approximately equivalent in age to the original Mesaverde and hence of Montana age, but the coal of this region may extend downward into the Colorado, as it is known to farther south and east, and its lower beds are supposed to be Mancos. Below the coal-bearing rocks occurs typical Mancos shale, but it is described as only 300 feet thick. A lower sandstone 200 feet thick is called Dakota. This thickness seems to be too great for the Dakota, and some of the sandstone may be equivalent to the sandstone of the Fort Wingate section near the base of the Cretaceous, which contains marine invertebrates and is therefore regarded as younger than Dakota. It is probable that here, as in many other places in western New Mexico and Colorado, where the lowest sandstone of the Upper Cretaceous is called Dakota, the name has little time significance beyond the fact that the sandstone lies below shale referable to some part of the Benton. It seems probable that this sandstone may, in some places at least, be of Benton age.

The coal measures of the Gallup section are homogenetically equivalent to the Mesaverde formation of the Cabezon section, but obviously they are not equivalent in age if the reference of their lower part to the Mancos is correct.

SUMMARY.

In this series of sections, as in those already described, purely marine conditions persisted longest near the present mountains. If the time correlations are correct, near-shore deposits were accumulating in the Wingate-Gallup region while offshore deposits were being formed in the Cabezon-Gallina region.

NORTHERN ARIZONA TO RATON, N. MEX.

Although the coal-bearing rocks of Black Mesa, in northeastern Arizona, are not now connected with those of the San Juan Basin, the two areas were probably connected at one time and are now separated only because of erosion. Hence, the sections of figure 19 show the variations in character of the several formations in the northern part of this basin, from its most westerly exposure eastward to the Rocky Mountains. At one time these formations probably extended across the space now occupied by the mountains and were continuous with those of the Raton section, which is included here for comparison.

NORTHEASTERN ARIZONA (15).[2]

The first section of this series was measured in the northeastern part of the Black Mesa coal field, near Chilchivito Spring, and shows the general relations of the formations throughout the field, although their thicknesses vary from place to place. From the unpublished notes of members of Gregory's party another measurement near this spring shows Mancos 565 feet thick and Mesaverde 865 feet. About 20 miles farther southeast the Mancos is reported as 470 feet thick and the Mesaverde formation as 820 feet. Near Oraibi, about 70 miles southwest of Chilchivito, the Mancos was found to be about 225 feet thick and is overlain by an unknown thickness of Mesaverde. In the western part of the field, 6 miles east of Blue Canyon store, the Mancos is 490 feet and the Mesaverde more than 221 feet thick.

The coal measures of the Black Mesa field are referred with doubt to the Mesaverde, the underlying shale to the Mancos, and the lowest sandstone of the Cretaceous to the Dakota. This correlation is doubtless homogenetically correct, as is indicated by the connecting lines in

[1] Gardner, J. H., The coal field between Gallup and San Mateo, N. Mex.: U. S. Geol. Survey Bull. 341, pp. 364-378, 1909.
[2] Campbell, M. R., and Gregory, H. E., The Black Mesa coal field, Ariz.: U. S. Geol. Survey Bull. 431, pp. 229-238, 1911.

figure 19, but few data for determining the age relations of these formations have been obtained. The lowest sandstone seems to have been called Dakota only because of its position. It is possible that the coal measures above the Mancos shale are the western continuation of the Mesaverde in the San Juan Basin, but the authors cited regard them as equivalent in age to the coal measures of the Mancos near Gallup.

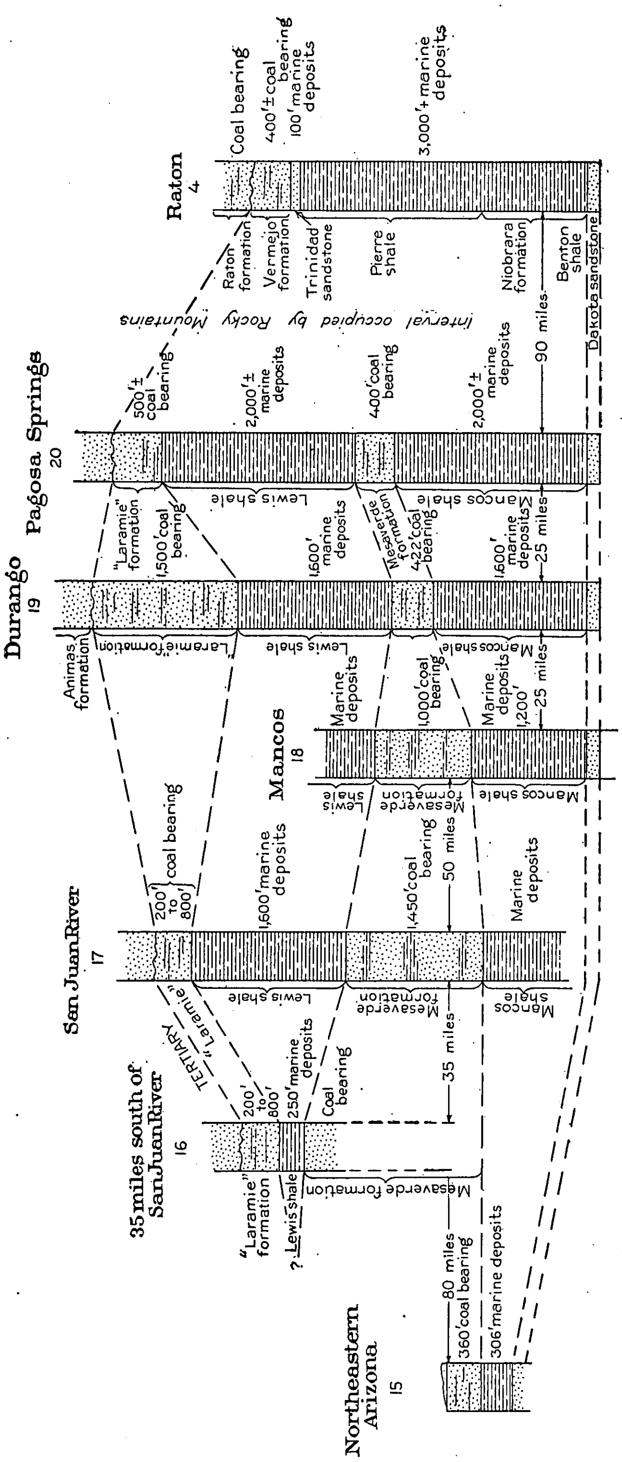


FIGURE 19.—Group of sections from Black Mesa, northern Arizona, to Raton, N. Mex. (For location see Pl. V.) The names at the left of each section indicate correlations that have been made. The lines connecting the sections are intended to show homogenetic equivalents rather than time equivalents.

SAN JUAN BASIN (16 to 20).

The coal measures on San Juan River consist of two formations, the "Laramie" above and the Mesaverde below, separated by a marine shale. This shale, the Lewis, has a thickness of 1,600 feet or more at locality 17 (see Pl. V) and farther east but thins to 250 feet 35 miles to the southeast, at locality 16.[1] These formations are exposed continuously eastward around the San Juan Basin. The original descriptions of the Mancos shale, the Mesaverde formation, and the Lewis shale were based on their occurrence near Mancos, Colo.[2] (section 18).

The Durango section[3] (No. 19) was prepared by J. H. Gardner, who examined the sedimentary rocks of the Ignacio quadrangle for folio publication. Although the name "Laramie" is retained for the upper coal measures they contain fossil plants regarded by Knowlton as of Montana age.

From Durango eastward to Pagosa Springs[4] (locality 20) and beyond the several Cretaceous formations have been traced continuously, and near Pagosa Springs the "Laramie" formation contains plants indicative of Montana age.

SUMMARY.

The Lewis shale seems to have its maximum thickness and the Mesaverde its minimum thickness in the northeastern part of the San Juan Basin. In this group of sections, as in those previously described, the marine shales are thickest near the Rocky Mountains and the coal-bearing sandstone formations become progressively thicker away from the mountains. It is obvious

[1] Shaler, M. K., A reconnaissance survey of the western part of the Durango-Gallup coal field of Colorado and New Mexico: U. S. Geol. Survey Bull. 316, pp. 376-426, 1907.
[2] Cross, Whitman, U. S. Geol. Survey Geol. Atlas, La Plata folio (No. 60), 1899.
[3] Lee, W. T., Stratigraphy of the coal fields of northern central New Mexico: Geol. Soc. America Bull., vol. 23, p. 584, 1912.
[4] Idem, pp. 615-619. Lee, W. T., and Knowlton, F. H., unpublished manuscript.

that the Mesaverde of the Pagosa Springs section is to be correlated with the Mesaverde of the San Juan River section, but it seems equally obvious that the 400 feet of the former does not represent the same interval of time as the 1,450 feet of the latter. It also seems obvious that the 250 feet of Lewis shale south of San Juan River does not represent the same time interval as the 2,000±feet of Lewis shale in the Pagosa Springs section.

The Lewis contains invertebrates that tend to correlate it with the upper part of the Pierre of the Raton field, east of the mountains (section 4). On the other hand, plants similar to those from the Vermejo formation if not identical with them occur in both the Mesaverde and the "Laramie" formations of this basin. It has been shown on page 42 that the Vermejo formation is probably the homogenetic equivalent of the Mesaverde formation of central New Mexico. The evidence of the fossils seems to indicate that the Vermejo of the Raton field is intermediate in age between the Mesaverde and the "Laramie" of the San Juan Basin. If we assume that the Cretaceous formations once extended across the area now occupied by the mountains, it seems probable that the Trinidad sandstone and the Vermejo formation are the homogenetic equivalents of the Mesaverde. It is possible, however, that could the formations be restored it would be seen that the Mesaverde thins out to the east before reaching Raton and that the Trinidad and Vermejo formations are the homogenetic equivalents of the "Laramie" of the San Juan Basin. The absence of marine deposits above the Vermejo renders it difficult to determine which alternative is more likely to be correct.

COLOB PLATEAU TO HENRY MOUNTAINS, UTAH.

The group shown in figure 20 contains the most westerly sections obtainable of the Cretaceous coal-bearing rocks of the southern Rocky Mountain region. However, the Henry Mountain section shows the probable connection of some, if not all, of the Cretaceous rocks of the Colob Plateau with the Mancos shale, the Mesaverde formation, etc., farther east.

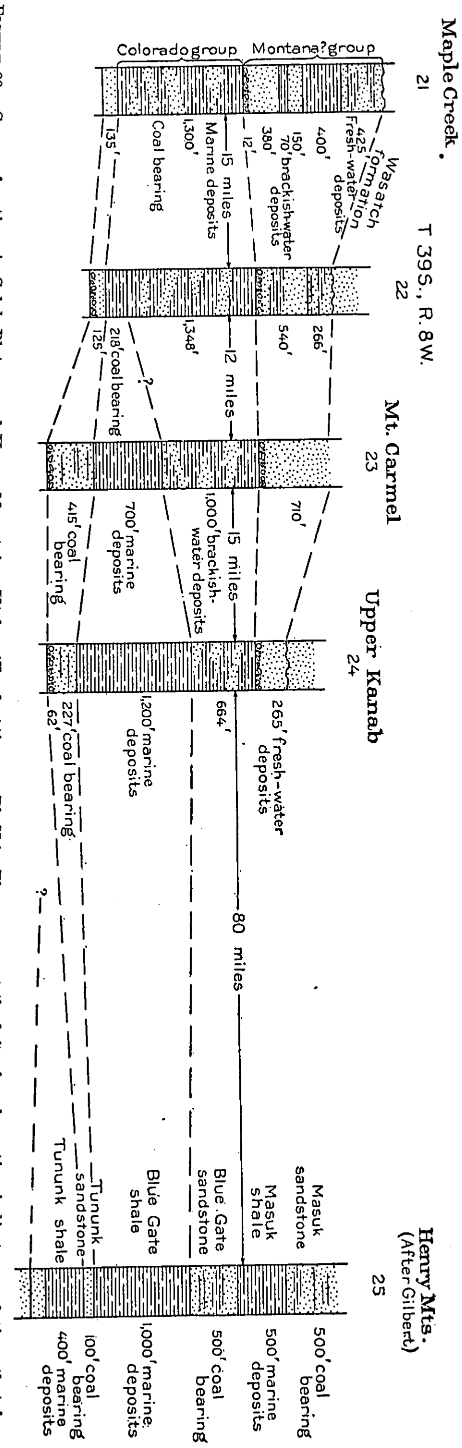


FIGURE 20.—Group of sections in Colob Plateau and Henry Mountains, Utah. (For location see Pl. V.) The names at the left of each section indicate correlations that have been made. The lines connecting the sections are intended to show homogenetic equivalents rather than time equivalents.

COLOB PLATEAU (21 to 24).[1]

The lower part of the coal-bearing and associated rocks of Colob Plateau is of Colorado age. The top of the Colorado is drawn at a conglomerate that seems to be persistent throughout the Colob Plateau region, but its significance has not been determined. The rocks above it contain fossil leaves, but unfortunately their affinities are not sufficiently well known to determine the

[1] Richardson, G. B., unpublished manuscript.

age of the rocks. Richardson has suggested that the sedimentary rocks above this conglomerate may be either Montana or Tertiary. At the westernmost locality for which a section is given (No. 21) the rocks consist of alternating layers of sandstone and shale with little evidence of differentiation into separate formations. Farther east the coal-bearing rocks occur in an upper and a lower group, separated by a marine shale, which seems to be the Mancos of localities still farther east. The coal measures above the shale seem to be homogenetically equivalent to Gilbert's Blue Gate sandstone of the Henry Mountains and to the Mesaverde of localities farther east.

The coal-bearing rocks of the Colob Plateau seem to have been connected at one time with those in northeastern Arizona but have been separated from them by erosion.

HENRY MOUNTAINS (25).[1]

The Henry Mountain section seems to be comparable in some ways to the section farther north, at locality 26, and in other ways to the sections in the San Juan Basin. Gilbert's Tununk sandstone is comparable to the Ferron sandstone member of the Mancos shale, his Tununk shale to the shale underlying the Ferron as described by Lupton, his Blue Gate shale to the main body of the Mancos shale, and his Blue Gate sandstone to the Mesaverde formation. The Masuk shale of Gilbert holds a position suggestive of the Lewis and his Masuk sandstone a position suggestive of the "Laramie" as developed farther south, but no satisfactory evidence of age has yet been found in these upper formations.

A group of sandstones at the base of the Cretaceous, called the Henrys Fork group, is of Benton age at the top, according to the fossil evidence, but may be Dakota and older below. By the method of correlation suggested in this paper the Cretaceous portion of this group of rocks is regarded as homogenetically equivalent to the Dakota, but it may be very different in age from the Dakota of other localities.

SOUTHERN PART OF UINTA BASIN.

The coal-bearing rocks are exposed continuously from central Utah eastward through central-western Colorado to the mountains, where they are upturned in the Grand Hogback. They have been observed throughout this distance and examined in detail at several localities, as shown by the sections in figure 21.

EMERY (26).[2]

The southwestern extremity of the coal measures of the Uinta Basin is exposed near Emery, Utah, about 75 miles northwest of the Henry Mountains. The Cretaceous formations of the two localities seem to be comparable both in the order of succession and in lithologic character, as just suggested, although Lupton regards his Mesaverde as probably equivalent to Gilbert's Masuk sandstone and correlates his Ferron sandstone member of the Mancos shale with Gilbert's Blue Gate sandstone. This correlation, assuming that the formations were continuous, requires that the 500 feet of Gilbert's Masuk shale represent the 2,500 feet of shale above the Ferron sandstone, and by comparison with sections farther south it would seem to necessitate the correlation of the Ferron with the original Mesaverde. This correlation is rendered doubtful by the nature of the fossils.

WELLINGTON (27).[3]

The same formations are exposed in the Wellington and Sunnyside areas, Utah, that were found by Lupton 50 miles farther southwest. Here also few data regarding the age of the beds were found in the upper portions of the Mesaverde. It is significant that the base of the arenaceous rocks of this formation occurs progressively lower in the section toward the west. In tracing exact horizons Clark found that the base of the Mesaverde is stratigraphically about 150 feet lower in the western part of the area that he examined than in the eastern part. Here, then, is found, in an area examined in detail, the same transition laterally from shale to sandstone

[1] Gilbert, G. K., Report on the geology of the Henry Mountains: U. S. Geog. and Geol. Survey Rocky Mtn. Region, 1877.
[2] Lupton, C. T., unpublished manuscript.
[3] Clark, F. R., unpublished manuscript.

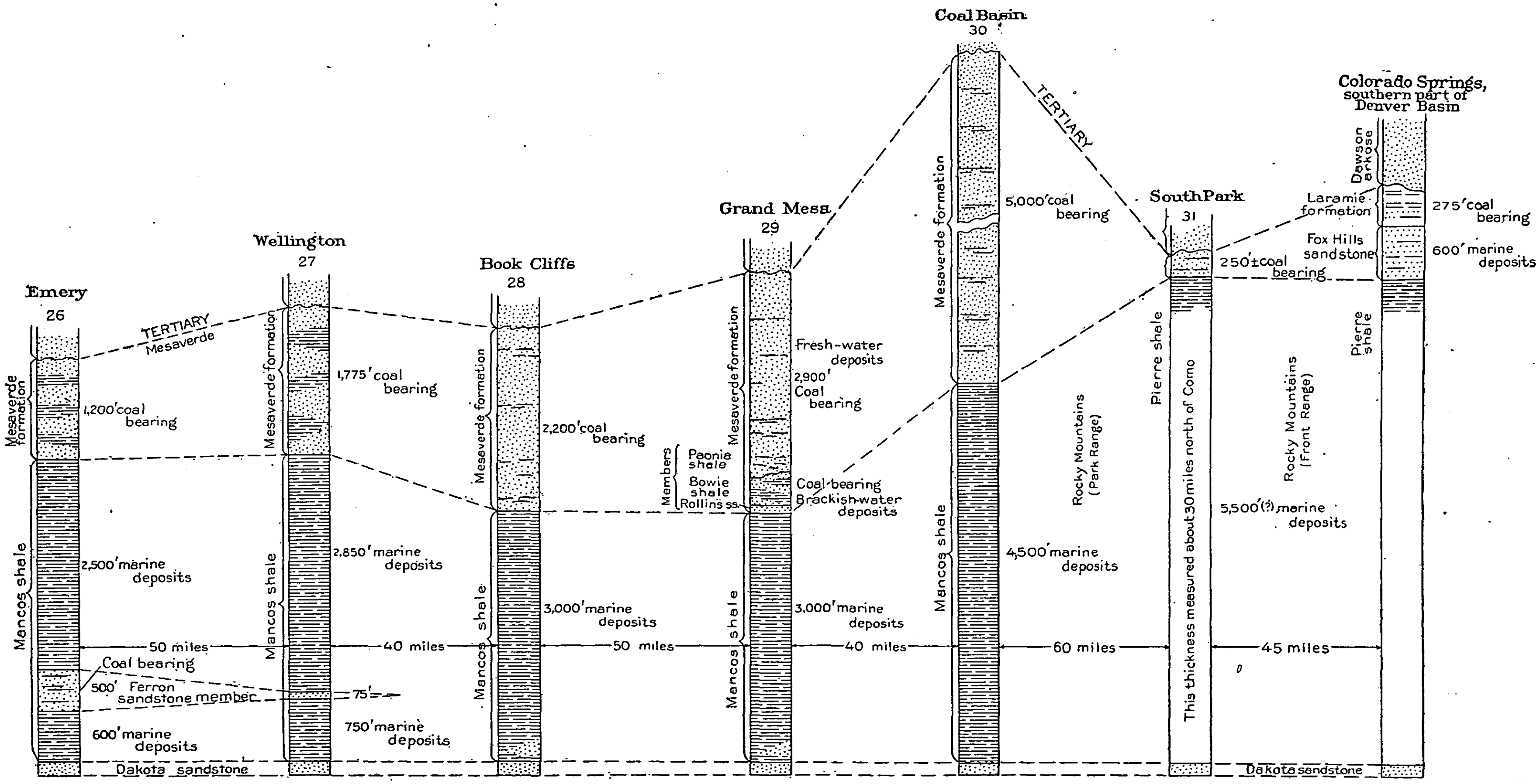


FIGURE 21.—Group of sections from Emery, Utah, along the southern border of the Uinta Basin eastward through South Park to the Denver Basin, Colo. (For location see Pl. V.) The names at the left of each section indicate correlations that have been made. The lines connecting the sections are intended to show homogenetic equivalents rather than time equivalents.

that was described for the San Juan Basin, where points of observation were far apart. The Ferron sandstone member of Lupton's section occurs in the Wellington area, but is notably thinner and seems to disappear farther east.

BOOK CLIFFS (28).[1]

The generalized section given for the Book Cliffs of Utah and western Colorado does not differ essentially from the one just described, except that Richardson makes no mention of the sandstone later named Ferron by Lupton. A well drilled 10 miles northeast of Grand Junction, Colo., indicates that the Mancos is more than 2,800 feet thick. The drill did not reach the Dakota sandstone. The sedimentary rocks between the Mancos shale and the rocks of Eocene age are all referred to the Mesaverde, with some qualifying statements, and no attempt is made to divide them into members. Some fossil plants and invertebrates were found, and dinosaur bones were obtained east of Green River, about 500 feet above the top of the Mancos shale.

GRAND MESA (29).[2]

A basal conglomerate lying unconformably on the Gunnison formation in the Grand Mesa field is referred to the Dakota because of its stratigraphic position. Certain coal-bearing rocks above this conglomerate heretofore regarded as Dakota are referred on fossil evidence to the Mancos. Above these the Mancos through an estimated thickness of 3,000 feet is principally shale. All the rocks between the Mancos shale and the base of the Tertiary are referred to the Mesaverde, although an unconformity is described as separating them into a marine and brackish-water division below and a fresh-water division above. The Mesaverde comprises a small sandstone member, the Rollins, overlain by a coal-bearing sandstone and shale member, the Bowie, both containing marine and brackish-water invertebrates; and a higher coal-bearing member, the Paonia, containing fossil plants and fresh-water shells. The Paonia member lies unconformably on the Bowie in some places and on the Rollins sandstone in other places. These members have not been differentiated in neighboring fields.

COAL BASIN (30).[3]

Beekly examined the formations in the neighborhood of Coal Basin, Colo., south of Glenwood Springs. His work consisted mainly in obtaining data for the classification of the coal lands, but his measurements of the formations were made with care. The section was measured at the Grand Hogback and is therefore at the eastern margin of the Uinta Basin. The thickness of the sedimentary formations in the Grand Hogback renders it obvious that they once extended much farther east over the area now occupied by the mountains. It seems probable that they once connected with those near Como, in South Park,[4] about 60 miles east of the Grand Hogback, where coal-bearing rocks overlie marine shale of great though unknown thickness. It seems to be a debatable question whether the coal measures of South Park shall be correlated with the Laramie to the east or with the Mesaverde to the west. From the fact that at the north end of this park, near Breckenridge,[5] about 30 miles north of Como, these marine rocks are estimated as 5,500 feet thick, it is reasonable to suppose that near Como they are comparable in thickness to the Mancos shale on the west and to the marine Cretaceous about 45 miles to the east, where they are reported as about 5,500 feet thick at Canon City (section 5, fig. 16) and more than 7,000 feet thick at Boulder (section 6).

SOUTH PARK (31) AND COLORADO SPRINGS.

Although the coal measures of the Denver Basin east of the mountains are known as Laramie and those west of the mountains as Mesaverde, the suggestion seems pertinent that could the eroded portions of the formations be restored the Mesaverde would be found to extend east-

[1] Richardson, G. B., Reconnaissance of the Book Cliffs coal field between Grand River, Colo., and Sunnyside, Utah: U. S. Geol. Survey Bull. 371, pp. 12-23, 1909.
[2] Lee, W. T., Coal fields of Grand Mesa and the West Elk Mountains, Colo.: U. S. Geol. Survey Bull. 510, pp. 18-19, 1912.
[3] Beekly, A. L., unpublished manuscript.
[4] Washburne, C. W., The South Park coal field, Colo.: U. S. Geol. Survey Bull. 381, pp. 307-316, 1910.
[5] Ransome, F. L., Geology and ore deposits of the Breckenridge district, Colo.: U. S. Geol. Survey Prof. Paper 75, p. 39, 1911.

ward and include the coal measures of South Park and the Laramie of the Denver Basin. In other words, the coal measures east and west of the mountains may be homogenetically equivalent although differing in age, just as the coal measures of the San Juan Basin seem to differ in age, although continuous from place to place. It may be equally pertinent also to inquire, first, if the Mesaverde of the Grand Hogback is the time equivalent of the original Mesaverde of the San Juan Basin; and second, if there is as great a difference in age between the Mesaverde of the Grand Hogback and the Laramie of the Denver Basin as the time significance of the names indicates.

NORTHERN PART OF UINTA BASIN AND AREA TO THE EAST.

The group of sections shown in figure 22 represents the Cretaceous formations that now extend from the Wasatch Mountains, in Utah, eastward to the Rocky Mountains and probably at one time extended eastward across the site of the Rocky Mountains. They are obscured in many places west of Axial, Colo., by the overlapping Tertiary strata, but from that point eastward to the mountains they are continuously exposed. Most of them have been eroded from the mountainous area farther east, but remnants have been preserved in the center of this area that serve to show the possible connection between the Cretaceous formations of the Uinta Basin and those of the Denver Basin.

BLACKTAIL MOUNTAIN (32).[1]

The sandstone at the base of the Cretaceous is referred with some doubt to the Dakota. Above this sandstone is a shale that is correlated with the Mowry shale member of the Benton of Wyoming. Above the shale is a coal-bearing formation that seems to correspond to the Ferron sandstone member of the Mancos shale, and this in turn is overlain by the marine shale that constitutes the main body of the Mancos. The Mesaverde is described as 3,263 feet thick and contains coal throughout the upper half. Unlike the Mesaverde of other localities, it is not coal-bearing in the lower part. The coals are described as lignitic or subbituminous like those above the unconformity within the Mesaverde of the Grand Mesa field. This suggests the question whether all the rocks here called Mesaverde constitute a single formation.

DEEP CREEK (33).[2]

Deep Creek is about 15 miles northwest of Vernal, Utah, and 70 miles east of Blacktail Mountain, described above. A sandstone at the base of the Cretaceous in this district is referred doubtfully to the Dakota, and above this sandstone occur other sandstones and shales 390 feet thick, with coal near the top, which obviously represent the lower shale and coal measures of the Blacktail Mountain field, but are notably thinner. Above this coal lies the main mass of the Mancos shale, 2,100 feet thick. The younger Cretaceous rocks have been eroded away at Deep Creek and the Wasatch formation rests unconformably on the Mancos shale. Near Vernal, however, the Mesaverde is present in normal development. Gale[3] states that it is about 1,500 feet thick at Green River and increases in thickness toward the east.

AXIAL (34).[4]

Axial is in the Yampa coal field described by Gale[5] several years ago. More recently Hancock has mapped the part of this field near Axial for folio publication. His section measured near Axial differs only in detail from that given by Gale for the whole field. The coal measures that occur near the base of the Mancos in the sections farther west are represented here by an inconspicuous sandstone that contains no coal and that disappears toward the east. The Mancos shale has an enormous thickness, and the marine conditions indicated by its fossils

[1] Lupton, C. T., The Blacktail (Tabby) Mountain coal field, Wasatch County, Utah: U. S. Geol. Survey Bull. 471, pp. 595–655, 1912.
[2] Lupton, C. T., The Deep Creek district of the Vernal coal field, Uinta County, Utah: U. S. Geol. Survey Bull. 471, pp. 579–595, 1912.
[3] Gale, H. S., Coal fields of northwestern Colorado and northeastern Utah: U. S. Geol. Survey Bull. 415, pp. 204–219, 1910.
[4] Hancock, E. T., unpublished manuscript.
[5] Gale, H. S., op. cit.

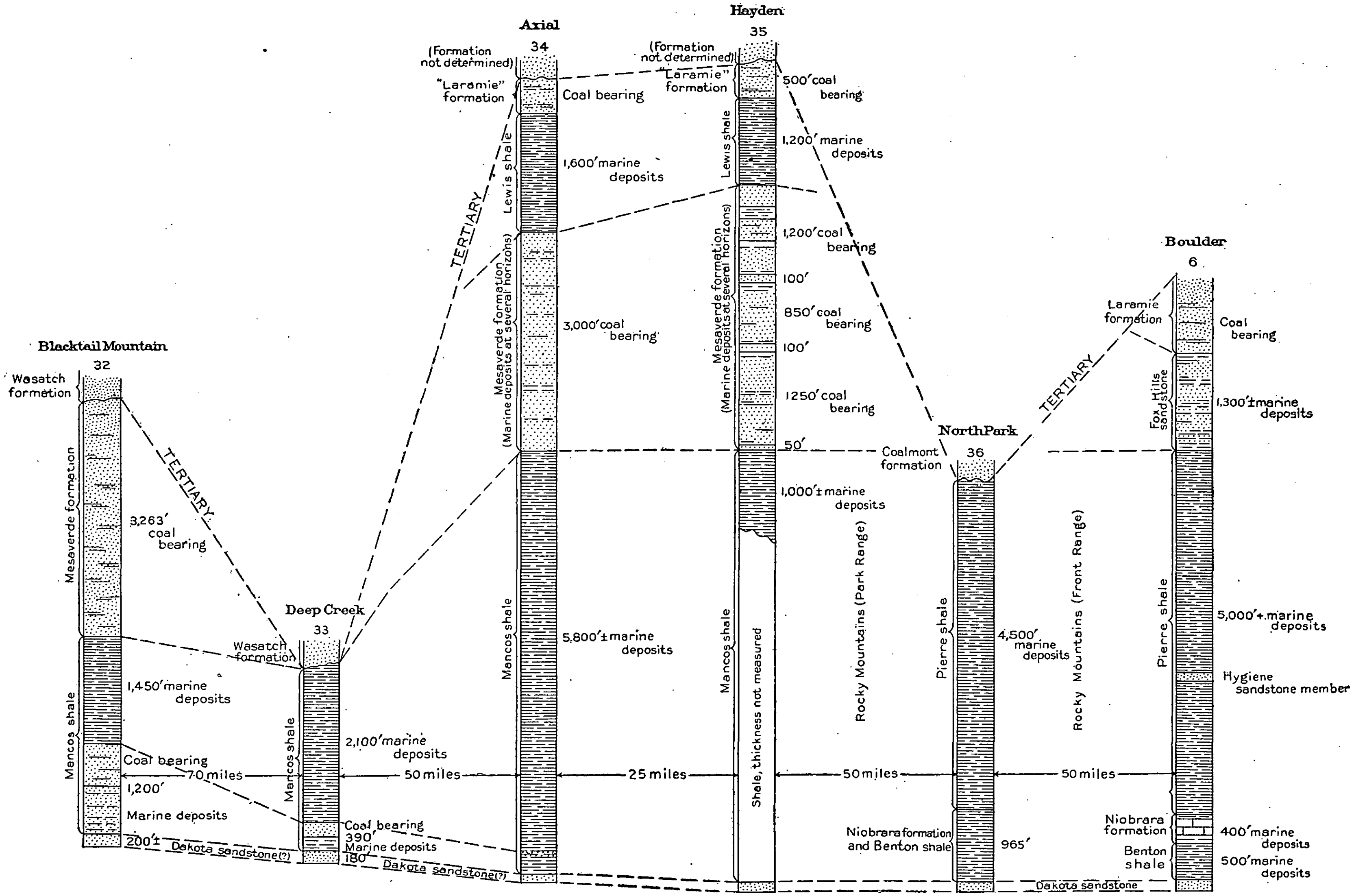


FIGURE 22.—Group of sections from the Blacktail Mountain coal field, Utah, along the northern border of the Uinta Basin eastward through North Park to Boulder, Colo. (For location, see Pl. V.) The names at the left of each section indicate correlations that have been made. Ths lines connecting the sections are intended to show homogenetic equivalents rather than time equivalents.

did not wholly cease with the beginning of the deposition of the overlying Mesaverde, which contains marine invertebrates at several horizons, the marine beds alternating with coal and its associated fresh or brackish water beds. The Mesaverde is separated from a younger coal-bearing formation by a thick marine shale which, because of its stratigraphic position, has been called the Lewis. This shale becomes sandy toward the west and in part at least merges into the "Laramie" above and into the Mesaverde below. This suggests that the enormous thickness of Mesaverde in other parts of the Yampa field—over 5,000 feet, according to Gale—may be due to the fact that the Lewis in these parts has not been distinguished because of its sandy character and that what has been called Mesaverde in that region may include equivalents of both Lewis and "Laramie."

HAYDEN (35).[1]

The section near Hayden, Colo., in T. 5 N., R. 89 W., was measured several years ago and the description was prepared for publication, but it has not yet appeared in print. The "Laramie" and Mesaverde formations were measured with considerable care because of their coal beds, which were being examined in detail, but the thickness assigned to the Lewis shale is believed to be less reliable, inasmuch as the shale occupies a broad valley and is not continuously exposed. In a reconnaissance trip through this field I received the impression that the Lewis shale thickens toward the east and that the Mesaverde becomes thinner and less sandy in the same direction, but while this impression accords with other observations in western Colorado no definite statement to that effect can now be made.

The Cretaceous formations extend eastward to Steamboat Springs, about 25 miles from Hayden, where they are upturned, the Dakota forming a prominent hogback. Thus, although the distance between the Hayden and North Park sections is about 50 miles, as shown on figure 22, the Cretaceous rocks are lacking over a mountainous area only about 25 miles wide.

NORTH PARK (36).[2]

The base of the Cretaceous in North Park consists of a sandstone that is presumably Dakota. Above this sandstone is 965 feet of shale referred on the evidence of the invertebrates to the Niobrara and Benton formations and 4,500 feet referred to the Pierre shale. The shales have the character and approximately the same thickness as the Mancos, to the west, and apparently differ but slightly from the Pierre and associated shales to the east. Unconformably overlying the Pierre shale are 4,000 to 6,000 feet of coal-bearing rocks of nonmarine origin consisting of shale, sandstone, and conglomerate, to which Beekly has given the name Coalmont formation. Although this formation is classed as "Cretaceous or Tertiary" it contains a flora said to be of Tertiary age and is correlated with the "Upper Laramie" of Veatch, which in turn is regarded by some as essentially equivalent in age to the Denver formation. These facts strengthen the assumption that the unconformity between the Pierre shale and the Coalmont formation is the same as the post-Laramie unconformity of the Denver Basin.

On the assumption that the upper part of the Mancos and the upper part of the Pierre occupy different positions in the time scale, according to current usage, there seems to be serious doubt as to whether the beds in North Park should be correlated with those east of the mountains, in which case the 4,500 feet of beds of Montana age would be Pierre, or whether they are more closely allied with those to the west, in which case all the marine Cretaceous beds of North Park would be referred to the Mancos. Whatever differences in age may be indicated by the invertebrates, it seems obvious that the Mancos is the homogenetic equivalent of the older marine Cretaceous rocks—in other words, that the Mancos of the Uinta Basin and the Pierre, Niobrara, and Benton of North Park and of the Denver Basin are parts of the same formation and were once continuous across the areas now occupied by the mountains.

[1] Davis, J. A., unpublished manuscript.

[2] Beekly, A. L., Geology and coal resources of North Park, Colo.: U. S. Geol. Survey Bull. 596, p. 20, 1915.

SUMMARY.

The sandstones at the base of the several sections of figure 22 are doubtless homogenetic but not necessarily time equivalents. The sandstones associated with the lower coal to the west lose their coal-bearing character toward the east and finally thin out altogether. Although the horizon is recognizable near Axial it has not been distinguished farther east.

The principal shale of the Mancos is relatively thin in Utah and thickens toward the east. The resemblance of the shale in North Park to the Mancos on the west and the Pierre on the east strengthens the hypothesis that no barrier existed in the Rocky Mountain region during Cretaceous time and that the Mancos and the Pierre are parts of a once continuous formation.

An inspection of the sections also suggests that the base of the Mesaverde of the Blacktail Mountain locality is older than the base of this formation as developed farther east and that this formation may be the homogenetic equivalent of the Fox Hills of the Boulder region, although the latter has generally been regarded as much younger than the Mesaverde.

The Lewis shale is well defined in some places, but toward the west it seems to become arenaceous and coal bearing and to merge into the Mesaverde below and the "Laramie" above. This fact, considered in connection with the occurrence of marine invertebrates at several horizons in the Mesaverde of the Uinta Basin, suggests that the Lewis shale of this basin may not be as definitely separable from the Mesaverde as some have supposed and that the Mesaverde, Lewis, and "Laramie" together of this basin may be comparable with the Fox Hills and Laramie of the Denver Basin. At first glance it seems difficult to reconcile this hypothesis with the great differences in thickness of the formations in the Uinta Basin and in the Denver Basin. But if the sediments came mainly from the lands to the west arenaceous beds should be thick in the western fields and should thin eastward. This difference seems to be even more conspicuously shown in the Cretaceous beds of southern Wyoming, north of the areas discussed in this paper.

The youngest coal-bearing rocks of Cretaceous age in this region occur on either side of the mountains at localities less than 100 miles apart, and there is good reason for believing that they were originally deposited in North Park. Remnants of them occur farther north, so distributed as to indicate that they originally occupied a relatively small area which may represent, so far as the region here described is concerned, the last part of the Cretaceous basin to be filled.

GENERAL CONCLUSIONS.

No claim is made that the views expressed in this paper are final. Many of them will doubtless be modified when more detailed work is done in the several areas described, but it is believed that they are worthy of consideration as field work is continued. Little is known of some of the sections discussed, while others have been examined carefully, but all are believed to be sufficiently accurate to show the broad general relations of the Cretaceous formations. The points to which especial attention is directed are as follows:

1. It seems evident that no notable crustal movement affected the southern Rocky Mountain region for a long period prior to the beginning of Upper Cretaceous time, and there was ample time for the peneplanation of this region before the invasion of the Cretaceous sea.

2. The distribution of the Dakota sandstone about the present mountains, its attitude toward them, its presence upon them and within them at great altitudes, and its relation to the older formations all indicate that the Dakota originally extended continuously over the area now occupied by the Rocky Mountains.

3. There are good reasons for believing that the marine Cretaceous formations overlying the Dakota also extended uninterruptedly over the areas now occupied by the Rocky Mountains. If islands persisted there throughout the Cretaceous period, their location is now not known. Among these reasons may be mentioned (*a*) the absence of conglomeratic or arkosic material in these formations near the mountains, (*b*) the fact that the marine formations are comparable in thickness and character on either side of the mountains as well as within them but do not in the mountain region contain intercalated beds of fresh-water origin, as they do farther west,

and (*c*) the fact that the marine shales in western New Mexico and Colorado thicken toward the present mountains while the sandstones thin in the same direction.

4. The several so-called basins containing Cretaceous rocks all seem to be of post-Cretaceous origin. Little evidence has been brought forward to show that they were separate basins of deposition during Cretaceous time. The physical evidence thus far produced seems to favor the hypothesis that the interior Cretaceous sea occupied a single basin extending from Utah and Arizona eastward over the present site of the Rocky Mountains. Certain paleontologic evidence, however, seems to oppose this hypothesis.

5. When rocks at two or more localities are correlated and designated by the same name, there may be no intention of implying that they are exact time equivalents, but that is the impression usually conveyed to the reader. There seems to be need of some definite term to express the fact that rocks at two or more localities may be equivalent in lithology and appear to hold the same stratigraphic position and even to contain essentially the same fossils and yet differ in age. Until a better term is proposed this relation may be expressed as "homogenetic." For example, the Mesaverde, a sandy, coal-bearing formation, known to be of Montana age in its type locality, seems to thicken downward at the expense of the underlying shale and has been described as continuous with coal-bearing rocks near Gallup, N. Mex., that contain fossils indicative of Colorado age. These rocks near Gallup are homogenetically equivalent to the Mesaverde. To follow this conception still further and apply it to beds that can not be traced through intervening areas, this term still seems useful, inasmuch as there may be less uncertainty in homogenetic correlation than in paleontologic correlation, especially where there is conflict of opinion arising from different classes of fossils. For example, there seems to be little doubt that the Vermejo formation of the Raton coal field is the homogenetic equivalent of the Mesaverde of the Cerrillos field (section 3), to the south, and of the Vermejo of the Canon City field (section 5), to the north; and yet some of the paleontologic evidence indicates that the Vermejo at Canon City is of late Montana age, while the Mesaverde at Cerrillos is early Montana.

6. The conceptions herein presented have an intimate bearing on the problem of the Cretaceous-Tertiary boundary in the Rocky Mountain region. Certain conglomerates that rest unconformably on Cretaceous beds are regarded as basal Tertiary by some geologists and as Cretaceous by others. These conglomerates contain great numbers of pebbles of crystalline and metamorphic rocks such as are now found in the mountains, and they are so distributed as to prove that they were derived from the present mountainous areas. Inasmuch as the Cretaceous formations were originally continuous over the site of these mountains, it follows that there must have been uplift and erosion sufficient to remove them and to reach the pre-Cretaceous rocks before the materials for the conglomerates could be obtained. In the Rocky Mountain region of Colorado and New Mexico all deposits above these conglomerates are of the nonmarine type that characterizes the undisputed Tertiary formations of the same regions. Such a measure of this unconformity has been severely criticised. Whether or not the post-Cretaceous erosion removed 20,000 or 14,000 feet of sediments, less or more, the uplift was obviously sufficient to cause the streams to cut through whatever Cretaceous formations were deposited over the areas now occupied by the mountains and enough more of the formations that underlie the Cretaceous to obtain the large quantities of coarse material now found in the lower part of the Tertiary.

Briefly stated, it is conceived that the interior Cretaceous basin was formed by the slow and somewhat intermittent downward warping of a nearly base-leveled surface, probably accompanied by a rise of sea level. This subsiding area, reaching from the Gulf of Mexico to the Arctic Ocean and from Utah to the Mississippi, is so large that the subsidence may be better called an epeirogenic movement rather than a downward warping, a term usually applied to smaller areas. The rate of sedimentation in this basin was comparable with the rate of subsidence. The sediments and the fossils they contain are of such a nature as to render it improbable that the sea was at any time very deep. It was probably for the most part so shallow that the sediments were somewhat uniformly distributed over its floor by waves and currents. The long period of quiescence was terminated and a new period of very different character was begun by an orogenic movement that resuscitated the mountains which had been worn down and whose roots had been buried beneath the Cretaceous strata. This movement was followed at short intervals by other similar movements, which produced the present highlands of the Rocky Mountain region and which also introduced the long series of volcanic events that characterized the Tertiary period in western America. As nearly as can now be determined, this movement corresponds in time with movements in other parts of the world which are universally recognized as terminating the Cretaceous period and introducing the Tertiary. It naturally follows that the conglomerates and other sediments derived by erosion from the newly uplifted mountains—such as those of the Denver, Arapahoe, Dawson, Raton, and related formations—belong to the Tertiary system.

AN ANCIENT VOLCANIC ERUPTION IN THE UPPER YUKON BASIN.

By Stephen R. Capps.

It has long been known that a large area in Alaska and Yukon Territory is covered by a layer of volcanic ash. The ash lies near the surface, beneath a thin covering of soil or silt, and gives evidence of an explosive volcanic eruption that in terms of geologic history is very recent, though antedating historic record in this part of the world. The first published description of this material is that given by Schwatka,[1] who observed the ash layer along the banks of Lewes River and its headward tributaries in 1883. In 1887 Dawson [2] extended the known area of the ash and estimated its total area, the direction from which it came, and the approximate length of time since it was deposited. In 1891 Hayes,[3] in company with Schwatka, conducted an exploration from Fort Selkirk, on the Yukon, to the Copper River basin. They traveled westward into an area in which the ash gradually increased in thickness to its maximum near the international boundary and rapidly thinned west of that line. In 1898 and 1899 Brooks [4] explored the headwaters of White and Tanana basins and made many observations on the areal distribution and thickness of the ash. The present article is based largely upon information personally obtained or collected by Mr. Brooks. The writer first became interested in this occurrence in 1908, when working in the Nabesna and White River district,[5] and a second expedition into the same general region in 1914 gave opportunity for a more extended study of the ash fall. Records of the outer limits of the ash-covered area have been taken from many sources, especially from the published and unpublished notes of the members of the Geological Survey of Canada and of the United States Geological Survey.

The general outlines of the ash fall are shown on figure 23, the relative thickness of the deposit being indicated by contours. The outer limits of the area are drawn to include all points at which the ash has been observed and at which it is still recognizable as a distinct layer. Without question a thin film of dust could at the time of the eruption have been observed over an enormously greater area than that here outlined, but, as will be shown, the ejection of the ash antedates recorded history in America, and the area affected can now be determined only by the presence of the ash that has been preserved. Less than one-fourth inch of ash falling at the time of this eruption over a vegetation-covered upland would probably be insufficient to form a layer that would now be generally recognizable.

The outermost observations recorded include, on the west, observations on Nabesna, Tanana, and Yukon rivers, by Brooks and others; on the northeast and east, on Gravel, Macmillan, and Pelly rivers, by Keele, Dawson, and McConnell; on the southeast, on Teslin River and at Lakes Marsh and Bennett, by Schwatka, Dawson, and others; and on the south and southwest, along the southeast flank of the St. Elias Range, by Hayes, Brooks, and the writer.

The ash usually appears along the cut banks of the rivers as a thin white band near the top of the bank, covered by only a few inches or a foot or two of soil, silt, or vegetable humus. It is remarkably persistent and is in places continuously exposed for miles. Over any given

[1] Schwatka, Frederick, Along Alaska's great river, Cassell & Co., New York, 1885.

[2] Dawson, G. M., Report on an exploration in the Yukon District, Northwest Territory, and adjacent northern portion of British Columbia: Canada Geol. and Nat. Hist. Survey Ann. Rept., vol. 3, pt. 1, pp. 43 B–46 B, 1889.

[3] Hayes, C. W., An expedition through the Yukon district: Nat. Geog. Mag., vol. 4, pp. 146–150, 1892.

[4] Brooks, A. H., A reconnaissance in the White and Tanana river basins, Alaska, in 1898: U. S. Geol. Survey Twentieth Ann. Rept., pt. 7, p. 475, 1900.

[5] Moffit, F. H., and Knopf, Adolph, Mineral resources of the Nabesna-White River district, Alaska, with a section on the Quaternary by S. R. Capps: U. S. Geol. Survey Bull. 417, pp. 42–44, 1900.

district of small area the ash tends to be rather uniform in thickness, although locally it thickens into lenses or thins out entirely. It occurs prevailingly in a single layer, was apparently ejected during one period of eruption, and fell as one continuous shower in which there were no time breaks of sufficient length to interrupt the vertical continuity of the deposit. At a few localities two or more ash beds, one above the other, separated by beds of soil or silt, have been observed, but the sporadic nature of these occurrences and the great preponderance of areas with but a single layer indicate that where two or more superposed layers occur the upper layers are composed of ash derived by erosion from the lowest one and deposited later by wind or by streams. The evidence, therefore, is strongly in favor of but a single period of eruption.

The ash bears a close relation to the present topography, occurring not only over the valley floors of the present stream basins but also over the intervening hills and ridges. Shallow excavations on hillsides and in valleys everywhere reveal its presence. Burrowing animals,

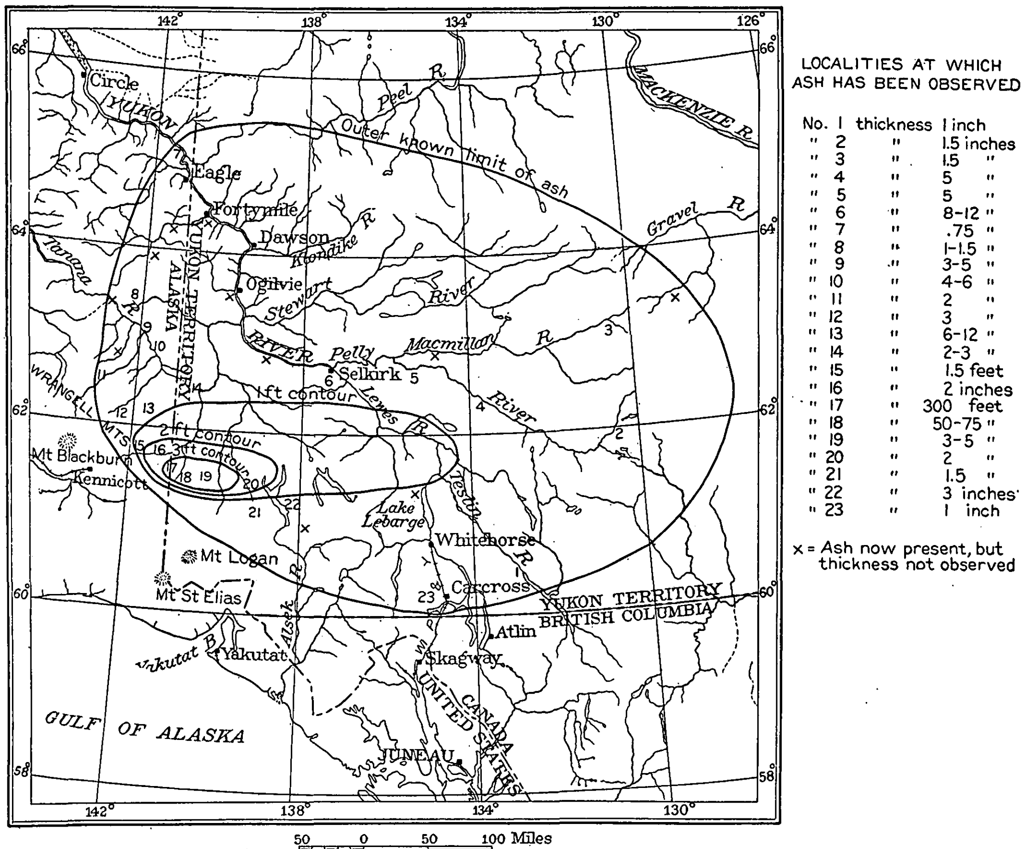
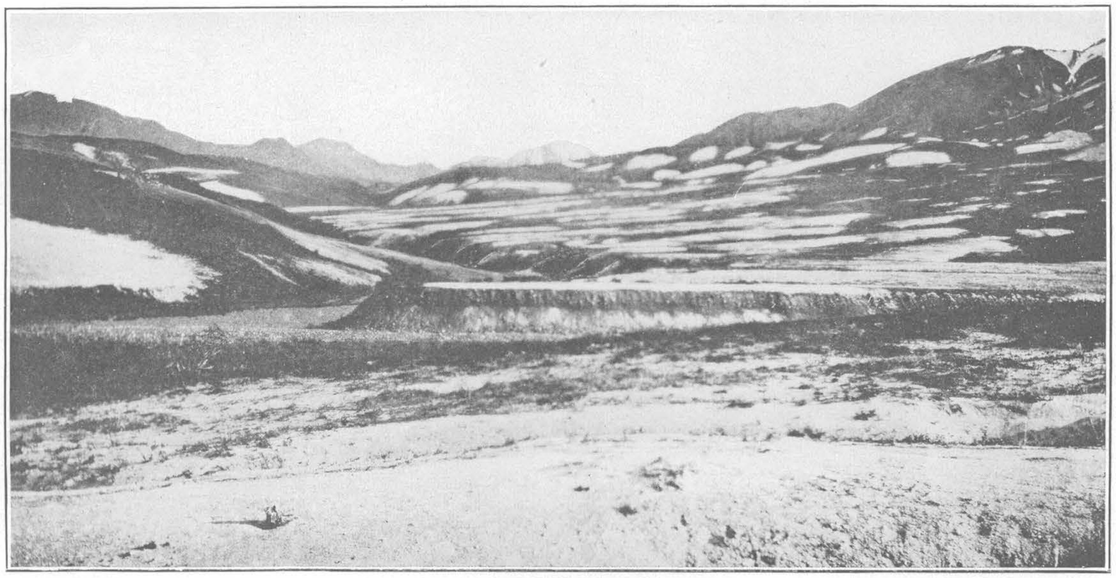


FIGURE 23.—Map of upper Yukon basin, Alaska and Yukon Territory, showing distribution of volcanic ash.

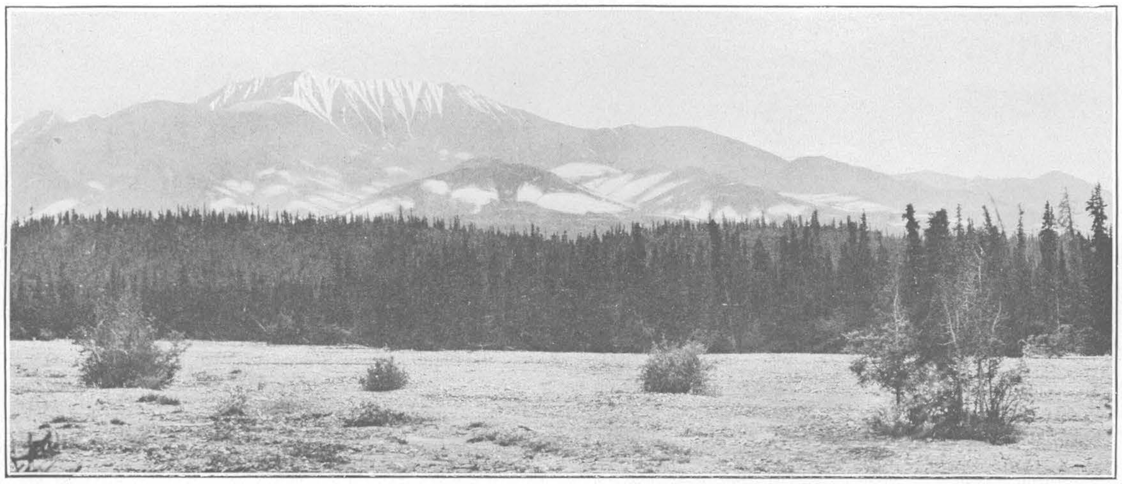
especially the spermophiles, or striped gophers, avail themselves of the ease with which the ash can be excavated, and their mounds are in many places composed almost entirely of this material. Furthermore, the low terraces of streams, covered with an ash layer, show that the material fell at a very late stage in the development of the present stream gravels. The ash overlies all but the most recent stream deposits and is much younger than the glacial materials deposited during the last great period of glaciation.

The thickness of the ash increases gradually, but by no means symmetrically, from the edges toward the center of the area covered. The great highway through this part of Yukon Territory and Alaska by way of the White Pass & Yukon route to the navigable waters of the Yukon basin follows directly across the ash-covered area, from southeast to northwest. Along this route the ash is particularly well exposed in the river banks. It first appears near Lake Bennett as a layer an inch or less in thickness, but increases to a maximum of about 1



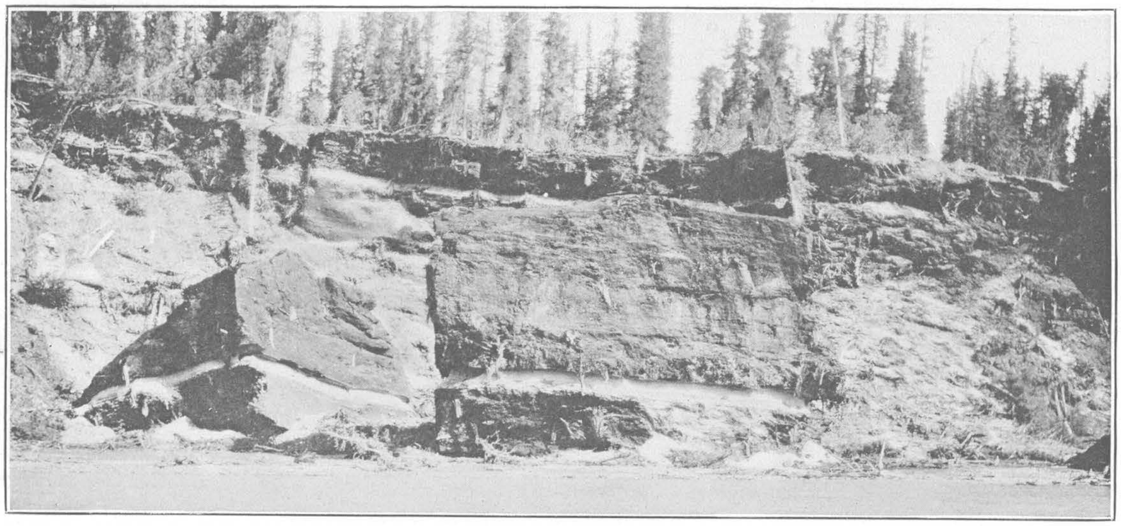
A. AN ASH-COVERED LANDSCAPE, UPPER KLETSAN CREEK, NORTHERN FOOTHILLS OF MOUNT NATAZHAT, ALASKA.

White deposit is ash except on high summits, which are covered with snow. Photograph by United States Coast and Geodetic Survey.



B. ASH DRIFT ON NORTHERN FOOTHILLS OF ST. ELIAS RANGE, ALASKA, NEAR INTERNATIONAL BOUNDARY.

Snow on high summits.



C. PEAT BLUFF, WITH VOLCANIC ASH LAYER, ON WHITE RIVER, ALASKA.

Overturned peat blocks in foreground.

foot toward the northwest in a portion of the Teslin and Lewes river basins. Below Fort Selkirk it thins gradually northwestward, and beyond Eagle it is only an inch or less in thickness. Dawson [1] early recognized that the ash thickens from the Pelly westward toward the Lewes and must have come from the west. He suggests that it may have been derived from a volcano of the Mount Wrangell group. Hayes,[2] however, who crossed from Fort Selkirk to the head of White River in 1891, observed the increasing thickness of the ash to an area between Klutlan Glacier and Kletsan Creek, on the north flank of the St. Elias Range, and a rapid decrease in thickness west of that area. Brooks [3] confirmed Hayes's observations in 1899. It was thus proved definitely that the material was not derived from the volcanoes of the Mount Wrangell group, but from some source much farther east. By a plotting of the observations obtained from all sources the data shown on figure 23 as to distribution and thickness of the ash were obtained. Within the area outlined by the 3-foot contour the ash occurs locally in great thickness. Hayes noted beds between 75 and 100 feet thick on the western bank of the Klutlan, where there is no reason to suppose that the original thickness had been increased at the expense of surrounding regions, except, perhaps, by wind drift. Near the head of Kletsan Creek, on both sides of the international boundary, there is an area 2 to 4 miles wide, along the mountain flank, in which the entire surface is covered with great white banks and dunes of ash (Pl. VI, *A*). The area is for the most part above timber line, vegetation on its surface is sparse or lacking, and from a little distance one receives the impression that he is looking over great banks of snow (Pl. VI, *B*). The surface of this area is dotted with lakelets, the ash shifts with the winds, and the hills are modified dunes. The presence of ground frost close to the surface, however, retards to some extent the movement of the ash by winds. The belt of thick ash has a relief of 200 to 400 feet, which is believed to be largely in the ash, as exposures of the underlying rocks are almost completely lacking.

It is quite evident from the great thickness of the ash along the south flank of the St. Elias Mountains near the international boundary that the vent from which it was ejected is in that neighborhood. Thomas Riggs, jr., while engaged in surveying the international boundary line, noticed a small crater in a glacial cirque 4 miles north-northeast of Mount Natazhat, from which he thinks it probable that the ash was ejected. The writer, in 1914, attempted to visit this crater, but a heavy snowfall early in July and a shortage of provisions prevented waiting until the snow should melt sufficiently to allow an inspection of the reported crater. All the evidence so far obtained, however, both as to the areal distribution of the ash and as to its thickness, points to some crater near the northern border of the St. Elias Mountains near the international boundary as the vent from which the ash came, and it is not improbable that the locality suggested by Riggs is the true one.

The distribution of the ash from its center of dispersion indicates that the winds at the time of the eruption blew from the west and south. The long east-west axis of the ash-covered area and particularly that of the area of ash 1 foot or more thick shows that the wind at the time of the greatest ash fall blew almost directly from west to east. The great breadth of the area in the north-south direction near its western margin also points to a shifting of the wind to the south, probably during the later stages of the eruption, for although ash was carried northward a distance of 300 miles from the crater, the 1-foot contour extends northward less than 50 miles from the center, whereas it reaches eastward a distance of at least 220 miles. The greatest distance from the center at which the ash layer has been recognized is on the eastern slope of the Mackenzie-Yukon Divide, in the basin of Gravel River, where J. Keele [4] reports it, 450 miles from the center of dispersion. The southern limits of the ash area in the vicinity of the crater are not known, for they lie in an unexplored and almost inaccessible field of glaciers and rugged mountains. In figure 23, therefore, the southern margin is extended little beyond the area of thickest ash, though the ash may have fallen considerably farther south.

Estimates of the area covered by this ash deposit have been made from time to time, based on the facts as to distribution then available. The first of these estimates was made by Dawson,

[1] Op. cit., p. 44 B. [2] Op. cit., p. 148. [3] Brooks, A. H., unpublished notes. [4] Letter to A. H. Brooks.

in 1887. Although stating that the total area must necessarily be much greater than the area of his observations, he estimated a minimum area of 25,000 square miles covered by ash. Hayes, in 1891, with additional information at his disposal, increased the estimate to 52,280 square miles. Brooks, in 1906, after having extended the known distribution westward to longitude 143° W. and northward to the Yukon below Eagle, placed his estimate at about 90,000 square miles. By using some additional data, in particular Keele's observation of the ash in the basin of Gravel River, the writer has mapped (fig. 23) an area of 140,000 square miles covered by a layer of ash. It is well known that in volcanic eruptions of this kind, with extensive ejections of pumice, the dust remains in the air for a long time, and a film of ash, too thin to be observable after the lapse of centuries, is deposited over large areas of the earth's surface. No doubt if the facts were known, the area over which a visible layer of volcanic dust was deposited after this eruption would be measured as several hundred thousand or perhaps several millions of square miles.

Two estimates of the volume of ash ejected have been published. Dawson, assuming an area of 25,000 square miles and an average depth of ash of 3 inches, estimated that the ash would form a prism 1 mile square and 6,240 feet high. Hayes, taking an area of 52,280 square miles, assumed that the ash had the shape of a flat cone of that base, and an apex 50 feet in height. His estimate gave a volume of 165 cubic miles, over 138 times the figure reached by Dawson. It is obvious that this estimate is not based on defensible grounds, for the ash is not in the form of a cone, but if deposited on a level area its surface slopes would be decidedly concave. The distance from the head of Kletsan Creek north to White River is only about 12 miles, yet in that distance the ash decreases in thickness from 200 feet or more to less than 3 feet. According to Hayes's assumption, the ash should be 25 feet thick at distances of 110 to 185 miles from the center of dispersion. Observations over the area affected are still far too few to afford a basis on which accurate estimates of the amount of ash discharged can be made, but a provisional estimate, from the data now at hand, is given here. In making this estimate it has been assumed that in the outer zone, beyond the 1-foot ash contour, the ash averages 2 inches in thickness. This assumption seems reasonable, for over a large area of the outer zone average thicknesses of 5 to 6 inches have been observed, and even near the outermost margins a thickness of 1 to 1½ inches is common. Between the 1 and 2 foot contours an average thickness of 15 inches is assumed, and between the 2 and 3 foot contours a thickness of 27 inches. The average thickness in the inner zone, with 3 feet or more of ash, is placed at 10 feet, although it is known that several hundred square miles is covered to depths of 25 to perhaps 300 feet or more with ash. The amount of ash derived by a calculation from the above figures gives a total volume of about 10 cubic miles. This figure is nearly eight and a half times that obtained by Dawson but only 6 per cent of that obtained by Hayes. The true figure is probably considerably more than 10 cubic miles, for no account has been taken of the great quantity of ash that fell as a thin film of dust far beyond the boundaries here shown.

The violence of the eruption at the time this ash was ejected may well be inferred by comparison with volcanic eruptions of historic times. Martin [1] has collected statistics on a number of such eruptions, and the figures used below are taken from his paper. The most violent volcanic eruption of historic record was that of Tomboro, on the island of Sumbawa, east of Java, in 1815. Estimates of the volume of material ejected reach figures of 26.6 to 50 cubic miles, and the area over which the ash fell was probably much greater than during the eruption here discussed. Krakatoa, in 1883, is said to have ejected an amount of ash about equal to that thrown out by Katmai, in June, 1912, or about 5 cubic miles. From the Katmai eruption the ash fall was perceptible at a distance of 1,200 to 1,500 miles. The greatest distance from the probable center of eruption in the White River basin to the margin of the ash fall, as now known, is only 450 miles, but it seems probable that if observations had been made at the time of the eruption, the distance would have been at least equal to that at which the Katmai ash was recognized. From the depth of the ash from the White River volcano at its thickest

[1] Martin, G. C., The recent eruption of Katmai Volcano, in Alaska: Nat. Geog. Mag., vol. 24, No. 2, 1913.

development, the area covered by it, and the enormous volume of material ejected, it is evident that the eruption was comparable in magnitude to any that have occurred during historic times. Unfortunately no facts are available, or are likely to be, as to the duration of the eruption, the violence of the detonations and the accompanying earthquakes, and the intensity and duration of the ash fall, which must have darkened the sun for days.

The physical and petrographic character of the ash at a number of places has been described by others, and no special study has been made by the writer. As was to be expected, the ash or pumice is coarsest near the center of eruption and becomes progressively finer as the distance from the center increases. Within the area of thickest ash the particles average perhaps from 1 to 3 millimeters in diameter, though larger pieces are numerous, and single fragments 8 or 10 centimeters in longest diameter were seen. Near the outer limits of the ash-covered area the material consists only of very fine dust. A sample collected by J. Keele from the basin of Gravel River, about 420 miles from the center of eruption, was subjected to a screening test and also measured under the microscope. The ordinary wire screens of 60, 80, 100, and 200 meshes to the inch were used, and the results are shown below, these sizes being reduced to millimeters:

Caught on 0.423-millimeter screen	per cent..	7.72
Caught on 0.317-millimeter screen	do....	2.46
Caught on 0.254-millimeter screen	do....	4.78
Caught on 0.127-millimeter screen	do....	11.28
Passed through 0.127-millimeter screen	do....	72.94

The material caught on the two coarsest screens contained a large proportion of vegetable matter and sand particles. As examined microscopically the largest particle of ash seen had a diameter of 0.25 millimeter; the smallest 0.002 millimeter; the average size appeared to be about 0.01 millimeter.

Dawson describes the ash from the Pelly and Lewes basins as—

a fine white sandy material, with a harsh feeling when rubbed between the fingers. Microscopically it is found to consist chiefly of volcanic glass, part being merely frothy and pumaceous, but of which the greater portion has been drawn out into elongated shreds, frequently resembling the substance known as Pele's hair, and in which the inclosed vesicles become more or less completely tubular. In addition to this glass, fragments and small perfect crystals of sanadine feldspar occur, together with portions of minute crystals of hornblende and probably other minerals.

Knopf,[1] who studied the coarser material from the White River basin in Alaska, gives the following description:

The "ash" is a white frothy glass, light enough to float on water. The larger fragments of the pumice inclose numerous small hexagonal plates of biotite, short prisms of hornblende a millimeter in length, and less conspicuous crystals of glassy feldspar. In thin section the hornblendes, which are deeply pleochroic in tones of brown, show ideally perfect cross sections and terminated prisms; the biotites are also finely developed and hold some inclusions of apatite. The feldspars are less perfectly crystallized. Both unstriated and lamellated varieties are present, but all possess indices notably higher than balsam. Zonal banding is not uncommon. Optical tests on striated Carlsbad twins prove that the feldspars belong to a species somewhat more calcic than Al_1An_1. They inclose some minute foils of biotite. Grains of magnetite occur sporadically. The matrix holding these phenocrysts is a pumaceous glass, clear and colorless, with a marked drawn-out, twisted, and fluidal appearance. Some of the phenocrysts show that they were broken by the movements of the surrounding glass. According to the microscopical determination the ash is an andesitic pumice.

So far as is known, the ejection of the ash was unaccompanied by the outflow of lavas. No volcanic bombs or pyroclastic materials other than the ash have been noted, and it is probable that the outburst consisted solely of violent explosions which carried the ash outward but failed to yield other types of volcanic material.

All who have written of the volcanic ash in this district have recognized the fact that the eruption must have happened no great number of centuries ago. Dawson observed that as the rivers have not cut their beds perceptibly deeper since the deposit was laid down on their flood plains, the period to which the ash belongs can not be exceedingly remote. He also noted that at one place on the Lewes the ash rests upon a layer of stratified sands a few feet thick, and the

[1] Moffit, F. H., and Knopf, Adolph, op. cit., pp. 43-44.

sands overlie a mass of drift logs still quite sound and undecayed. From these and other facts Dawson believes that the date of the eruption, though at least several hundred years ago, can scarcely be more than a thousand years ago. Hayes arrives at a similar conclusion, but from different facts. He believes that the freedom of large ash areas from tundra moss, which covers with great readiness even the most barren surfaces, indicates the youth of the ash. He states that although great quantities of ash must have fallen on the surface of Klutlan Glacier and its névé fields, the fact that nearly all the ash now found there is in the terminal moraines, that on the stagnant ice extending only a short distance back from its front, indicates that since the eruption the ice which then formed the névé has moved the entire length of the glacier and deposited its ash in the terminal moraine. This he thinks must have required at least several hundred years. He also notes a retreat of the glacier front of about 3 miles since the ash fell.

During the summer of 1914 the writer made observations in White River basin that afford an opportunity for a more accurate calculation of the time that has elapsed since the ash fell. On White River, about 25 miles northwest of the supposed center of eruption, an excellent exposure shows a deposit of 39 feet of peaty vegetable material, interrupted 7 feet below its top by a 2-foot layer of ash (Pl. VI, *C*). The peculiar appearance of the roots of spruce trees growing on the surface of the peat suggested the possibility of determining the rate of peat accumulation at that place. The ordinary spruce tree of this region has a flat root base and sends its roots out radially, parallel with the surface. The roots penetrate only a few inches below the surface of the ground. In the locality just mentioned, however, each spruce tree has a central stem root, some of them several feet long, from which roots branch off at irregular intervals, including an upper set of roots near the surface, corresponding to those of the normal tree. The lower roots are in permanently frozen ground, and only the upper ones are functioning. It therefore seems evident that the trees as they grew were surrounded by a constantly thickening layer of vegetable material. In this material the level of ground frost rose as the deposit increased in thickness, the lower roots of the trees became permanently frozen, and the trees were forced to throw off adventitious roots near the surface repeatedly, in their efforts to survive. This study, details of which have been published elsewhere,[1] showed that dividing the age of a living tree, as indicated by the annual rings, by the thickness of the peaty deposit above the lowest roots gives a rate of accumulation of the peat of about 200 years to the foot. On that basis the volcanic eruption that caused the ejection of the widespread sheet of volcanic ash in the upper Yukon basin took place approximately 1,400 years ago.

Although perhaps the most recent volcanic eruption within the Yukon basin, the White River eruption offers by no means the only evidence of comparatively recent volcanic activity in that district, where lavas that were poured out subsequent to an earlier stage of Pleistocene glaciation are extensively developed. On the east branch of Dennison Fork of Fortymile River a volcanic crater, with associated lava flows, is so young that it still retains much of its original topographic form, and Quaternary lavas have been recognized elsewhere.

[1] Capps, S. R.: An estimate of the age of the last great glaciation in Alaska: Washington Acad. Sci. Jour., vol. 5, pp. 108-114, 1915.

EVAPORATION OF POTASH BRINES.

By W. B. Hicks.

INTRODUCTION.

It has long been known that many American brines, including ocean water, contain potassium along with much larger quantities of other salts, and during the last few years investigations have shown that brines from several different localities in the United States contain a high percentage of potassium. The development of an economic process for the extraction of potassium from these brines is a problem of great importance. The most practical methods so far proposed depend on evaporation and fractional crystallization. These facts suggest the desirability of knowing just what effect evaporation will have on the various constituents of a brine. Much is already known about the subject in a general way, and it is possible to predict certain qualitative relations concerning such simple salt solutions as those of sodium and potassium chlorides and also concerning solutions in general whenever the solid phases are known. Theoretically a saturated solution of sodium chloride containing a small amount of potassium chloride will deposit on evaporation only sodium chloride until the solution becomes saturated with respect to both salts; and a saturated solution of potassium chloride containing a small amount of sodium chloride will likewise deposit potassium chloride alone until equilibrium is reached. At 30° C. the saturated mixture [1] of these two salts contains 11.7 per cent of potassium chloride and 19.7 per cent of sodium chloride. On further evaporation at this temperature no change takes place in the composition of the solution, both salts being deposited in such quantities that the potassium-sodium ratios in both liquid and solid phases remain constant. Other instances of such simple relations could be given. Usually, however, solutions of two or more salts present much more complicated relations. The number of different ions present and the possible formation of other compounds, hydrates, and isomorphous mixtures are the chief factors influencing the complexity of the system. Consequently it is difficult to predict what changes will result through the evaporation of solutions containing several different ions. Furthermore, experiments with even the simplest systems do not yield the results that might be expected from a theoretical consideration. Precipitates often carry down mechanically or otherwise appreciable quantities of other salts, supersaturation may easily occur, and equilibrium is often slow in reaching its final adjustment. These are all factors of practical importance.

Experimental results relative to the changes which take place during evaporation, particularly with reference to potassium salts, are rather meager. In his evaporation studies on sea water Usiglio [2] found that the potassium in solution increased as evaporation proceeded, and the results of his experiments indicate in a general way what happens when sea water evaporates. However, in those early days the determination of potassium, and perhaps other constituents, was not capable of the refinement exacted in modern times. Usiglio found that the saline residue from sea water contained 0.71 per cent of potassium, while according to modern analyses [3] the figure is about 1.1 per cent. Accordingly, it is assumed that Usiglio's determinations of potassium in the products of evaporation may have been likewise erroneous. Hence, it is not possible to calculate with any degree of assurance the amount of potassium which was lost by deposition from solution during evaporation. However, it appears that in

[1] Precht and Wittjen, Deutsch. chem. Gesell. Ber., vol. 14, p. 1667, 1881.
[2] Annales chim. phys., 3d ser., vol. 27, pp. 92, 172, 1849.
[3] Clarke, F. W., The data of geochemistry, 2d ed.: U. S. Geol. Survey Bull. 491, p. 113, 1911.

concentrating the brine from 5 liters to about 100 cubic centimeters approximately 8 per cent of the potassium originally present was lost from solution. In the final mother liquor 3.31 per cent of the total salts was potassium, a condition which indicates that the potassium had still not saturated the solution, as the total salts of several sea water bitterns from the vicinity of San Francisco are reported [1] to contain 5 to 10 per cent of potassium.

Chatard [2] evaporated large quantities of the water of Owens Lake, Cal., which, after being reduced to the point of crystallization contained about 0.8 per cent of potassium. The experiments were carried out at the normal temperature in the vicinity of Owens Lake. A series of crops of crystals were obtained, each of which contained about 1 per cent of potassium chloride. Unfortunately the weights of the salts and the mother liquors in each experiment are not reported, and consequently the relations can not be followed in detail. Another important factor, the analysis of the final mother liquor, is also lacking. However, it is probable that the solution did not become saturated with salts of potassium because each crop of crystals contained approximately the same percentage of this constituent. This conclusion is strengthened by similar results of the evaporation studies on the water of Mono Lake, Cal.[2] In the experiments at Mono Lake the final mother liquor was evaporated to dryness and the residue was analyzed. The potassium-sodium ratio in this product was 0.27, which is very strong evidence that the final mother liquor was not saturated with salts of potassium, experiments recorded elsewhere in the present paper having shown that in solutions very similar to that in Owens Lake the potassium-sodium ratio may become as high as 0.59. According to Chatard's results, about 15 per cent of the potassium originally present was lost in the evaporation water of Owens Lake long before the bittern became saturated with potash salts.

Evaporation studies on artificial potash brines were undertaken by the writer in the hope of throwing further light on the conditions governing the deposition of salts from solutions. It was planned to begin the investigation with simple salt mixtures and, by gradually including other salts, to deal finally with complex brines comparable with those found in nature. Though it has been possible to do only a small part of the experimental work contemplated, it seems advisable to publish the data thus far obtained, with the hope of supplementing them later.

In conducting the experiments an attempt was made to reproduce as far as possible commercial conditions. It is not believed that equilibrium reached final adjustment in the solutions, and consequently the results can not be considered as solubility determinations.

METHODS.

PREPARATION OF SOLUTIONS.

In the preparation of the solutions pure anhydrous chemicals were used except in the experiments with borates, for which borax was employed. The required amount of each salt was weighed out and dissolved in a definite volume of water. The composition of the original solutions as recorded in the tables was calculated from the data thus obtained.

METHOD OF EXPERIMENTATION.

In the preliminary experiments 150 grams of the solution under investigation was evaporated in a small beaker on the steam bath to about one-fourth its original volume and was allowed to cool at room temperature, which was between 25° and 30° C. The solution was stirred occasionally while cooling, and care was taken to start crystallization in order to prevent supersaturation. After the solution had cooled, it was filtered from the crystals by strong suction into a small flask, weighed, and analyzed.

In all other experiments 500 to 1,000 grams of solution was evaporated in beakers at intervals on the steam bath, and the progress of the results of evaporation was watched by removing from time to time the deposited salts and weighing and analyzing the solution. After each

[1] Phalen, W. C., The salt industry of the United States: U. S. Geol. Survey Bull. — (in preparation).
[2] Chatard, T. M., Natural soda: U. S. Geol. Survey Bull. 60, pp. 27-101, 1888.

stage in the evaporation the solution was stirred vigorously for several hours in an electrically controlled thermostat, which deviated less than 0.05° from 30° C., until the solution attained the temperature of the bath and appeared to be in equilibrium otherwise. It was then allowed to settle, and without change of temperature a sample of it was transferred by means of a pipette to a flask and weighed. The sample was drawn out through a filter consisting of a piece of cotton held in a small funnel which was attached to the pipette by a piece of rubber tubing. The pipette had a capacity of 8.606 cubic centimeters at 20° C., and from these data the specific gravity of the solution was calculated. The main portion of the solution was filtered into a smaller beaker with strong suction, as in the preliminary experiments, care being taken to remove as much as possible of the adhering liquid from the crystals. The filtrate was then returned to the steam bath and was further concentrated to about half its volume. It was then cooled in the thermostat, filtered from the crop of crystals, and otherwise treated as described above for the first product of evaporation, the filtrate being returned to the steam bath. The concentration was similarly continued at intervals until only a small amount of liquid remained. In all the experiments the procedure above described was followed in each succeeding stage in the evaporation.

METHODS OF ANALYSIS.

The weighed samples of solution obtained by the concentration just described were diluted to definite volume, and aliquot portions representing 3 to 4 grams of solution were taken for analysis. The determinations were made in duplicate, and practically all the figures given in the tables (pp. 68, 69, 71) are the average of two closely agreeing results. Common methods of analysis were usually employed, but short cuts were taken wherever possible, and a brief description of the procedure therefore seems advisable. The sulphate radicle was precipitated and weighed as barium sulphate, and potassium was estimated by the modified chlorplatinate method.[1] Sodium was determined by weighing the combined bases as chlorides or as sulphates and subtracting the corresponding equivalent of the potassium, borates when present being first removed by repeated evaporation with methyl alcohol and hydrochloric acid. Chlorine was determined by titration with N/10 silver nitrate after neutralizing the solution with nitric acid. The borate radicle was estimated by titration of the boric acid with N/10 sodium hydroxide in the presence of mannite and phenolphthalein. The carbonate radicle was determined by titrating with N/10 hydrochloric acid in the presence of methyl orange and subtracting the borate equivalent.

The calculations were made with the slide rule, and a few of the results may differ slightly from the true amounts. The percentage of the various constituents lost during evaporation is stated in round numbers with two significant figures, and no correction was made for the amount of salts removed with the sample for analysis.

[1] Hicks, W. B., A rapid modified chlorplatinate method for the estimation of potassium: Jour. Ind. Eng. Chem., vol. 5, pp. 650-653, 1913.

EXPERIMENTAL RESULTS.

PRELIMINARY EXPERIMENTS.

In the preliminary experiments solutions nearly saturated with salts of sodium and containing much smaller amounts of salts of potassium were concentrated on the steam bath to about one-sixth their original volume, it being assumed that the resulting solutions would be approximately saturated with potash salts. The solutions were cooled at room temperature, filtered, and analyzed. The results are given in the following table, together with the composition of the original solution and other data:

Changes resulting from the evaporation of artificial potash brines containing one acid radicle.

Character of solution.	Solution before evaporation.			Solution after evaporation.					Potassium lost (per cent).	K/Na ratios.		
	Quantity (grams).	Sodium (grams).	Potassium (grams).	Quantity.		Sodium (per cent).	Potassium.			Before evaporation.	After evaporation.	Saturated solution.
				Grams.	Per cent.		Per cent.	Grams.				
$KCl+NaCl$	150	5.901	1.573	24.1	16	8.50	4.58	1.104	30	0.27	0.54	[a]0.79
$K_2CO_3+Na_2CO_3$	150	4.882	1.698	21.3	14	9.36	6.22	1.326	22	.35	.67	......
$K_2SO_4+N_2SO_4$	25	.737	.225	6.3	25	4.72	2.72	.170	24	.31	.58	......

[a] Precht and Wittjen, Deutsch. chem. Gesell. Ber., vol. 14, p. 1667, 1881.

According to these results, the potassium appears to have concentrated most rapidly in the carbonate and least rapidly in the sulphate solution, and the potassium-sodium ratio after evaporation is greatest in the carbonate solution. It is apparent from the column of ratios that the chloride solution had not become saturated with potassium, and it is probable that the other concentrated brines had not reached equilibrium. The loss of 20 to 30 per cent of the potassium during evaporation shows that a large part of the potassium is removed from such brines before the solution becomes saturated with this constituent.

ALKALI BRINES CONTAINING TWO ACID RADICLES.

In the evaporation experiments with brines containing two acid radicles the original solutions were approximately of the same strength and contained three to four times as much sodium as potassium. In each series of experiments 500 grams of the solution was evaporated in stages, and the effect of each partial concentration was determined by analyzing the solution according to the methods already described. The character of the brines, their original composition, and the results of evaporation are given in the accompanying table. The changes in the concentration and the percentage loss of potassium as evaporation proceeded are also shown graphically in figures 24 and 25 (p. 70).

Changes resulting from the evaporation of artificial potash brines containing two acid radicles.

Character of solution.	Stages in the evaporation.[a]	Solution after evaporation.		Specific gravity.	Percentage composition of the solution.					Percentage loss.				K/Na ratio.
		Grams.	Per cent.		K.	Na.	Cl.	CO_3.	Total salts.	K.	Na.	Cl.	CO_3.	
$KCl+Na_2CO_3$	A	500	100.0	......	2.10	6.94	1.90	9.06	20.00	......	....	......	......	0.30
	1	236	57.2	1.35	4.09	11.51	3.68	15.05	34.33	8.0	22	8.5	22	.36
	2	141	28.2	1.36	5.67	10.97	5.14	14.44	36.22	24	55	24	55	.52
	3	49	9.8	1.36	7.48	10.03	6.71	13.28	37.50	65	86	65	86	.73
							SO_4					SO_4		
$K_2SO_4+Na_2CO_3$	A	500	100.0	......	1.80	6.94	2.20	9.06	20.00	......	....	......	......	.26
	1	192	38.4	1.39	3.06	13.00	3.12	17.33	36.51	35	28	46	27	.24
	2	58	11.6	1.38	3.68	12.30	2.56	17.17	35.71	76	79	87	78	.30
							Cl	SO_4				Cl	SO_4	
$KCl+NaCl+Na_2SO_4$	A	500	100.0	......	2.10	6.87	11.61	1.19	21.77	......	....	......	......	.31
	1	249	49.8	1.24	3.99	9.16	16.16	2.26	31.57	5.3	34	27	5.4	.44
	2	128	25.6	1.25	5.55	8.54	16.72	1.96	32.77	32	68	63	58	.65
	3	41	8.2	1.26	6.24	8.22	17.18	1.56	33.20	76	90	88	89	.76
								CO_3					CO_3	
$KCl+NaCl+NaCO_3$	A	500	100.0	......	2.10	8.03	11.61	2.26	24.00	......	....	......	......	.26
	1	277	55.4	1.26	3.55	10.06	14.72	3.43	31.76	6.4	31	30	16	.35
	2	117	23.4	1.29	5.51	9.77	14.02	5.18	34.48	39	72	72	46	.56
	3	60	12.0	......	5.39	10.50	12.30	7.47	35.66	69	84	87	60	.51
	4	40	8.0	......	5.10	11.12	11.22	8.98	36.42	81	89	92	68	.46
								B_4O_7					B_4O_7	
$KCl+NaCl+Na_2B_4O_7$	A	500	100.0	......	2.10	(?)	11.61	(?)	......	......	....	......	......	....
	1	166	33.2	......	5.14	8.38	17.29	1.08	31.89	19	(?)	51	(?)	.61
	2	95	19.0	......	6.21	8.00	17.41	1.60	33.22	44	....	71	......	.78
	3	38	7.6	......	6.11	8.15	17.10	2.28	33.64	78	....	89	......	.75

[a] A=original solution.

The highest concentration of potassium, 7.48 per cent, was obtained with the solution containing potassium chloride and sodium carbonate and the lowest, 3.68 per cent, with that containing potassium sulphate and sodium carbonate. In the chloride-sulphate and chloride-borate brines the concentration of potassium increased to a little more than 6 per cent, but in the solution containing potassium chloride, sodium chloride, and sodium carbonate it increased to a maximum and then decreased. In general the contents of sulphate and sodium varied comparatively little after the first concentration. The chlorine concentration usually increased as evaporation progressed, but in the solution containing potassium chloride, sodium chloride, and sodium carbonate it decreased after the first concentration. In that solution the content of carbonate continually increased, but in the other carbonate brines it rapidly rose to a maximum and then slowly declined. The final mother liquor always contained a large amount of carbonate. The borate concentration steadily increased. The amount of dissolved salts increased in all the solutions to more than 33 per cent. The two solutions containing both chloride and carbonate yielded the strongest bitterns. The variations in the potassium-sodium ratio correspond closely to the changes in the concentration of the potassium. The highest ratio was reached in the chloride-borate solution, and the lowest in the sulphate-carbonate solution. The loss of potassium during the first concentrations was greatest in the sulphate-carbonate solution. The loss of potassium during the first concentrations was greatest in the sulphate-carbonate brine. In all the other solutions the loss was only 5 to 8 per cent while the solution was being concentrated to about half its original volume and the content of potassium was being doubled. During further evaporation the loss was very rapid in all the solutions. The steady increase in the percentage of total salts and the continual variations in the concentration of the constituents prove that equilibrium in the solutions did not reach final adjustment.

The variations in concentration of the potassium in the several solutions as evaporation proceeded are shown graphically in figure 24. The curve representing the solution containing potassium sulphate and sodium carbonate is practically a straight line whose moderate slope indicates that the concentration of the potassium is slow and the loss of it necessarily large. The curves representing the concentration of potassium in the other solutions are similar to one another up to a concentration of about 5.5 per cent; beyond that point the curve for the solution of potassium chloride, sodium chloride, and sodium carbonate declines immediately and that of the borate reaches a maximum at 6.21 per cent.

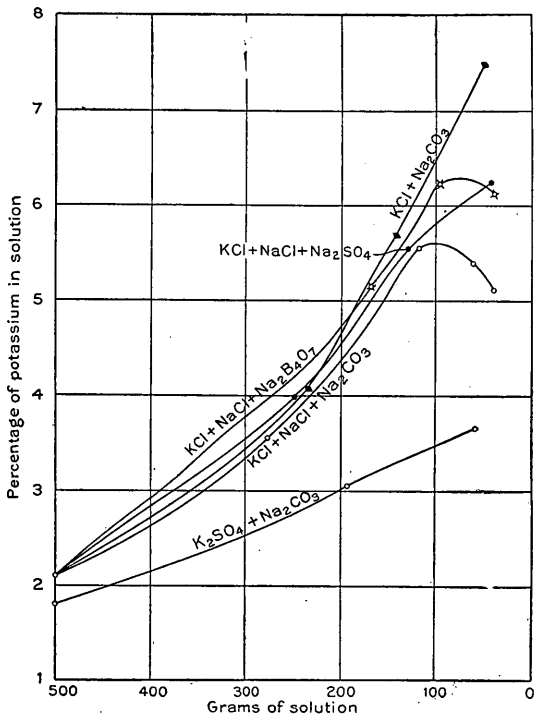


FIGURE 24.—Diagram showing the rate of concentration of potassium in various brines during evaporation.

Figure 25 gives a better idea of the losses of potassium sustained by the solutions than the table. From this it appears that at any particular stage in the evaporation the loss was least in the solution containing potassium chloride and sodium carbonate and greatest in that containing potassium sulphate and sodium carbonate. With the exception of the curve for the latter solution the curves are all very much alike, sloping gently to a point corresponding to about half the quantity of the original solution and then becoming very steep. In other words, the loss of potassium sustained by the solutions during reduction to half their original volume and during concentration of the potassium to about 4 per cent is 5 to 8 per cent of that originally present, but during further evaporation the loss is very rapid.

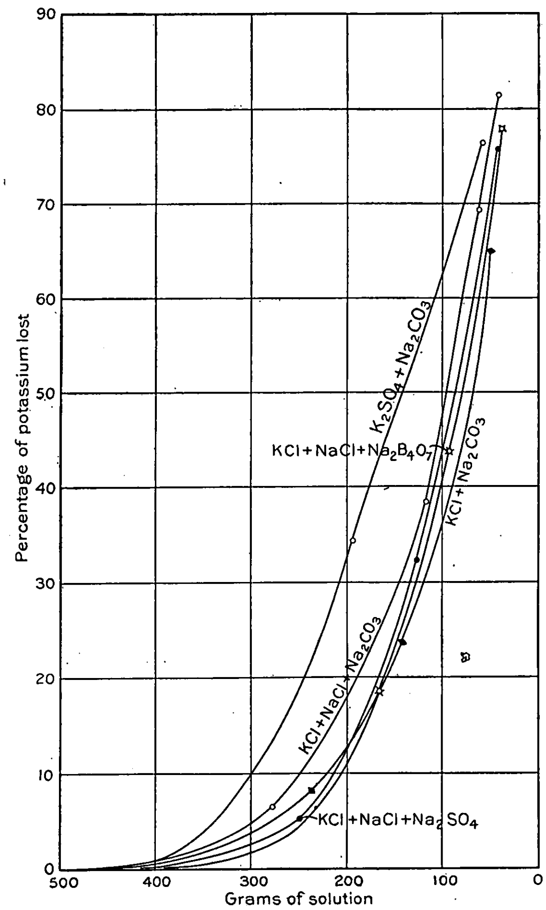


FIGURE 25.—Diagram showing the loss of potassium in various brines during evaporation.

ALKALI BRINES CONTAINING THREE ACID RADICLES.

More extensive evaporation experiments were carried out with solutions of the alkalies containing sulphate or borate in addition to chloride and carbonate. The character and composition of the brines used and the changes resulting through evaporation are given in the accompanying table. The change in concentration and the percentage loss of potassium for the sulphate solution is plotted in fig. 26 (p. 72). The corresponding curves for the borate solution are so nearly identical with those given that they would unnecessarily confuse the diagram.

Changes resulting from the evaporation of artificial potash brines containing three acid radicles.

Character of the solution.	Stages in the evaporation.[a]	Solution after evaporation (grams).	Specific gravity.	Percentage composition of the solution. K.	Na.	Cl.	CO_3.	SO_4.	Total salts.	Potassium in total salts (per cent).	Percentage loss. K.	Na.	Cl.	CO_3.	SO_4.	K/Na ratio.
$KCl+NaCl+Na_2CO_3+Na_2SO_4$	A	1,000	1.223	2.10	9.18	11.60	2.26	2.39	27.53	7.63	....	....	....	....	....	0.23
	1	723	1.268	2.86	10.64	13.53	2.68	3.05	32.76	8.73	1.6	16	16	14	7.5	.27
	2	547	1.278	3.67	10.40	13.51	3.16	2.96	33.70	10.89	4.4	38	36	24	32	.35
	3	337	1.285	4.88	9.82	13.71	3.63	2.30	34.34	14.20	22	64	60	46	67	.50
	4	213	1.295	5.75	9.79	13.39	4.79	1.79	35.51	16.19	42	77	75	55	84	.59
	5	148	1.300	5.70	9.93	13.20	5.08	1.67	35.58	16.02	60	84	83	67	90	.57
	6	99	1.314	5.53	10.33	12.18	6.51	1.55	36.10	15.31	74	89	89	71	93	.54
	7	55	1.327	5.34	11.01	11.24	7.84	1.56	36.99	14.44	86	93	95	81	96	.49
	8	22	1.335	5.28	11.26	10.86	8.36	1.59	37.35	14.14	94	97	98	92	98	.47
								B_4O_7							B_4O_7	
$KCl+NaCl+Na_2CO_3+Na_2B_4O_7$	A	1,000	1.238	2.10	(?)	11.60	2.27	(?)	....	....	....	....	....	....	....	....
	1	653	1.260	3.13	10.18	14.37	3.05	1.46	32.19	9.72	2.6	....	19	12	....	.31
	2	541	1.270	3.57	10.25	14.10	3.57	1.70	33.19	10.76	8	....	34	15	....	.35
	3	355	1.284	4.65	9.86	13.80	3.88	2.18	34.37	13.53	23	....	58	39	....	.47
	4	248	1.310	5.60	9.74	13.23	4.67	3.01	36.25	15.45	34	....	72	49	....	.57
	5	165	1.339	5.26	10.53	11.82	6.23	4.13	37.97	13.85	59	....	83	55	....	.50
	6	104	1.368	5.11	11.10	10.90	7.02	5.45	39.58	12.91	75	....	90	68	....	.46
	7	49	1.378	5.03	11.45	9.46	8.77	6.29	41.00	12.27	88	....	96	81	....	.44
	8	17	1.388	4.82	11.80	9.42	8.63	6.39	41.06	11.74	96	....	98	93	....	.41

[a] A = original solution.

As evaporation progressed the potassium concentration of both solutions increased to about 6 per cent and then gradually decreased. The chlorine concentration rose to a maximum in each solution and then decreased. The carbonate concentrates increased rapidly in both brines, but finally showed a slight decrease in the borate solution. The borate concentration rose steadily to 6.39 per cent. The changes in the percentages of sulphate and sodium were slight. The quantity of dissolved salts in both solutions became greater as evaporation progressed. The final sulphate mother liquor contained 37.35 per cent of salts and that of the borate 41.06 per cent.

In the sulphate solution the potassium-sodium ratio increased from 0.23 to 0.59 and then decreased to 0.47. In the borate solution it reached a maximum of 0.57 and then decreased to 0.41.

The percentage of potassium lost from both solutions increased slowly until the brines had been reduced to about half their original volume. At this point the concentration of the potassium was about 4 per cent, and the loss amounted to 5 or 6 per cent of the potassium originally present. On further evaporation the loss was very rapid. At the maximum concentration of potassium only about one-fifth of the solution remained, and a loss of more than 35 per cent is recorded. By means of the curves in figure 26 the percentage loss corresponding to any concentration of potassium can be directly determined.

CONCLUSION.

According to the results set forth in this paper, the potassium is concentrated best in brines containing carbonates and chlorides, and poorest in those containing sulphates and carbonates, though a small amount of sulphate does not seem to hinder the concentration materially. In brines that contain several acid radicles the concentration of potassium may increase to a maximum as evaporation proceeds and then decline. The evidence at hand indicates that a large percentage of the potassium in a solution is lost during evaporation before the maximum concentration of potassium is attained. The loss is small until the potassium reaches a concentration of about 4 per cent, but it is very rapid during further evaporation. Therefore in the commercial extraction of potash from brines, especially those of the alkalies, it would seem

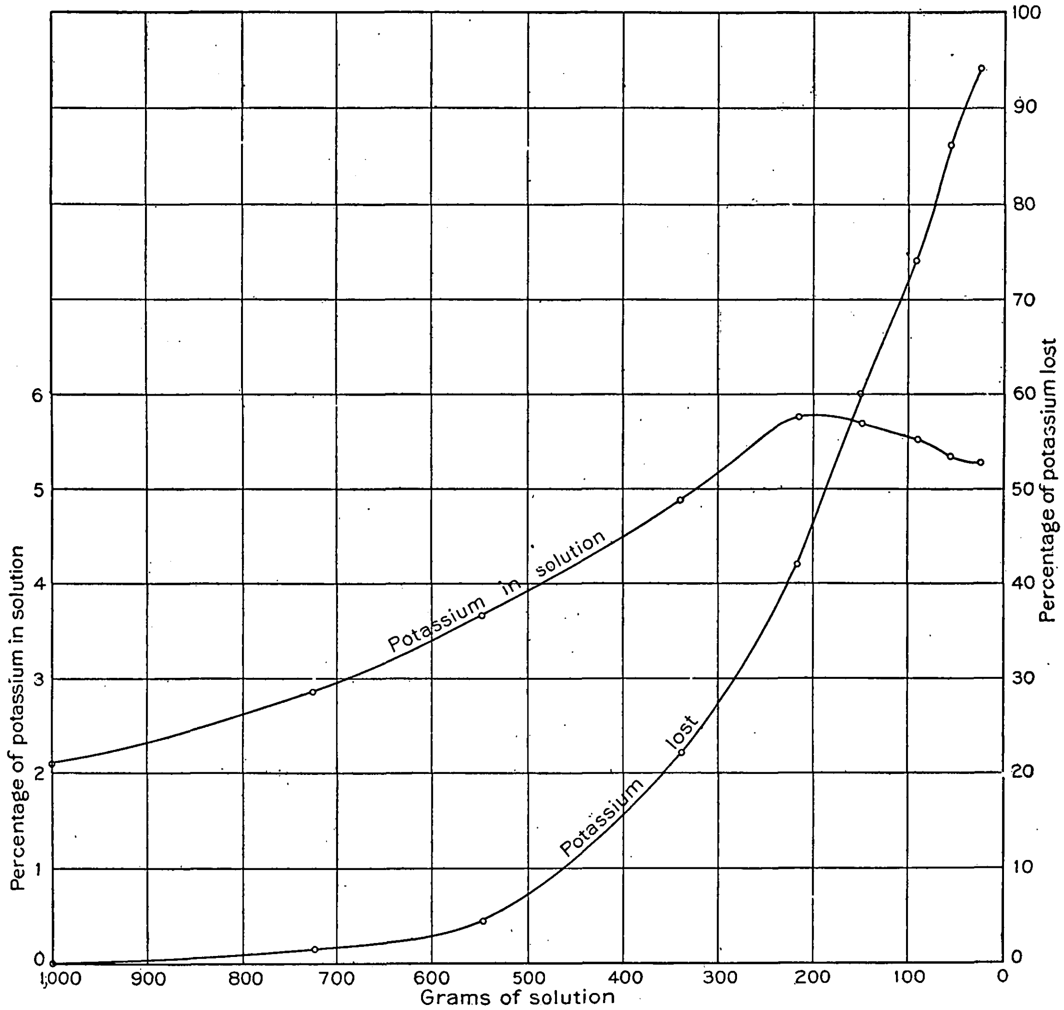


FIGURE 26.—Diagram showing the rate of concentration and the loss of potassium during the evaporation of a brine containing chlorides, carbonates, and sulphates of the alkalies.

best first to concentrate the solution by evaporation until it contained about 4 per cent of potassium, and then to subject the resulting bittern to other processes of manufacture. The most advantageous point of concentration would, however, have to be determined for each particular brine.

EROSION INTERVALS IN THE EOCENE OF THE MISSISSIPPI EMBAYMENT.

By Edward Wilber Berry.

INTRODUCTION.

The unequaled series of older Tertiary deposits of the Gulf Coastal Plain comprise several thousand feet of sands, clays, marls, lignites, and impure limestones. These deposits have always been considered as forming an uninterrupted and conformable series, extending from the lower Eocene (Midway) to the top of the Oligocene (Vicksburg and Apalachicola). It is the purpose of the present paper to show that the strand line migrated back and forth over this area several times during the period represented by these deposits, and that the sedimentation of Eocene time was interrupted during several intervals, of considerable duration in terms of organic evolution. I have attempted to indicate the geologic history of the embayment Eocene in a general way in the diagram forming figure 27, which is self-explanatory.

The essential lithologic similarity of the great bulk of these deposits and their great variability, due to their littoral character and the reworking of unlithified deposits concomitant upon transgressions and withdrawals of the sea, inhibit the recognition of physical evidences of unconformity.

To ignore for the present the restricted formational names based on local lithologic characters, the standard section of the Eocene may be said to comprise a series of formations assembled in groups, at their base resting upon Upper Cretaceous rocks and succeeded by deposits of Oligocene age. These groups are the Midway, Wilcox, Claiborne, and Jackson, the oldest being named first.[1] There is a pronounced unconformity between the Upper Cretaceous and the basal Eocene, visible in a number of sections, and discussed by me with reference to the paleobotanic evidence in unpublished papers on the Upper Cretaceous and Eocene floras. Stephenson [2] has recently summarized the paleozoologic and physical facts bearing on this subject for the whole Coastal Plain. Obvious breaks indicating similar unconformities occur in the later Tertiary (post-Eocene) deposits at several points in the Mississippi embayment area.

EVIDENCE OF EROSION INTERVAL BETWEEN THE MIDWAY AND WILCOX EPOCHS.

The Midway or basal Eocene deposits form a border on the inner side of the Tertiary of the Gulf Coastal Plain, from Flint River in Georgia to the Rio Grande and beyond. Over this vast distance their continuity is uninterrupted except for the relatively short distance of about 125 miles in southeastern Missouri and northeastern Arkansas, where later Tertiary erosion and subsequent Pleistocene deposition have removed or concealed them. This continuity is important, for the Midway serves as a datum plane for succeeding deposits.

The Midway deposits retain their marine character and traces of marine faunas well toward the head of the embayment. (See fig. 28.) The overlying Wilcox deposits are readily distinguishable lithologically. The northernmost point at which marine faunas have been found in the Wilcox is about latitude 33° N., or at least 3° south of the known northward range of Midway invertebrates. The Wilcox deposits might presumptively be interpreted as representing

[1] Detailed tables of formations for different States have been compiled by T. W. Vaughan and published in U. S. Geol. Survey Prof. Paper 71, 1912.

[2] Stephenson, L. W., The Cretaceous-Eocene contact in the Atlantic and Gulf Coastal Plain: U. S. Geol. Survey Prof. Paper 90, pp. 155–182, 1915 (Prof. Paper 90–J).

a succession of estuarine, littoral, and continental deposits in the wake of the southward-retreating sea. This is doubtless true of a part of the basal Wilcox, but it is by no means the whole story. Before considering the evidence furnished by the fossil flora some of the details of the stratigraphy and the lithologic evidence of a break in the sedimentation should be discussed.

The Wilcox group in its area of greatest development, southern Alabama, comprises four formations—the Nanafalia, Tuscahoma, Bashi, and Hatchetigbee.

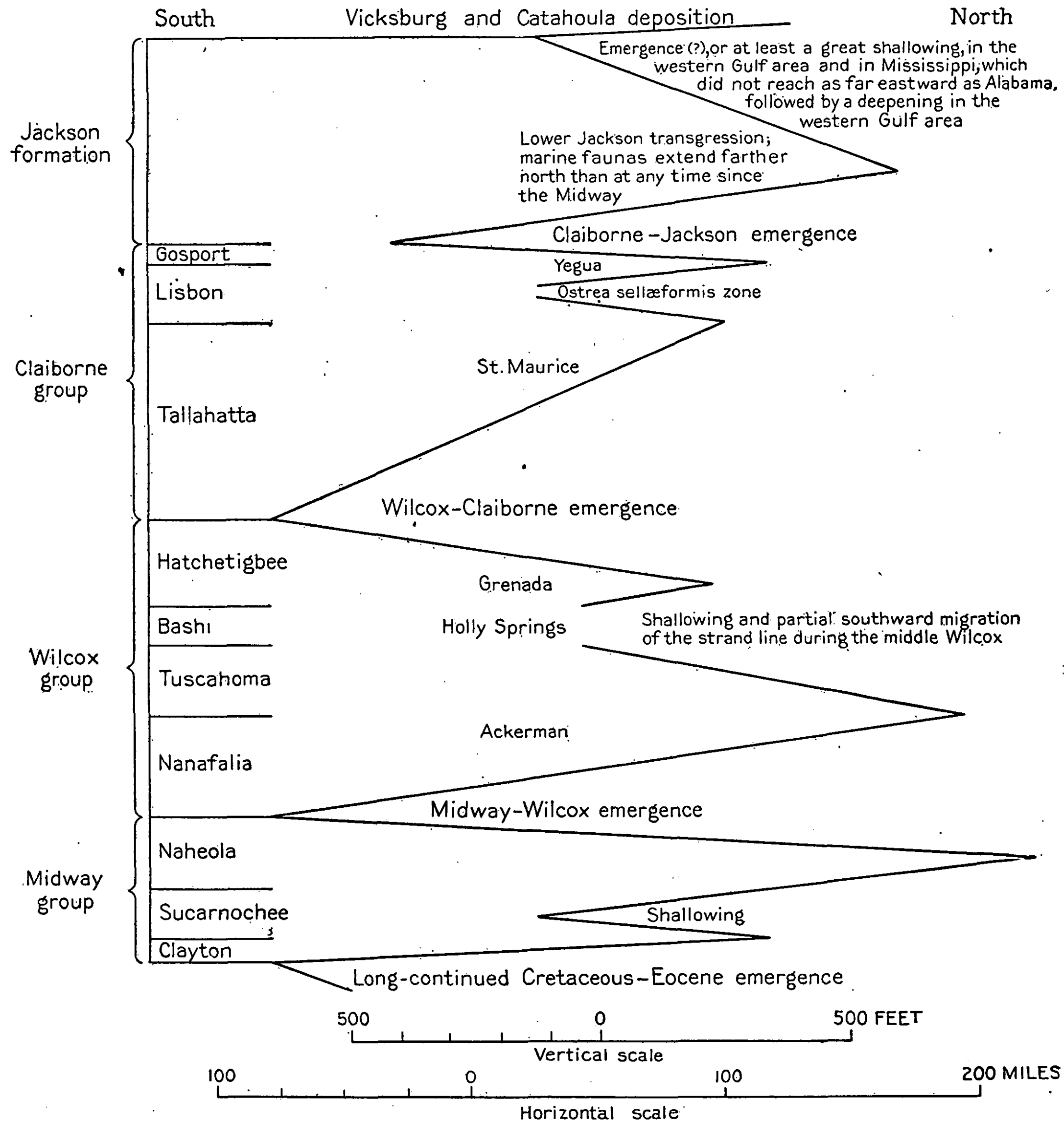


FIGURE 27.—Diagram showing the migrations of the strand line in the Gulf area during the Eocene epoch.

The Nanafalia or basal Wilcox formation consists of sandy glauconitic beds alternating with grayish calcareous clays, which in places are fossiliferous enough to be termed shell marls. At the base of the formation, resting on the top of the Naheola, the uppermost formation of the Midway group, is a bed of lignite from 5 to 7 feet in thickness which has been traced from Pike County, Ala., westward beyond Tombigbee River and which is represented by similar lignites through the greater part of the outcrop in Mississippi. The Nanafalia formation maintains a rather uniform thickness across Alabama of about 200 feet. The fauna of the Nanafalia as it stands recorded in the literature is small and of very shallow water facies, the most abundant form being the small oyster *Ostrea thirsæ* Gabb. That few species are restricted to this horizon is partly explained by the lack of monographic studies which would tend to increase the number of forms recognized. Nine Nanafalia species, prevailingly long-lived forms, are common to the Midway, only four of which are, however, restricted to the Nanafalia and the Midway. The Nanafalia fauna is really very distinct from that of the Midway, for it marks the initiation of many of the most characteristic Gastropoda. The pelecypods known are of less than a dozen species, and evidently collectors have missed many of the smaller members of this order. The distinctly Wilcox types form about 87 per cent of the known Nanafalia fauna.

Overlying the Nanafalia formation is the Tuscahoma formation, a series of about 140 feet of gray or yellowish cross-bedded sands and sandy clays, massive below and laminated above, generally poor in the remains of marine life except at two horizons, where glauconitic shell marls carry an abundant fauna. This fauna includes about 168 species, well diversified and

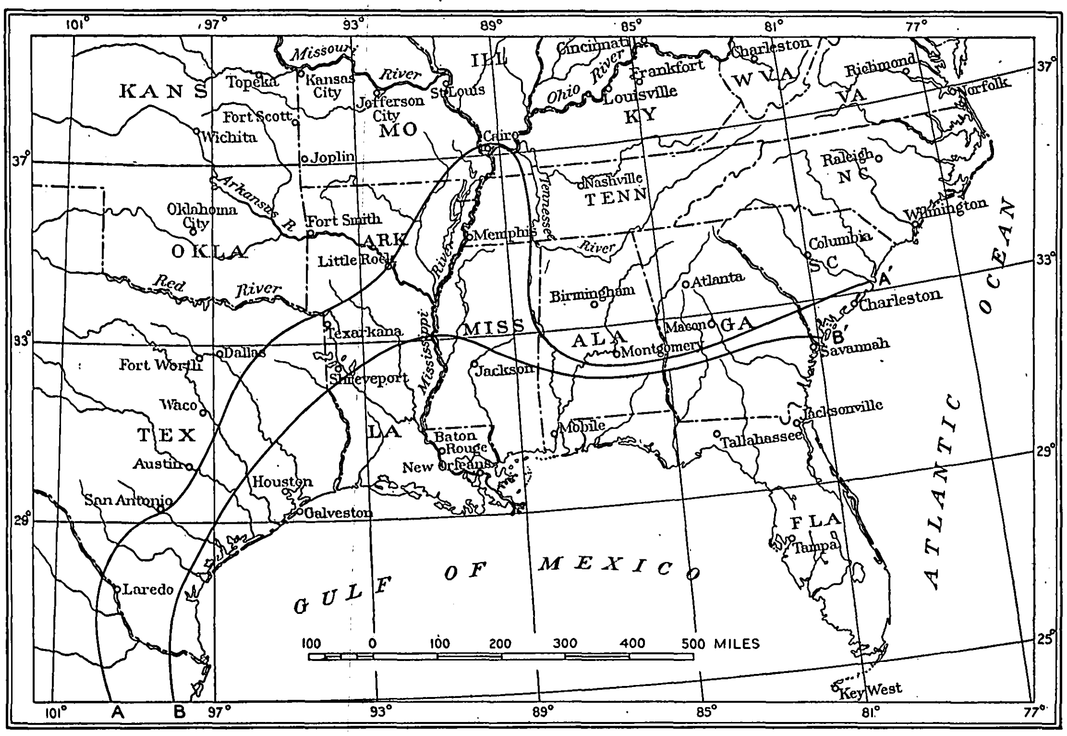


FIGURE 28.—Sketch map showing maximum transgression of the Midway sea (A-A′) and probable withdrawal during the interval between the Midway and Wilcox epochs (B-B′).

indicative of a slightly deeper habitat than the Nanafalia fauna. About 50 per cent of the Tuscahoma species are restricted to this horizon—a high percentage when it is recalled that additions of peculiar species would probably result from a detailed study of the fauna.

The Tuscahoma formation is overlain by the Bashi formation, at the base of which is a lignite bed 2 feet thick. Above the lignite occur sandy clays and thick lenses of calcareous glauconitic sands carrying an abundant and diversified fauna. This fauna has been studied more intensively than that of any of the other Wilcox formations. About 200 species are known, of which more than 50 per cent are peculiar to this zone.

The Hatchetigbee formation overlies the Bashi and consists of about 175 feet of laminated sandy clays and cross-bedded, more or less glauconitic and calcareous fossiliferous sands. The fauna of the Hatchetigbee is the most obviously shallow-water fauna known from the Wilcox. In this epoch were introduced a few new forms which later became prolific, but for the most part the fauna represents the end product of evolution during Wilcox time. About 85 species are recorded, of which about one-third are restricted to this horizon. Of the 38 species which persisted from earlier Wilcox time 33 became extinct during Hatchetigbee time, only 5 passing up into the Claiborne, and 14 additional Hatchetigbee forms are also recorded from the Claiborne.

This indication of shallowing water toward the close of Wilcox time is just what might be expected, and it is significant, if my interpretation of a series of transgressions and withdrawals of the sea is true, that the numerous and varied ostreids, capulids, and other forms which indicate a near-by strand line were found at localities in southern Alabama, several hundred miles south of the head of the embayment.

The lithologic differentiation of the Wilcox [1] in Mississippi is somewhat different from that of Alabama. In Mississippi a threefold division is recognizable. The basal formation is the Ackerman, which consists of about 300 feet of dark-gray lignitic and ferruginous sandy clays, beds of lignite reaching a maximum thickness of 6 feet, considerable concretionary and bedded carbonate of iron, and ferruginous sandstones, in places carrying fossil plants.

The Ackerman is overlain by the Holly Springs sand. As the name indicates, this formation is prevailingly arenaceous and consists of about 350 feet of cross-bedded, mostly coarse, micaceous, in many places highly colored, and locally indurated sands containing lenses of prevailingly pink or white usually siliceous clays and carrying an abundant flora.

The Holly Springs sand is overlain by the Grenada formation, which is prevailingly argillaceous and consists of about 200 feet of pinkish, yellow, or chocolate-colored sandy micaceous laminated clays and ferruginous sands.

The divisions of Wilcox time in Mississippi only partly retain their integrity in western Tennessee and Kentucky. The Ackerman formation can not be positively recognized, although it may be represented in the southeastern part of the area. In general the highly varied lithology of the deposits of Wilcox age in the northern part of the embayment falls into a twofold division, the lower part being more like the Holly Springs sand and the upper more like the Grenada formation but with a somewhat less amount of clay. The upper part is also much more lignitic in the northern area than it is in the south.

The only known erosional unconformity between the Midway and Wilcox is near Fort Gaines, Ga., where numerous pothole-like depressions in the Midway, as much as 20 feet deep, are filled with Wilcox deposits. Less certainly correlated erosional unconformities have been reported along the Rio Grande.[2] The most convincing evidence of such an erosion interval was brought to light during a study of the fossil floras, and this led to the assembling of much additional evidence, which will be given after a brief consideration of the flora.

The Wilcox flora comprises about 350 species scattered throughout the area of outcrop, but especially well represented in the eastern Gulf area in Mississippi and Tennessee and in the western Gulf area in northwestern Louisiana. It falls naturally into three florules—a lower, middle, and upper—corresponding to the threefold lithologic divisions established for Mississippi. The lower Wilcox flora is the smallest, as it has been found at fewer localities and as the outcrop of the Ackerman formation covers a smaller area than that of either of the two succeeding formations. Nevertheless fossil plants of Ackerman age occur in Kemper, Choctaw, Lauderdale, Lafayette, and Benton counties, Miss. The Ackerman flora consists of 36 species, of which 13 are restricted to beds of this age, 16 species persist into the Holly Springs sand, and 7 continue to the top of the Wilcox. The Holly Springs sand has furnished a flora of 256 species, of which 193 are found only at this horizon, 23 are common to the Ackerman, and 47 are common to the Grenada. The Grenada formation contains a flora of 116 species, of which 60, or over 50 per cent, are peculiar to the upper Wilcox. It may be considered established, without going into greater detail, that those three floras constitute well-defined units. Their distribution is most significant. The lower Wilcox or Ackerman flora is confined to northeastern Mississippi, where it characterizes beds resting on the Midway; in fact, the largest florule of this age, that from Hurleys, in Benton County, is less than 100 feet from the Midway contact.

[1] For numerous sections see Berry, E. W., The lower Eocene floras of southeastern North America: U. S. Geol. Survey Prof. Paper 91 (in press).

[2] See a recent paper by E. T. Dumble, Some events in the Eocene history of the coastal area of the Gulf of Mexico in Texas and Mexico: Jour. Geology, vol. 23, pp. 481-498, 1915, especially statements on p. 486.

The lithologically characteristic beds containing the middle Wilcox or Holly Springs flora, which, in Lafayette County, Miss., are between 300 and 350 feet above the Midway contact, are throughout Tennessee found to rest almost directly on beds of Midway age. Thus at Pinson, in Madison County, the plant bed is less than 100 feet above the beds of Midway age. At Peryear, in Henry County, in northern Tennessee, a flora of 181 species is not only near the top of the beds of middle Wilcox age—that is, stratigraphically above the flora from the middle Wilcox localities around Grand Junction, Holly Springs, and Oxford, Miss.—but also less than 100 feet above the contact with beds of Midway age. Although the Wilcox formations lose their lithologic identity at the head of the embayment and along its western shore in Arkansas, Louisiana, and Texas, it is found that only middle and upper Wilcox plants occur at the head of the embayment and throughout

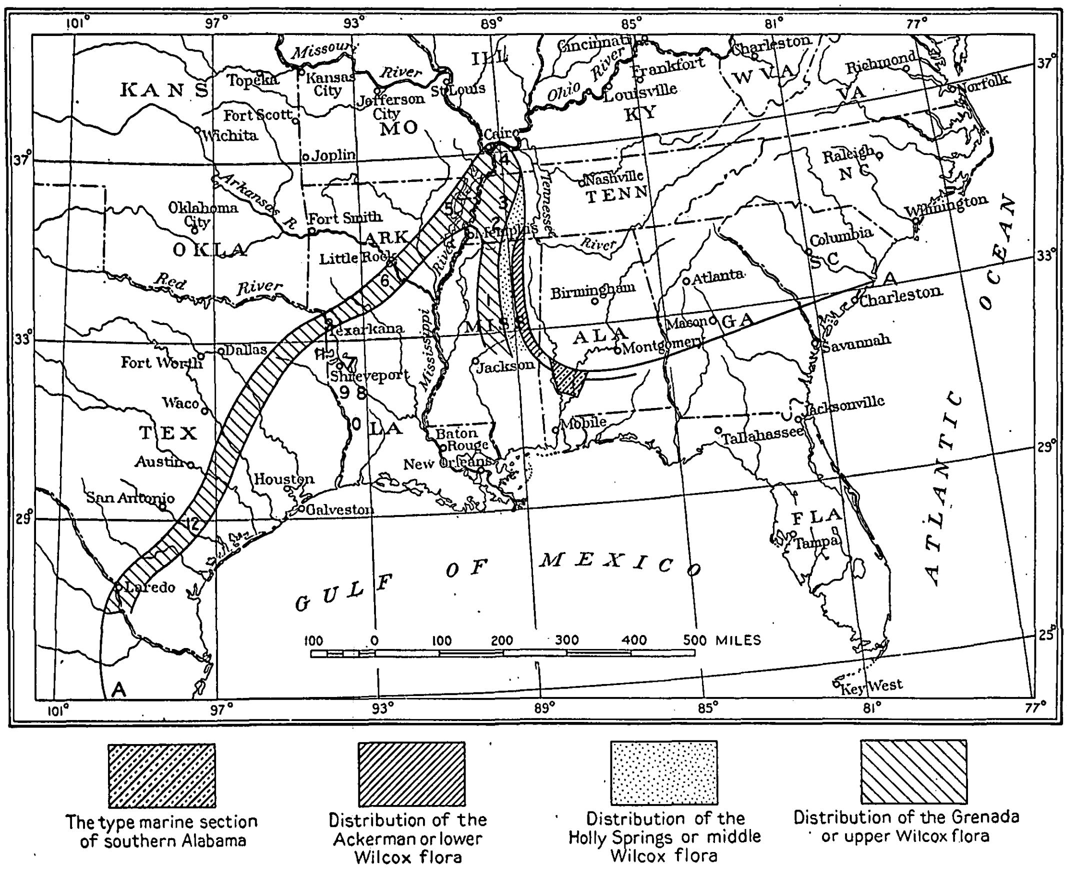


FIGURE 29.—Sketch map showing areal relations of the Wilcox floras. A–A, Maximum extent of the Wilcox transgression. Localities at which upper Wilcox species have been collected: 1, Grenada, Miss.; 2, Somerville, Tenn.; 3, near Trenton, Tenn.; 4, Wickliffe and Boaz, Ky.; 5, Bolivar Creek, Hardys Mill, and other localities on Crowleys Ridge, Ark.; 6, Benton and Malvern, Ark.; 7, several localities at or near Shreveport, La.; 8, Coushatta, La.; 9, around Mansfield and Naborton, La.; 10, Sabine River; 11, Old Port Caddo Landing, Tex.; 12, Calaveras Creek, Tex.

the western Gulf area. The distribution of these floras is shown on the accompanying sketch map (fig. 29).

In summarizing the evidence for an extensive erosion interval between the Midway and Wilcox, it may be noted that after the Midway epoch, during which marine animals penetrated northward at least into Tennessee and deposits of marine character reached southern Illinois, there was preserved on top of these marine beds in southern Alabama at the base of the Nanafalia formation an extensive 5 to 7 foot bed of lignite. That this bed of lignite was formed in place (autochthonous) by terrestrial vegetation and that the marine waters had withdrawn southward beyond the present outcrop of the lignite bed is almost certainly established. (See fig. 30.) Northward from this southernmost region along the Midway-Wilcox contact successively younger beds rest upon the Midway, the Middle Wilcox of Oxford and Holly Springs, Miss., several hundred feet above the base in that latitude, being the extreme basal part of the beds of Wilcox age in Henry County, Tenn. From the numerous well records recently collected by Matson and Hopkins in the Naborton oil field of Louisiana, it is obvious that the lower and most if not all of the middle Wilcox are completely transgressed by the upper Wilcox. Furthermore, while the evidence is not as complete as would be desirable for positive conclusions, the available well records show a thickening of the Wilcox down the dip, a sure indication either of erosion or of deposition during an advance and subsequent retreat of the Gulf waters. I have attempted to indicate on the accompanying sketch map (fig. 30) the southward migration of the strand line from the maximum limit of the Midway transgression, its approximate position at the beginning of the Wilcox transgression, and the subsequent maximum extent of the Wilcox sediments.

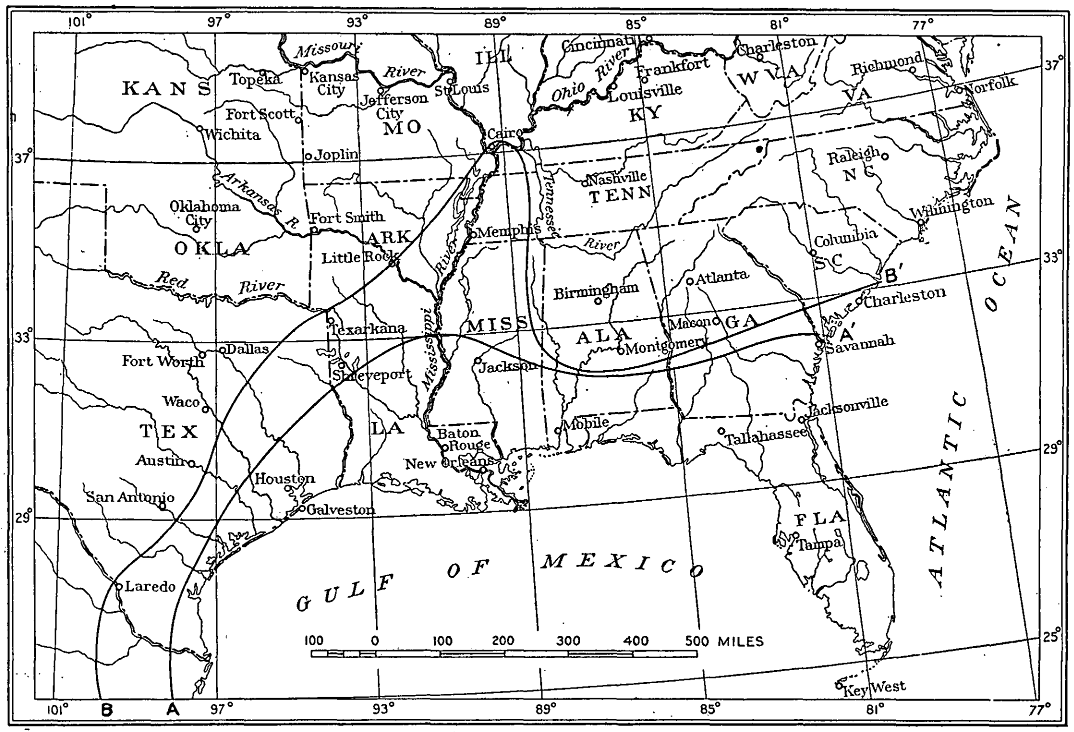


FIGURE 30.—Sketch map showing the approximate position of the strand line at the beginning of the Wilcox epoch (A–A') and the maximum extent of the Wilcox transgression (B–B').

That the geologic history was more complex than I have indicated is shown by the heavy beds of lignite at various levels toward the head of the embayment, by the 2-foot bed of lignite at the base of the Bashi formation in the Alabama section, by the extremely shallow-water character of the Hatchetigbee marine fauna, and by the marked littoral lithology of the Hatchetigbee deposits and the corresponding lagoon and sand flat lithology of the middle Wilcox deposits in the upper part of the embayment.

EVIDENCE OF EROSION INTERVAL BETWEEN THE WILCOX AND CLAIBORNE EPOCHS.

The evidence of an interval between the Wilcox and the Claiborne is not so conclusive as that of an interval between the Midway and the Wilcox, but rests on the complete agreement of all the various data. The type section of the Claiborne group is found in southern Alabama, where it is capable of a threefold division. The basal formation, known as the Tallahatta buhrstone, is an aluminous sandstone or siliceous claystone, calcareous and fossiliferous toward the east, where it is about 200 feet thick, but becoming practically unfossiliferous in western

Alabama, where it reaches a thickness of about 400 feet and is distinctly littoral, a character which it maintains in its outcrop northwestward across Mississippi. Overlying the Tallahatta is the Lisbon formation, consisting of 100 to 150 feet of calcareous, argillaceous, and glauconitic, abundantly fossiliferous sands, which also can be traced across Mississippi. The Lisbon is overlain by the Gosport sand, consisting of 30 or 40 feet of highly fossiliferous glauconitic sands which have not been recognized outside of the Alabama area.

The physical evidence for a Wilcox-Claiborne interval consists of erosional evidence reported by Veatch and Stephenson [1] from several localities in western Georgia on the littoral character of the basal beds or Tallahatta buhrstone, the undoubted great overlap of the lower Claiborne in Georgia, the overlap of the upper Claiborne toward the head of the embayment, and the great thinning of the deposits in that region.[2] This may be illustrated by the following section, kindly furnished by Mr. Stephenson:

Section along Bolivar Creek, Crowleys Ridge, Ark.

	Feet.
Pleistocene: Brownish loam underlain by gravel	5
Claiborne formation (incomplete):	
Argillaceous, faintly laminated sand	14
Massive sand	5
Argillaceous laminated sand	8
Lignite	5
Wilcox formation:	
Dark argillaceous sand	5
Lignitic sand	1
Chocolate-colored lignitic clays with fossil plants	3
Tough light-colored clay	2
	43

The significant feature is the 5-foot bed of lignite at the base of the Claiborne, indicating the site of terrestrial vegetation. The evidence is the same, whether this bed is referred to the top of the Wilcox or the base of the Claiborne. The Claiborne is unfossiliferous at this outcrop and therefore the reference may be open to question, but fossiliferous upper Claiborne beds occur at the near-by locality of Cherry Valley, and the field relations indicate that a part of the Bolivar section is of Claiborne age. It is true that the thinness of the Claiborne is partly accounted for by erosion, but erosion would not be sufficient to explain the disparity in thickness between the beds at this locality and those farther south. Lignitic beds at other localities in the upper part of the embayment indicate old land surfaces, but it has not yet been possible to determine at every locality whether they are at the base or the top of the Claiborne. The northernmost points at which the lower or middle Claiborne has been recognized in the embayment area are about latitude 34° N. in Mississippi and somewhat south of 34° in southern Arkansas. The upper Claiborne, however, carrying typical fossil plants, is found as far north as Cherry Valley, a distance of 150 miles farther north than the recognizable lower Claiborne.

The faunal and floral evidence is very striking. Fossil plants have not been found in the lower Claiborne (Tallahatta) of the eastern Gulf area, so that the time required for its deposition has to be considered in determining the amount of evolution shown by the later Claiborne floras. A few fossil plants have been found in the lower Claiborne (St. Maurice) of the western Gulf area, and the middle and upper Claiborne contains an extensive and well-distributed flora from Georgia westward to Texas.

The flora of the Claiborne group known at the present time amounts to 90 species. Of the 338 species known from the Wilcox group only six are found in the Claiborne, and two of these occur only in the basal Claiborne or St. Maurice formation of the western Gulf area, while one other, *Taxodium dubium*, is a very wide ranging and probably polymorphous form, both in this

[1] Veatch, Otto, and Stephenson, L. W., Preliminary report on the geology of the Coastal Plain of Georgia: Georgia Geol. Survey Bull. 26, p. 228, 1911. See U. S. Geol. Survey Prof. Paper 90, pp. 172–173, 1915 (Prof. Paper 90-J), for similar evidence along the Rio Grande.

[2] Dumble, in the recent paper previously cited, states that there is much evidence of emergence and erosion between the Wilcox and the Claiborne in southwestern Texas and northeastern Mexico.

country and Europe, so that it has no particular significance in the present discussion. This leaves only three species out of a total known flora of 428 species that are common to the Wilcox and the Claiborne, a fact which is very significant not only in its bearing on the interval unrecorded in exposed sediments between the Wilcox and Claiborne but in the evidence it affords that terrestrial floras are much more susceptible to climatic and other physical changes than marine invertebrates.

The Claiborne fauna embraces between 200 and 300 species, most of which occur in the Lisbon formation. A very small fauna is found in the Tallahatta buhrstone at the base. The Gosport at the top of the Claiborne presents no striking faunal differences when compared with the Lisbon formation. Over half the species in the Claiborne fauna are peculiar to this horizon, and there are striking differences between it and the Wilcox fauna. These differences represent not only different species but a different grouping of genera and indicate slightly deeper waters. Thus Terebra, which is absent in the Wilcox, has four species in the Claiborne.

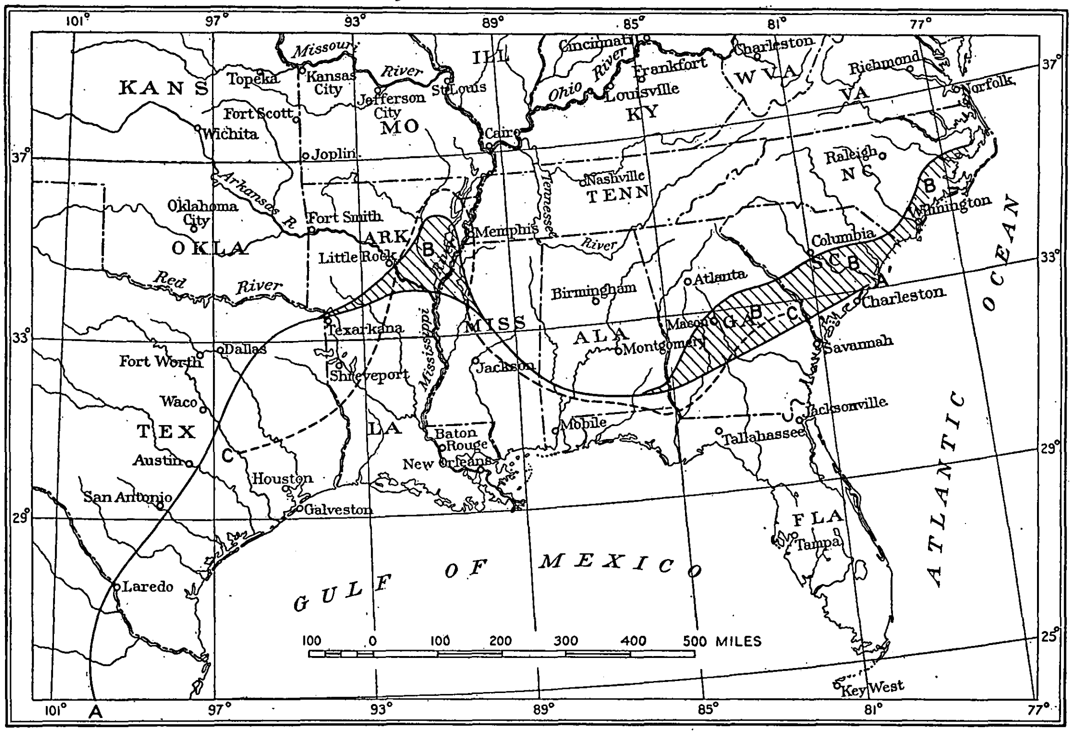


FIGURE 31.—Sketch map showing the extent of the lower Claiborne (A–A′), the area covered by the upper Claiborne transgression (B, B), and the strand line of the lower Jackson (C–C′).

The Pleurotomidæ have twenty-seven Wilcox species and only six Claiborne species. Cancellaria, a shallow-water genus, has nine Wilcox and only one Claiborne species. The genera Marginella and Limopsis, unrepresented in the Wilcox, have respectively three and six Claiborne forms. Trophon, with four Wilcox species, Triton, with five Wilcox species, and Epitomium, with three Wilcox species, are unrepresented in the Claiborne. The Claiborne has fewer oysters than the Wilcox and many more species of Mitra, Sigaretus, Dentalium, Nucula, Astarte, Venericardia, Cytherea, and Corbulâ. These comparisons might be continued indefinitely, but in view of the absence of any monographic work on these faunas there is a certain lack of finality in comparative statements. The conclusion that there is a most decided change in the faunas between the Wilcox and the Claiborne is, however, not likely to be invalidated by future work.

From the foregoing concurrent testimony of lithology, areal distribution, and floral and faunal character, it is believed that the presence of an erosion interval between the Wilcox and Claiborne has been demonstrated. What I conceive to be the general relations are indicated on the accompanying sketch map (fig. 31).

EVIDENCE OF EROSION INTERVAL BETWEEN THE CLAIBORNE AND JACKSON EPOCHS.

The character of the transition from Claiborne to Jackson in the extreme western part of the embayment area has not been worked out in detail, and as I am personally more familiar with the region east of Sabine River I will confine my discussion to that region.

The Jackson is very well marked paleontologically, but its lithologic similarity to underlying and overlying deposits over part of its area of outcrop has prevented a complete elucidation of its extent and delimitation. The field work of the last few years, prosecuted under the direction of T. W. Vaughan by Vaughan, Stephenson, Matson, Deussen, and Cooke, as well as the accompanying studies of the Bryozoa by Bassler, the corals by Vaughan, the Mollusca by Cooke, and the plants by Berry, will shortly result in a complete account of this important upper Eocene horizon.

The evidence of a southward withdrawal of the Claiborne sea has been more or less indicated in the preceding section of this paper. Evidence of the partial emergence of the northern end of the embayment is furnished by the palustrine character of much of the upper Claiborne material (Yegua or "Cockfield"). Evidence from a more southern locality is furnished by the Claiborne-Jackson contact at Claiborne Landing, on the east (left) bank of Alabama River in Monroe County, Ala.

The celebrated section at Claiborne Landing, famous as having furnished the fossils which enabled Lea in 1833 to apply the term Eocene to American deposits for the first time, shows a very instructive contact between the top of the Claiborne group (Gosport sand) and the base of the Jackson. The detailed section was given by Hale [1] as early as 1848, and it has been discussed by Tuomey [2] and in great detail by Smith,[3] so that it is not worth while to repeat the complete section in this place. The top of the Gosport in this general region is a glauconitic fossiliferous sand, at this and neighboring outcrops, completely oxidized. In places it contains somewhat lignitic layers. At the top of that part of the section exposed along the old ferry road to the upper landing there is a lens of laminated gray clay carrying an abundance of leaf impressions. Fifteen species have been determined from this exposure, and these furnish intrinsic evidence of the upper Claiborne age of the deposits, for nearly all of them are represented in the Yegua formation ("Cockfield beds") of Louisiana and Arkansas. Overlying this clay is a few feet of coarse ferruginous or glauconitic, calcareous, more or less indurated sand, grading upward into the *Scutella lyelli* bed of the Jackson. There is no physical evidence of a break in sedimentation, but the following considerations are of some significance. Although all the formations of the Claiborne group are distinctly shallow-water deposits throughout southern Alabama, nowhere below the top has a similar lens of clay carrying the remains of terrestrial vegetation been discovered. The sand which replaces the clay in near-by sections is completely oxidized throughout, and this condition may be legitimately considered to be due to emergence at the close of the Claiborne, because in the immediately overlying beds of the Jackson, although the sands are ferruginous, the glauconite is not completely oxidized. No evidence of discordance in bedding would be expected, nor would erosion make itself visible where the materials in contact were practically identical in lithologic character. Furthermore, unless the emergence was considerable in a vertical direction, which is improbable, scarcely any erosion would take place.

The palustrine beds of upper Claiborne age toward the head of the embayment are overlapped by marine deposits of lower Jackson age which carry the life of marine waters farther northward than at any time subsequent to the Midway. (See fig. 31.) Numerous localities in Arkansas have furnished invertebrate remains, and along Little Crow Creek, in the northeastern part of the State, extensive oyster reefs are present as well as an abundant shallow-water fauna preserved in a glauconitic sand. East of Mississippi River traces of the marine Jackson fauna have not been found north of latitude 33° N., but the Jackson flora has been recognized as far north as latitude 35° 24′ N. in western Tennessee, which is 135 miles farther north than

[1] Hale, C. S., Am. Jour. Sci., 2d ser., vol. 6, p. 354, 1848.
[2] Tuomey, M., First biennial report on the geology of Alabama, p. 153, 1850.
[3] Smith, E. A., On the geology of the Coastal Plain of Alabama, pp. 127-132, pls. 5, 20, Alabama Geol. Survey, 1894.

the northernmost recognized upper Claiborne of this area, a fact clearly indicative of a greater or less emergence in the last third of Claiborne time and a pronounced transgression marking the beginning of the Jackson. The known flora of the Jackson is unfortunately meager, but the fauna is extensive. The available paleobotanic evidence corroborates the faunal evidence in suggesting that the erosion interval between the Claiborne and the Jackson was shorter than any of those which preceded it.

The Jackson flora, as at present known, comprises only 22 species, but this number is likely to be considerably increased with additional studies. Eleven of these species are restricted to the Jackson, notwithstanding the fact that much more abundant floras are known from the underlying Claiborne and the overlying Vicksburg and Catahoula. Two of the Jackson forms are characteristic Claiborne forms, and five additional Claiborne species have been doubtfully recognized in the Jackson. Four Jackson species are found in the Catahoula, and two of these are also found in the Vicksburg.

The Jackson fauna, according to unpublished information kindly communicated by C. W. Cooke, comprises over 200 species, of which about 23 per cent are common to the Claiborne. When it is recalled that the Claiborne fauna also comprises over 200 species, about 50 common species in a total of over 400 seems like a very small common element. The two faunas are, in fact, very well marked paleontologically, but there is little change in general facies, closely related species appearing in both faunas and the same association of genera being largely identical in both. The immigration of the active and predaceous Zeuglodon into the embayment area during Jackson time is a factor of some importance in contrasting the life of the two epochs. The similarities between the floras and faunas of the Claiborne and Jackson, as well as comparable similarities between those of the Jackson and the basal Oligocene, might be considered to represent uniformity of climatic and other physical conditions rather than a greatly reduced interval of time.

The areal relations as I interpret them are shown on figure 31 (p. 80).

PRELIMINARY REPORT ON THE DIFFUSION OF SOLIDS.

By C. E. Van Orstrand and F. P. Dewey.[1]

INTRODUCTION.

Although 19 years has elapsed since Roberts-Austen[2] published his classical paper on the diffusion of solid metals, no attempt seems to have been made to verify his important results and conclusions or to extend the investigations to minerals and to the great number of solids in which diffusion may be expected to occur. Progress has been made by means of chemical and electrical methods[3] in the detection of diffusion in a number of metals in the solid state, some progress has been made in explaining the phenomena of diffusion on the basis of osmotic pressure and the kinetic theory, and recent measurements of the vapor pressures[4] of solids have contributed indirectly to the progress of the science, but investigators have not undertaken the difficult and essential task of making definitive determinations of the coefficients of diffusivity at various pressures and temperatures.

The investigation of which this paper is a preliminary note has for its first object the determination of the coefficients of diffusivity over a considerable range of pressures and temperatures for metals and minerals. The investigation was first undertaken in connection with some experiments on the elasticity and plasticity of metals. Although it is believed that the results are essential for the construction of a complete theory of the physical properties of elastic and plastic bodies in the normal state or in a state of isostatic adjustment, it is realized that this is only one of many fields in which the results are of fundamental importance. Roberts-Austen emphasized the importance of diffusion in its relation to the formation of alloys and the more vital problem of the constitution of matter; the importance of the general problem of diffusion in the elucidation of geologic problems has been emphasized by Becker,[5] who also prepared a table for the computation of diffusivities; Elsden[6] and Liesegang[7] give an extended discussion of the subject in their textbooks; Desch[8] has pointed out the possibility of explaining secondary replacements of minerals, the formation of pseudomorphs, schiller inclusions, and other geologic features on the basis of the diffusion of minerals in the solid or molten state; and recently Gillette[9] has discussed a theory of ore deposition in which osmotic pressure is assumed to be one of the fundamental factors.

In their more general aspects the phenomena of diffusion are not confined to the inorganic world. It is well known that diffusive processes play an important part in living matter, and

[1] Dr. Dewey is assayer to the Bureau of the Mint, United States Treasury Department, and this paper is published with the permission of the Director of that bureau.

[2] Roberts-Austen, W. C., On the diffusion of metals: Roy. Soc. London Philos. Trans., vol. 187 A, pp. 383–415, 1896; On the diffusion of gold into solid lead at the ordinary temperature: Roy. Soc. London Proc., 1900, pp. 435–441; also vol. 67, pp. 101–105.

[3] Guillet, L., and Bernard, V., Local prevention of casehardening and diffusion in solids: Rev. métallurgie, vol. 11, pp. 752–765, July, 1914. Desch, C. H., Report on diffusion in solids: British Assoc. Rept., 1912, pp. 348–372. (As this report contains an excellent summary of the literature of the subject, the references need not be repeated in this paper.)

[4] Hulett, G. A., The distillation of amalgams and the purification of mercury: Phys. Rev., vol. 33, pp. 307–317, 1911. (Hulett made an approximate determination of the vapor pressure of platinum at a temperature of 200° C.) Langmuir, Irving, The vapor pressure of metallic tungsten: Idem, 2d ser., vol. 2, pp. 329–343, 1913. Langmuir, Irving, and Mackay, G. M. J., The vapor pressure of the metals platinum and molybdenum: Idem, 2d ser., vol. 4, pp. 377–387, 1914. Wartenberg, H. von, Über Metalldampfdrucke: Zeitschr. Elektrochemie, vol. 19, p. 482, 1913.

[5] Becker, G. F., Note on computing diffusion: Am. Jour. Sci., 4th ser., vol. 3, pp. 280–286, 1897.

[6] Elsden, J. V., Principles of chemical geology, Whittaker & Co., London, 1910.

[7] Liesegang, R. E., Geologische Diffusionen, Theodor Steinkopff, Dresden and Leipzig, 1913. (An important review of this work is given by Adolph Knopf in Econ. Geology, December, 1913, pp. 803–806.)

[8] Desch, C. H., op. cit.

[9] Gillette, H. P., Osmosis as a factor in ore formation, in Emmons, S. F., Ore deposits, pp. 450–454, Am. Inst. Min. Eng., 1913.

it will be interesting in this connection [1] to quote from the conclusion of the paper by Roberts-Austen, already cited. Referring to Graham's great work on the diffusion of salts into liquids and of liquids into each other, he says:

His work in experimental physics, more than that of any other investigator, taught the physiologist that tracing the relations of the phenomena of life as revealed in diffusion, transpiration, and osmosis will afford natural history its most precious records.

The evidence gathered by the metallurgist of active atomic movement in fluid and solid metals may sustain the hope of the physiologist that he will ultimately be able to measure the atomic movements upon which vitality and thought depend.

THEORETICAL CONSIDERATIONS.

The phenomenon of diffusion as exemplified by gases, salts, liquids, solids, and certain constituents of organisms is supposed to be a transfer of mass in a given direction due to the continuous haphazard motion of the molecules of which the substances are composed. A simple analogy is that of spheres moving over a smooth horizontal surface bounded on the edges by perfectly elastic walls. We may imagine one system to consist of white and the other of red spheres, and the two systems to be separated from each other by a perfectly elastic partition. If the spheres are set in motion and the air resistance is negligible, they will continue to collide with one another for an indefinite time. The mean kinetic energy of each system, corresponding in our analogy to the temperature of the system, may or may not be the same, but in either case if the partition is removed the red and white spheres begin to collide with one another and to occupy areas previously occupied by spheres of a single color. A strip on each side of the line marking the original position of the partition will thus contain spheres of both colors, the greatest number of mixed colors being in the immediate vicinity of this line. It is conceivable that a very small number of spheres will reach the boundary wall parallel to the partition in a very short time, and that as the process continues spheres of the opposite color will accumulate in this region and there will then be reflection or resultant motion in the direction toward the partition, the tendency being always for a sphere to move away from the region in which the number per unit area of spheres of its particular kind is greatest. Statistical equilibrium in density will be attained when the number of red spheres per unit area is constant throughout the entire area, and similarly for the white spheres. The paths traced out by the spheres are of course very irregular, and even after equilibrium is established the spheres zigzag back and forth across the plane, but always in such a way that the average number of different spheres per unit area remains unchanged. It is evident that equilibrium of this kind implies that the average number of red or white spheres entering any fixed area of the surface over which the spheres are moving is the same as the number leaving the same area in a given interval of time.

That the interdiffusion of gases, liquids, and solids and the diffusion of gases into solids and of gases and solids into liquids are mechanical processes analogous to the simple process just described may be inferred from the observations and verifications with theory of the Brownian movements. A study of these phenomena has sufficed to establish Maxwell's fundamental laws for the equipartition of energy and the distribution of velocities about the average velocity for liquids and has thus provided a sound foundation on which the kinetic theory of matter in the three states—solid, liquid, and gaseous—may be constructed. The remarkable theoretical and experimental investigations of Perrin,[2] Einstein, and others leave no doubt as to the reality of molecules and molecular motion in liquids, and it therefore seems reasonable to infer that solids are mechanical systems of the same kind, in which the molecular displacements are much restricted, and in some solids, such as crystals, the law of restriction varies from one form of crystal to another. It is conceivable that molecules possess axes along which the attractive forces vary. In the liquid and gaseous states the molecules are in constant rotation, and the distance between centers is so great that the directional forces are inappreciable, but in the solid crystalline state these forces may predominate to such an extent that the

[1] See also, for example, Livingston, B. E., The rôle of diffusion and osmotic pressure in plants, Univ. Chicago Press, 1903.
[2] Perrin, Jean, Brownian movement and molecular reality, by F. Soddy, Taylor & Francis, London, 1910.

strictly random rotations and displacements do not occur. The number of degrees of freedom of the system has been diminished.

Attempts have been made to explain diffusion and osmotic pressure on the basis of chemical affinity, the formation of loose chemical compounds, and the influence of surface tension.[1] Chemical affinity, however, is merely the potential energy of a dynamic system; the formation of loose compounds is simply aggregation and dissociation, and surface tension has long been known to be due to unequal molecular attractions. Each explanation is in reality the application of a special feature of dynamic theory, although it was apparently intended by the advocates of these hypotheses to obtain an explanation of the phenomenon which would be independent of mechanical systems. The fact that there is an observed transportation of matter would seem in itself to be a sufficient justification for the assumption that the system is mechanical, but the additional fact that solids possess a vapor pressure would seem to leave little doubt in regard to the validity of the hypothesis that solids [2] are composed of discrete particles in a state of rapid oscillation, although restricted somewhat in their movements.

In the consideration of the migration of the particles in the diffusion process, one of the simplest methods of procedure is to adopt a certain average value or constant which corresponds to a certain type and state of molecular activity of the given substances. The quantity selected, the coefficient of diffusivity (k), may be defined by considering the exchange of molecules between two cylinders of different substances when the ends are placed in contact with each other and the entire system is maintained at constant temperature. The principle of sufficient reason suffices to show that the molecular transfer will take place in such a manner that the concentration, the mass of dissolving substance per unit volume of solution, is constant throughout a layer of infinitesimal thickness perpendicular to the common axis of the cylinders. The simplest assumption that can be made in regard to the interdiffusion of the two substances is to assume that the amount of diffusing substance which passes any plane perpendicular to the axis of the cylinder is proportional to the time, the area of cross section, and the rate of change of concentration per unit length, measured in the direction in which the solute is moving into the solvent. Expressed in the form of an equation, the assumption may be written

$$m = ka\frac{(v_1 - v_2)\,t}{\Delta x} \qquad (1)$$

wherein

m = mass of solute
k = coefficient of diffusion
a = area
t = time
Δx = distance between two planes at which the concentrations are v_1 and v_2.

Now put a, t, Δx, and $(v_1 - v_2)$ each equal to unity; then k is the mass of solute passing through a unit cube of the solvent in unit time when the difference between the concentrations at the opposite faces of the cube is equal to unity. It will be noted that equation (1) represents also the quantity of heat flowing through a plate of cross-sectional area a, thickness Δx, in time t, when the temperatures of the respective surfaces are v_1 and v_2. The quantity k is here called the thermal conductivity of the substance.

With this definition of the coefficient of diffusivity as a basis, we now proceed to find the amount of solute in any given volume of the solution whose center is at distance x from the plane of contact, after a given time interval t has elapsed. If we imagine the two parallel planes which are perpendicular to the direction of flow of the solute to approach each other, we have in the limit, when the time interval also is infinitesimal,

$$dm = ka\frac{\partial v}{\partial x}dt$$

[1] For a discussion of these and other explanations, see Whetham, W. C. D., Theory of solution, Cambridge Univ. Press, 1902; Findlay, Alexander, Osmotic pressure, Longmans, Green & Co., 1913.

[2] See also Nernst, Walther, The theory of the solid state, Univ. London Press, 1914. Bragg, W. H. and W. L., X rays and crystal structure, G. Bell, London, 1915. Magie, W. F., Relation of osmotic pressure to temperature: Phys. Rev., October, 1912, pp. 272–275.

Here again it is evident that our assumption is the simplest possible, for it would not be unreasonable to assume that dm is a function of the higher powers of $\partial v/\partial x$. Our equation merely amounts to stating that

$$f_x = k\frac{\partial v}{\partial x} \qquad (2)$$

is the rate per unit time at which the solute flows through unit area of a plane which is perpendicular to the axis of the cylinder and at distance x from the plane of contact. The term flow is here used to designate the resultant motion of the solute in a given direction and is merely the summation in a given direction of the very irregular displacements of the molecules. The resultant at right angles to the direction of flow is zero, on account of reflection at the surface, but there is always a small resultant displacement of the particles in the direction from higher to lower concentration.

Now imagine a parallelepiped whose edges are $2dx$, $2dy$, $2dz$, and whose center is at distance x from the plane of contact. The change in concentration per unit volume at x in time dt is $(\partial v/\partial t)\,dt$ and the increment in the mass of the solute in this elementary volume is therefore represented by the equation

$$\text{volume} \times \text{change in concentration} = 8\,dxdydz\frac{\partial v}{\partial t}dt \qquad (3)$$

We can obtain another expression for the same quantity, for the rate at which the solute is flowing into the parallelepiped across the plane nearest to the plane of contact is

$$4\,dydz\left(f_x + \frac{\partial f_x}{\partial x}\right)dx$$

Similarly the rate of outflow across the plane farthest from the plane of contact is

$$4\,dydz\left(f_x - \frac{\partial f_x}{\partial x}\right)dx$$

and the total gain to the parallelepiped in time dt is therefore

$$8\,dxdydz\,\frac{\partial f_x}{\partial x}dt$$

Equating this expression to (3) and making use of (2) we get the result

$$\frac{\partial v}{\partial t} = \frac{\partial f_x}{\partial x} = k\frac{\partial^2 v}{\partial x^2} \qquad (4)$$

An integral of (4) is

$$v = v_0\left[1 - \frac{2}{\sqrt{\pi}}\int_0^q e^{-q^2}dq\right] \qquad (5)$$

in which

$$v_0 = \text{constant}$$
$$q = x/2\sqrt{kt}$$

This result may be established by expressing the integral as a function of the limits of integration and performing the necessary differentiations.[1]

[1] For other methods of integration, see, for example, Carslaw, H. S., Fourier's series and integrals, Macmillan & Co., 1906; Ingersoll, L. R., and Zobel, O. J., Mathematical theory of heat conduction, Ginn & Co., 1913; Byerly, W. E., Fourier's series and spherical harmonics, Ginn & Co., 1895; Woodward, R. S., A new method of integrating one of the differential equations of the theory of heat diffusion: Phys. Rev., vol. 16, pp. 176-177, 1903; On the free cooling of a homogeneous sphere: Annals Math., vol. 3, pp. 75-88, 1887

If k is replaced by

$$\kappa = \frac{h}{\rho c}$$

where ρ, h, and c are respectively density, conductivity, and specific heat of the substance, equation (5) will then represent the distribution of temperature in an insulated bar of great length, initially at a uniform temperature of 0° throughout the mass, and subjected at one end to a constant temperature v_0 for the time interval t. Similarly, equation (5) represents the distribution of concentration in a cylinder of initially pure substance in the solid or liquid state when a layer of constant concentration v_0 is maintained at the base of the cylinder for a time t. When $t=0$, equation (5) gives $v=0$ for all values of x, thus expressing the fact that at the beginning of the experiment the cylindrical mass contained no solute. For all finite values of t other than zero, equation (5) gives $v=v_0$ for $x=0$, which agrees with the condition that constant concentration is maintained at the plane of contact; and for other values of x, v diminishes as x increases until for $x=\infty$, $v=0$. These results agree with the general form of the observed curve indicated in figure 32 (p. 94). As time proceeds, the curves continue to rise, and when an infinite time has elapsed, $v=v_0$ for all values of x. In other words, constant concentration is attained in a cylinder of infinite length in an infinite time. Stefan [1] assumed that reflection occurs at the ends of a cylinder of finite length and that the concentration at any point is the sum of the concentrations at corresponding points in a cylinder of great length, the long cylinder being supposed to be cut into lengths equal to that of the short cylinder and then folded backward and forward upon itself until the extreme portion containing solute is contained within the short length. The correctness of the assumption has been abundantly verified by the experiments of Roberts-Austen on molten metals.

EXPERIMENTAL METHODS.

Roberts-Austen determined the coefficients of diffusion of solid gold into solid lead at temperatures of 100°, 165°, 200°, and approximately 18° C. In some experiments a gold plate was fused to the end of the lead cylinder; in others a gold plate or a 5 per cent alloy of gold and lead was pressed against the surfaced end of the lead cylinder by means of binding screws. The specimens were maintained at constant temperatures for various time intervals ranging from 10 to 41 days for the high temperatures and 4 years for the ordinary temperature, after which they were sliced and the gold content of each section determined to a high degree of precision by means of a careful assay.

We have conducted similar experiments at temperatures of 100°, 150°, 180°, and 197° C., using for some of the specimens 0.5-millimeter gold plates clamped to the ends of the lead cylinders, and for others a gold electroplate on one or both ends of the lead cylinder, in accordance with a suggestion of Dr. N. E. Dorsey, of the Bureau of Standards. After the specimens were heated for a number of days in an air thermostat controlled by a mercury regulator, they were cut into sections by means of a sharp bevel-edged wheel attached to a turning lathe.

The distances from the planes of contact to the boundary planes of the section were first determined with a micrometer attached to the lathe, but this method proved to be unsatisfactory on account of the necessity of shifting the specimen in the lathe chuck. A more satisfactory method consisted in marking the beginning and end of each section with a dividing engine. A slight error results from inaccuracy in setting the cutting tool, but such errors are accidental and are therefore not of a serious character. The method of determining the lengths from the densities will be used in connection with the preceding method for determinations of the very highest precision.

As the edges of the electroplate must be turned off to obtain a perfect cylinder, the plates frequently tend to curl, and it is therefore necessary to clamp the ends lightly in order to insure perfect contact throughout the plane surface. None of the electroplated specimens failed to show

[1] Stefan, J., Über die Diffusion der Flussigkeiten: K. Akad. Wiss. Sitzungsb., Band 79, Abt. 2, pp. 161-214, 1879.

diffusion when heated to a temperature above the normal, but in some of our trials with 0.5-millimeter gold plates only 20 per cent of the specimens showed diffusion at temperatures of 100° and 180° C. In another experiment, however, in which five pairs of gold and lead were heated to a temperature of 150° C., each specimen was found to contain a sufficient quantity of gold for the determination of the coefficient of diffusion (k). We have no explanation to offer for the cause of failure other than the possibility of oxidation and imperfect mechanical treatment. The ends of the lead cylinders were carefully surfaced on a lathe. Oil was used in the surfacing process and afterward removed by the use of caustic soda and a 10 per cent solution of nitric acid. The 0.5-millimeter gold plates (20 millimeters in diameter) require no preparation other than cleansing in dilute nitric acid and distilled water.

Pure gold was obtained from Mr. Jacob B. Eckfeldt, of the United States Mint at Philadelphia. Lead was obtained from the Pennsylvania Smelting Co., Pittsburgh, in the form of bars 1 by 3 by 6 inches. It was found to be free from gold and silver but contained a trace of copper.

The thermostat is provided with two heating coils, one consisting of insulated resistance tape attached to a cylinder of coarse wire screen and placed just within the inside wall, and the other consisting of 20 nickel coils wound on soapstone cylinders (2 by 3½ inches) and placed on the bottom of the thermostat. The insulation powder (Silox) was obtained from the General Electric Co.

Temperatures were measured with standardized mercury thermometers placed at various points. The temperature gradients were found to be so slight that no errors could have arisen from this source.

METHODS OF EVALUATION OF CONSTANTS.

In the evaluation of the coefficient k, investigators frequently use Stefan's tables,[1] which are very convenient when an alloy or concentrated solution of known height and concentration diffuses into pure solvent. In order to apply the tables it is necessary to make the height of the section selected for analysis equal to one-half the height of the alloy or solution from which diffusion emanates. Such tables are not adapted to our needs, and we have used instead some manuscript tables of the probability integral which have been prepared especially for the computation of diffusivities.

The observed concentrations require no correction for the differences in density of the two metals, but the observed distances (x') from the plane of contact must be corrected for the expansion of the solvent over the temperature interval $(T-T_0)$ where T_0 is the temperature at which the specimen is sliced and T is the temperature at which diffusion takes place. If α is the coefficient of expansion of the solvent, the value of x to be used in the formula for q is

$$x=x'\ [1+\alpha(T-T_0)].$$

With q as an argument the values of the probability integral are taken from the special tables for points which correspond to the upper, middle, and lower planes of the section, and in accordance with the approximate formula of Cotes, the average value of the integral for the entire section may be taken to be

$$\frac{1}{6}[\text{sum of end ordinates}+4\times\text{middle ordinate}].$$

Designating the difference between unity and this value of the integral by i, equation (5) may be written

$$v=v_0 i \qquad (6).$$

[1] Stefan, J., op. cit.

Equation (5) contains two unknown constants, v_0 and k. Numerous solutions may be obtained by adopting different methods of procedure or by assigning different weights to the observation equations. As the different methods lead to slightly different values of the constants, it is essential that the method adopted should be theoretically correct.

For the data of this paper the maximum error in the determination of the gold content of each section is of the order of magnitude of 0.005 milligram. The probable error of a single determination is of course less than this quantity, and there is no reason for assuming it to vary for the different sections. The weight of each point on the concentration curve is therefore equal to unity for sections of normal height and one-fourth for sections of one-half the normal height.

Roberts-Austen determined the value of v_0 by extending the concentration curve backward until it intersected the axis of ordinates. This method is not entirely satisfactory on account of the rapid changes in curvature of the concentration curve in the vicinity of the origin. For this reason we have adopted the linear equation

$$idv_0 + qe^{-q^2}\frac{v_0}{\sqrt{\pi k}}dk = dv \quad \text{(7)}$$

or

$$idv_0 + qe^{-q^2}dk' = dv \quad \text{(8)}$$

which enables us by the method of least squares to determine both constants at the same time. The approximate values necessary for the computation of dv were determined by selecting at least three values of k at equal intervals apart and over a sufficient range to include the correct value. Substituting each value of k in (6) and solving in the form

$$v_0 = \frac{\Sigma piv}{\Sigma pi^2} \quad \text{(9)}$$

wherein weights are designated by p, we obtain the corresponding weighted values of v_0. The sum of the weighted squares of the residuals was then computed in the usual manner and plotted with the values of k as abscissas. The value of k which corresponds to a minimum value of the sum of the weighted squares of the residuals was ascertained by drawing a tangent to the curve parallel to the k axis. The corresponding value of v_0 was determined by interpolation, using k as an argument. A rough check on the computation consists in plotting the sum of the weighted squares of the residuals for the new values of v_0 and k on the original diagram. The new point should of course fall at the vertex of the curve. A more satisfactory check is obtained by solving equations (7) and (8). The coefficients and absolute terms of the observation equations are computed from one of the original pairs of values of v_0 and k that are adjacent to but do not coincide with the minimum point of the curve which represents the sum of the weighted squares of the residuals.

In order to show the influence which the data from the various sections exert in fixing the final values of the constants, and at the same time to illustrate the method of computation, the observation equations for the data of Table 1 are tabulated below.

0.68722 dv_0	+0.14949 dk'	=+0.00059
.44324	.27868	− .00005
.26730	.37185	− .00037
.15024	.42083	− .00053
.07850	.42608	− .00040
.03802	.39519	+ .00009
.01704	.34005	+ .00015
.00706	.27351	+ .00014
.00269	.20665	+ .00009
.00095	.14715	+ .00008
.00031	.09899	− .00023
.00009	.06302	− .00006

The normal equations are

$$1.69266\ dv_0 + 0.94621\ dk' = -0.0000016$$
$$0.94621\ dv_0 + 1.02166\ dk' = -0.0003281$$

from which we obtain

$$dk' = -0.000664$$
$$dv_0 = +0.00037$$

As

$$\frac{v_0}{\sqrt{\pi k}} = 1.54386$$

we have

$$dk = -0.00043$$

and

$$k = 0.0080 \quad -0.0004 \quad = 0.0076$$
$$v_0 = 0.02189 + 0.00037 = 0.02226$$

The approximate values

$$k = 0.0080$$
$$v_0 = 0.02189$$

were determined as explained above from the following quantities:

k	v_0	$\Sigma(\text{residuals})^2$
0.0070	0.02283	126
.0075	.02234	84
.0080	.02189	105

The numbers tabulated in the third column are the first two or three digits only of the actual sums. If these numbers are plotted with the values of k as abscissas, it will be found that the minimum point of the curve falls at $k=0.0076$. With this value of k as argument, the corresponding value of v_0 is found by interpolation to be $v_0=0.02230$. These values agree almost identically with those just found by solving the above system of observation equations. The number found for $\Sigma(\text{residuals})^2$ is 82, which is practically the same as the value found by the graphic method. As the coefficients and absolute terms of the normal equations are summations of squares and products of coefficients and products of coefficients and absolute terms of the observation equations, it is evident that the equations at the bottom of the list exert but little influence in the determination of the constants. The final values would remain practically unchanged if the last two or three equations were omitted. The weights of v_0 and k are each finite and may be determined in the usual manner. The respective weights of these quantities resulting from the use of equation (9) are Σpi^2 and ∞. Another solution consists in assigning an infinite weight to v_0, and then taking the weighted mean of the resulting values of k. It is thus evident that the relative weights of v_0 and k must be taken into account, as well as the relative weights of the observation equations. These distinctions may be of practical importance when the deviations from the theoretical curve are of considerable magnitude.

COMPARISON OF OBSERVATION WITH THEORY.

The data on the diffusion of gold into solid lead under atmospheric pressure are presented in Tables 1 to 11 inclusive. The values in the first columns are the observed distances at temperature T_0 from the plane of contact to the center of the section. The 1-millimeter section adjacent to the plane of contact was always rejected. Column 6 gives the percentage of gold computed from the weight of the alloy and the weight of the gold contained in the alloy as tabulated in columns 2 and 3 respectively. Columns 4 and 7 contain the computed theoretical values, and columns 5 and 8 contain the residuals or the differences between the observed and computed values. It will be noted that in each case equation (5) represents the observed facts to a high degree of precision.

TABLE 1.

Distance (x') from plane of contact (centimeters).	Weight of alloy (grams).	Weight of gold (milligrams).			Percentage of gold (v).			Constants.
		Observed.	Computed.	Observed — computed.	Observed.	Computed.	Observed — computed.	
1	2	3	4	5	6	7	8	
0.2	6.7250	1.26	1.23	+0.03	0.0187	0.0184	+0.0003	
.4	6.6105	.96	.97	− .01	.0145	.0146	− .0001	
.6	6.6680	.73	.75	− .02	.0109	.0113	− .0004	
.8	6.6600	.53	.56	− .03	.0080	.0084	− .0004	α=0.0000293.
1.0	6.6310	.38	.40	− .02	.0057	.0060	− .0003	T=197° C.
1.2	6.6535	.29	.27	+ .02	.0044	.0041	+ .0003	t=53.92 days.
1.4	6.6510	.20	.18	+ .02	.0030	.0027	+ .0003	v_0=0.02226.
1.6	6.5785	.13	.11	+ .02	.0020	.0017	+ .0003	k=0.0076.
1.8	7.3140	.09	.08	+ .01	.0012	.0010	+ .0002	
2.0	6.6850	.05	.04	+ .01	.0008	.0006	+ .0002	
2.2	6.7030	.01	.02	− .01	.0002	.0003	− .0001	
2.4	6.5480	.01	.01	.00	.0001	.0002	− .0001	

TABLE 2.

0.2	5.5255	0.71	0.70	+0.01	0.0129	0.0127	+0.0002	
.4	5.4750	.53	.53	.00	.0097	.0097	.0000	
.6	5.4775	.37	.39	− .02	.0068	.0070	− .0002	
.8	5.5130	.25	.27	− .02	.0045	.0049	− .0004	
1.0	5.4940	.18	.18	.00	.0033	.0032	+ .0001	T=197° C.
1.2	5.4935	.12	.11	+ .01	.0022	.0020	+ .0002	t=53.92 days.
1.4	5.5250	.08	.06	+ .02	.0015	.0012	+ .0003	v_0=0.01587.
1.6	5.4880	.04	.04	.00	.0007	.0007	.0000	k=0.0057.
1.8	5.4590	.02	.02	.00	.0004	.0003	+ .0001	
2.0	4.8595	.02	.01	+ .01	.0004	.0002	+ .0002	
2.2	5.5080	Trace.	.004	....	....	.0001	....	
2.4	5.4915	Trace.	.002	....	....	.0000	....	

TABLE 3.

0.2	5.5980	0.80	0.79	+0.01	0.0143	0.0141	+0.0002	
.4	5.5200	.59	.60	− .01	.0107	.0109	− .0002	
.6	5.5645	.44	.45	− .01	.0079	.0081	− .0002	
.8	5.5695	.31	.32	− .01	.0056	.0057	− .0001	
1.0	5.4845	.22	.21	+ .01	.0040	.0039	+ .0001	T=197°C.
1.2	5.5590	.15	.14	+ .01	.0027	.0025	+ .0002	t=53.92 days.
1.4	5.5120	.10	.08	+ .02	.0018	.0015	+ .0003	v_0=0.01739.
1.6	5.6080	.04	.05	− .01	.0007	.0009	− .0002	k=0.0063.
1.8	5.5655	.03	.03	.00	.0005	.0005	.0000	
2.0	5.5620	.02	.01	+ .01	.0004	.0003	+ .0001	
2.2	5.8775	Trace.	.008	....	....	.0001	....	
2.4	5.5470	Trace.	.003	....	....	.0001	....	

TABLE 4.

0.2	7.8865	1.03	1.00	+0.03	0.0131	0.0127	+0.0004	
.4	7.8200	.74	.76	− .02	.0095	.0098	− .0003	
.6	7.8140	.54	.56	− .02	.0069	.0072	− .0003	
.8	7.8295	.39	.39	.00	.0050	.0050	.0000	
1.0	7.8225	.26	.26	.00	.0033	.0033	.0000	T=197° C.
1.2	7.8310	.17	.16	+ .01	.0022	.0021	+ .0001	t=53.92 days.
1.4	7.6505	.11	.10	+ .01	.0014	.0013	+ .0001	v_0=0.01588.
1.6	7.8265	.07	.05	+ .02	.0009	.0007	+ .0002	k=0.0059.
1.8	7.8235	.05	.03	+ .02	.0006	.0004	+ .0002	
2.0	7.7865	.01	.01	.00	.0001	.0002	− .0001	
2.2	7.8535	.01	.01	.00	.0001	.0001	.0000	
2.4	7.7580	.01	.003	+ .007	.0001	.0000	+ .0001	

TABLE 5.

Distance (x') from plane of contact (centimeters).	Weight of alloy (grams).	Weight of gold (milligrams).			Percentage of gold (v).			Constants.
		Observed.	Computed.	Observed – computed.	Observed.	Computed.	Observed – computed.	
1	2	3	4	5	6	7	8	
0.2	7.9530	1.04	1.02	+0.02	0.0131	0.0128	+0.0003	
.4	7.8310	.76	.78	– .02	.0097	.0099	– .0002	
.6	7.8025	.55	.58	– .03	.0071	.0074	– .0003	
.8	7.8530	.41	.41	.00	.0052	.0053	– .0001	
1.0	7.8180	.29	.28	+ .01	.0037	.0036	+ .0001	
1.2	7.7710	.19	.18	+ .01	.0024	.0023	+ .0001	T=197° C. t=53.92 days. v_0=0.01580. k=0.0064.
1.4	7.7970	.13	.11	+ .02	.0017	.0014	+ .0003	
1.6	7.7950	.07	.07	.00	.0009	.0008	+ .0001	
1.8	7.7780	.04	.04	.00	.0005	.0005	.0000	
2.0	7.8805	.01	.02	– .01	.0001	.0003	– .0002	
2.2	7.7940	Trace.	.010	......	......	.0001	......	
2.4	8.0590	.01	.005	+ .005	.0001	.0001	.0000	
2.6	7.6385	Trace.	......	......	......	......	......	

TABLE 6.

Distance (x') from plane of contact (centimeters).	Weight of alloy (grams).	Gold observed (mg).	Gold computed (mg).	Gold observed – computed.	Percentage observed.	Percentage computed.	Percentage observed – computed.	Constants.
0.2	7.8095	0.99	0.98	+0.01	0.0127	0.0125	+0.0002	
.4	7.8490	.74	.75	– .01	.0094	.0095	– .0001	
.6	7.8385	.51	.54	– .03	.0065	.0069	– .0004	
.8	7.8175	.38	.38	.00	.0049	.0048	+ .0001	
1.0	7.7950	.25	.25	.00	.0032	.0032	.0000	
1.2	7.8280	.17	.16	+ .01	.0022	.0020	+ .0002	T=197° C. t=53.92 days. v_0=0.01554. k=0.0058.
1.4	7.7425	.11	.09	+ .02	.0014	.0012	+ .0002	
1.6	7.8155	.06	.05	+ .01	.0008	.0007	+ .0001	
1.8	7.8160	.03	.03	.00	.0004	.0003	+ .0001	
2.0	7.8210	.01	.01	.00	.0001	.0002	– .0001	
2.2	9.2530	.01	.01	.00	.0001	.0001	.0000	
2.4	7.8790	Trace.	.003	......	......	......	......	
2.6	7.8350	Trace.	......	......	......	......	......	

TABLE 7.

Distance (x') from plane of contact (centimeters).	Weight of alloy (grams).	Gold observed (mg).	Gold computed (mg).	Gold observed – computed.	Percentage observed.	Percentage computed.	Percentage observed – computed.	Constants.
0.15	3.7347	0.29	0.28	+0.01	0.0078	0.0074	+0.0004	
.3	7.7415	.46	.47	– .01	.0059	.0060	– .0001	
.5	7.8412	.33	.34	– .01	.0042	.0044	– .0002	
.7	7.8305	......	.24	......	......	.0030	......	T=150° C. t=63.29 days. v_0=0.00878. k=0.0043.
.9	7.9955	.18	.16	+ .02	.0023	.0019	+ .0004	
1.1	7.9550	.09	.09	.00	.0011	.0012	– .0001	
1.3	8.0085	.05	.05	.00	.0006	.0007	– .0001	
1.5	7.9655	.03	.03	.00	.0004	.0004	.0000	
1.7	8.0165	.005	.02	.015	.0001	.0002	– .0001	
1.9	8.0818	Trace.	.007	......	......	.0001	......	

TABLE 8.

Distance (x') from plane of contact (centimeters).	Weight of alloy (grams).	Gold observed (mg).	Gold computed (mg).	Gold observed – computed.	Percentage observed.	Percentage computed.	Percentage observed – computed.	Constants.
0.15	4.0910	0.46	0.42	+0.04	0.0112	0.0103	+0.0009	
.3	7.7562	.63	.65	– .02	.0081	.0084	– .0003	
.5	7.7805	.46	.48	– .02	.0059	.0061	– .0002	
.7	7.8545	.34	.33	+ .01	.0043	.0043	.0000	T=150° C. t=63.29 days. v_0=0.01223. k=0.0044.
.9	7.9800	.24	.22	+ .02	.0030	.0028	+ .0002	
1.1	8.0210	.14	.14	.00	.0017	.0017	.0000	
1.3	8.0762	.09	.08	+ .01	.0011	.0010	+ .0001	
1.5	7.9545	.02	.04	– .02	.0003	.0005	– .0002	
1.7	8.0075	.01	.02	– .01	.0001	.0003	– .0002	
1.9	7.9967	.01–	.01	.00	......	.0001	......	

TABLE 9.

Distance (x') from plane of contact (centimeters).	Weight of alloy (grams).	Weight of gold (milligrams).			Percentage of gold (v).			Constants.
		Observed.	Computed.	Observed — computed.	Observed.	Computed.	Observed — computed.	
1	2	3	4	5	6	7	8	
0.15	3.7090	0.22	0.23	−0.01	0.0059	0.0062	−0.0003	
.3	7.7700	.40	.39	+.01	.0051	.0051	.0000	
.5	7.8110	.29	.29	.00	.0037	.0037	.0000	
.7	7.8028	.21	.20	+.01	.0027	.0026	+.0001	T=150° C.
.9	7.8800	.13	.13	.00	.0017	.0017	.0000	t=63.29 days.
1.1	7.9560	.09	.08	+.01	.0011	.0010	+.0001	v_0=0.00738.
1.3	7.8985	.04	.05	−.01	.0005	.0006	−.0001	k=0.0044.
1.5	7.7985	.02	.03	−.01	.0003	.0003	.0000	
1.7	7.8360	.01	.01	.00	.0001	.0002	−.0001	
1.9	7.7175	.005	.006	−.001	.0001	.0001	.0000	

TABLE 10.

0.15	4.0060	0.45	0.41	+0.04	0.0112	0.0103	+0.0009	
.3	7.7520	.63	.65	−.02	.0081	.0084	−.0003	
.5	7.7710	.46	.47	−.01	.0059	.0061	−.0002	
.7	7.8545	.33	.33	.00	.0042	.0041	+.0001	T=150° C.
.9	7.9950	.23	.21	+.02	.0029	.0027	+.0002	t=63.29 days.
1.1	8.1765	.15	.13	+.02	.0018	.0016	+.0002	v_0=0.01231.
1.3	7.9370	.06	.07	−.01	.0008	.0009	−.0001	k=0.0042.
1.5	7.8960	.03	.04	−.01	.0004	.0005	−.0001	
1.7	7.8355	.02	.02	.00	.0003	.0002	+.0001	
1.9	7.8320	.01	.01	.00	.0001	.0001	.0000	

TABLE 11.

0.15	3.9050	0.04	0.04	0.00	0.0010	0.0011	−0.0001	T=100° C.
.3	8.1800	.03	.03	.00	.0004	.0004	.0000	t=103.43 days.
.5	8.0000	.01	.00	+.01	.0001	.0000	+.0001	v_0=0.0023.
.7	8.1380	.01−	.002	....	.0001−	.0000	....	k=0.0002+.

The agreement of theory with observation is further shown in figure 32, in which the heavy line represents the theoretical and the dotted line the observed concentrations of Table 1. The short vertical lines drawn perpendicular to the x axis mark the points at which the lead cylinder was sliced. The remarkable agreement between the different determinations of k is shown in Table 12.

TABLE 12.

Temperature. (° C.).	Time (days).	v_0 (per cent).	k	Mean.	Remarks.
197	53.92	0.0223	0.0076	0.0076	Gold cylinder.
197	53.92	.0159	.0057	....	Electroplate.
197	53.92	.0174	.0063	....	Do.
197	53.92	.0159	.0059	....	Do.
197	53.92	.0158	.0064	....	Do
197	53.92	.0155	.0058	0.0060	Do.
150	63.29	.0088	.0043	....	0.5-millimeter gold plate.
150	63.29	.0122	.0044	....	Do.
150	63.29	.0074	.0044	....	Do.
150	63.29	.0123	.0042	0.0043	Do.
100	103.43	.0023	.0002+	0.0002+	Do.

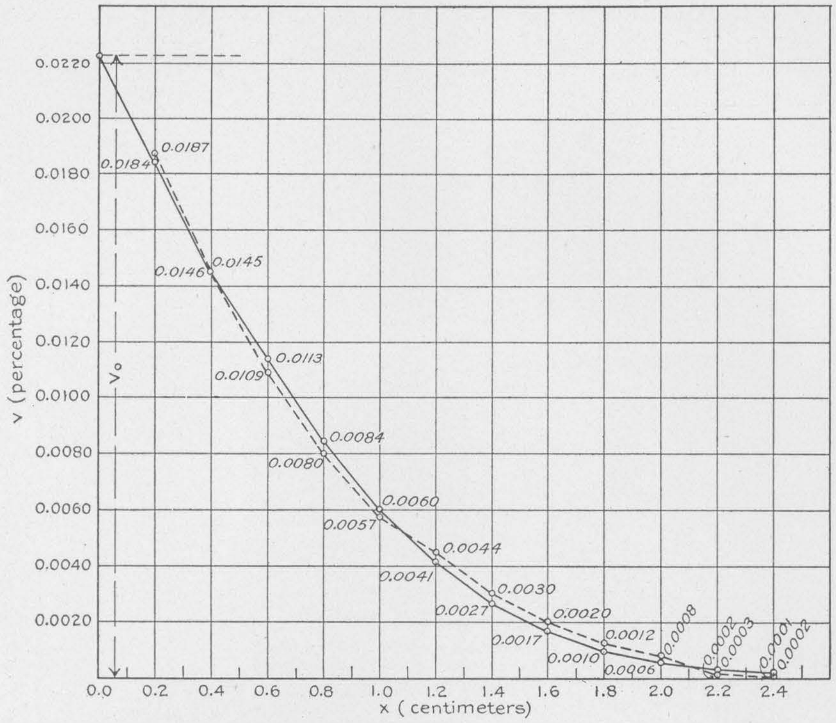


FIGURE 32.—Comparison of observed and theoretical concentrations in experiments on diffusion of solids. The latter are represented by the continuous line; the former by the dotted line.

The value $k=0.0076$ at 197° agrees well with Roberts-Austen's values 0.007 and 0.008 at 200°. The fact that all the values determined from electroplates are low is suggestive, but the deviation of the highest value (0.0076) from the mean of the entire set is less than five times the probable error of a single observation, consequently it must be inferred that the distribution of values is accidental. The value $k=0.0043$ at 150° is in close agreement with Roberts-Austen's values 0.004 and 0.005 at 165°, but our value 0.0002+ at 100° is ten times his value at the same temperature.

VARIATION OF THE COEFFICIENT OF DIFFUSIVITY WITH PRESSURE.

Only a few preliminary attempts have been made to determine the effect of pressure on the diffusion process. The lead cylinders used for this purpose were about 20 millimeters in diameter and 5 or 6 centimeters in length. The ends of each cylinder were electroplated with gold. A small hole was drilled from one end to the center of the cylinder for the insertion of a thermo-element. Pressures were applied by means of oil. The observations and the constants obtained from them are summarized in Table 13. The data are barely sufficient for the determination of the two constants, as in most of the experiments there were only two observed values. The results obtained from A and C are quite as trustworthy as those obtained from B. The latter shows a very large increase in the rate of diffusion; the former practically none at all. Each end of specimen D was melted during the progress of the experiment. This may have been due to a slight variation in the temperature gradient within the bomb, or to some other accidental irregularity of which we have no knowledge. Specimens E and F were subjected to high pressures at ordinary temperature. No gold was found in either of these specimens. Figure 33 is a photograph of specimen F. The double system of fractures was probably produced by differential stresses resulting from the increased viscosity of the oil at high pressures. A small portion only of the total number of lines on the surface of the lead cylinder

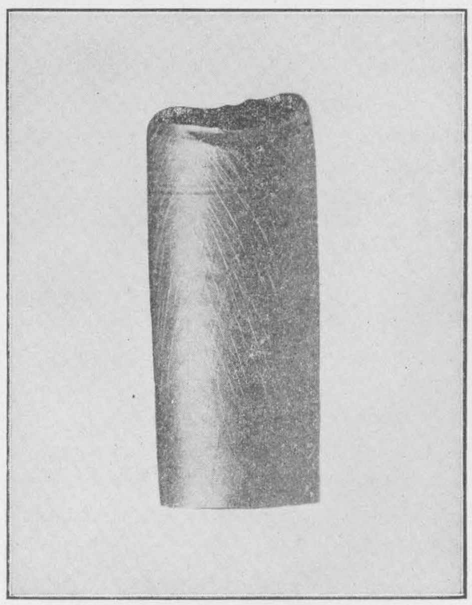


FIGURE 33.—Lead fractured by small differential stresses when subjected to a hydrostatic pressure of 10,200 atmospheres to the square inch.

was reproduced in the photograph. Markings of a somewhat similar character are known as Luder's lines.[1]

TABLE 13.

Specimen.	Distance (x') from plane of contact (centimeter).	Weight of alloy (grams).	Weight of gold (milligrams).	Percentage of gold.	Pressure (atmospheres per square inch).	Temperature (° C.).	Time (days).	Constants.
A....	0.15	4.7125	0.09	0.00191	1,000	150	2.00	$v_0=0.006$, $k=0.006$
	.25	3.4570	.02	.00058				
	.35	3.0780	Trace.	....				
	.15	4.9690	.09	.00181	1,000	150	2.00	$v_0=0.007$, $k=0.004$
	.25	3.6800	.01	.00027				
	.35	3.2115	Trace.	....				
B....	.2	6.8120	.19	.00279	1,650	150	1.229	$v_0=0.012$, $k=0.010$
	.4	6.3735	.01	.00016				
	.6	6.3985	None.	....				
	.2	6.8725	.18	.00262	1,650	150	1.229	$v_0=0.010$, $k=0.013$
	.4	6.8900	.02	.00029				
	.6	6.8970	None.	....				
C....	.15	3.2125	.07	.00218	1,900	150	2.00	$v_0=0.006$, $k=0.007$
	.25	4.3400	.03	.00069				
	.35	3.8350	Trace.	....				
	.45	3.6270	Trace.	....				
	.15	3.5480	.09	.00254	1,900	150	2.00	$v_0=0.008$, $k=0.005$
	.25	3.6375	.02	.00055				
	.35	4.1900	Trace.	....				
	.45	3.0655	Trace.	....				
D....	.05	5.2525	147.04	....	1,650	190	1.250	$v_0=0.079$, $k=0.022$
	.15	3.4670	1.40	.04038				
	.30	7.1680	1.19	.01660				
	.50	7.1479	.26	.00364				
	.70	7.1808	.02	.00028				
	.90	7.1964	None.	....				
	.05	3.1250	93.14	....	1,650	190	....	$v_0=0.079$, $k=0.023$
	.15	3.6390	1.54	.04232				
	.30	7.1850	1.19	.01656				
	.50	7.4616	.22	.00295				
	.70	7.4728	.01	.00013				
	.90	7.5469	None.	....				
E....	.15	3.8075	None.	....	7,200	20	2.825	....
	.30	7.2725	None.	....				
	.50	7.1885	None.	....				
	.70	7.1700	None.	....				
F....	.2	8.5932	None.	....	10,200	17	2.94	....
	.4	8.3433	None.	....				
	.6	8.4005	None.	....				
	.8	8.3940	None.	....				

CONCLUSIONS AND INFERENCES.

Roberts-Austen's values of the coefficients of diffusion of gold into solid lead are practically correct except for the value at 100° C., which is probably too small. The close agreement of the values of the coefficients obtained from specimens subjected to the same temperature indicate that a higher degree of precision may be attained in their determination. The value of the coefficients probably increases with pressure.

[1] Mason, W., The Luder's lines on mild steel: Phys. Soc. London Proc., vol. 23, pp. 305–333, 1911.

The observed values tabulated in Table 1 and shown graphically in figure 32 represent the diffusion into lead from a gold cylinder 20 millimeters in diameter and 10 millimeters in height. A very sensitive test failed to detect the diffusion of the lead into the gold at depths greater than 0.2 millimeter, but the methods of detecting lead under these conditions are far less precise than those for detecting gold in lead.

The tendency of molecules to diffuse must always exist when there is a heterogeneous distribution of concentration and the temperature of the masses is above the absolute zero. Considered as a dynamic system operative at all times, the transportation of matter by diffusion in the solid crust of the earth may be very extensive. The possible effects of these persistent motions may be indicated by considering the migration of gold into pure lead at a temperature of 200° C. If we accept the lower value of the coefficient $k=0.007$ and put the initial concentration $v_0=0.02$ per cent, particles of gold would have passed through 6.4 centimeters (2.5 inches) of lead in one year and 64 centimeters (25 inches) of lead in 100 years in sufficient quantities to have produced a concentration of 0.0001 per cent at these points.

If a portion of the materials constituting the crust of the earth are capable of diffusing into one another under pressure, it would seem that the argument for isostatic adjustment is greatly strengthened, for a substance in which the particles glide over one another possesses one of the essential characteristics of a liquid and may therefore be expected to yield slowly when subjected to small stresses operating during geologic epochs.

ACKNOWLEDGMENTS.

The electroplates used in these experiments were prepared by Mr. R. C. Wells, of the United States Geological Survey. The pressure tests were conducted by Drs. John Johnston and L. H. Adams, of the Geophysical Laboratory of the Carnegie Institution. We are greatly indebted to these gentlemen for their suggestions and cooperation.

NOTES ON THE GEOLOGY OF GRAVINA ISLAND, ALASKA.

By Philip S. Smith.

INTRODUCTION.

Gravina Island is in the extreme southern part of Alaska and is about 20 miles long and 10 miles wide. It lies about 30 miles north of the international boundary and is separated by a narrow channel from the town of Ketchikan, the southernmost port of call in Alaska. Its general position with regard to other parts of southeastern Alaska is shown on figure 34. An opportunity of studying the coast exposures of this island was afforded the writer in the summer of 1913. This work, amplified by the earlier investigations of Brooks[1] and the Wrights,[2] showed the presence of Triassic rocks, which previously had been reported definitely at only one other locality in southeastern Alaska. Inasmuch as the structure and general relations of Gravina Island furnish an insight into the geology of this region, the following notes are presented. Little of the island away from the seacoast has been studied, and therefore the geology of the interior is practically unknown.

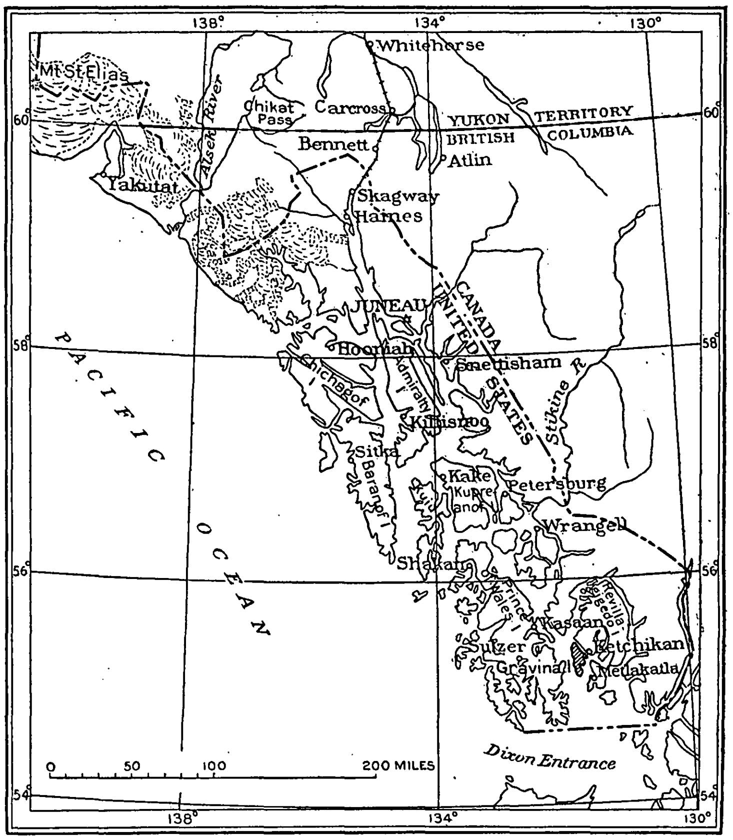


Figure 34.—Map of southeastern Alaska showing position of Gravina Island (indicated by shading).

Both igneous and sedimentary rocks are represented in the region. The sedimentary rocks range in character from thoroughly recrystallized schists to unmetamorphosed conglomerates, sandstones, and limestones. The igneous rocks include both deep-seated intrusives and surface flows. The general distribution of these rocks is shown on the geologic map (fig. 35).

SEDIMENTARY ROCKS.

GNEISS AND AMPHIBOLITE.

The oldest rocks recognized on Gravina Island are exposed at the extreme southern point, Dall Head. At this place they consist of highly metamorphic gneisses and amphibolites which

[1] Brooks, A. H., Preliminary report on the Ketchikan mining district, Alaska: U. S. Geol. Survey Prof. Paper 1, 120 pp., 1902.
[2] Wright, F. E. and C.W., The Ketchikan and Wrangell mining districts, Alaska: U. S. Geol. Survey Bull. 347, pp. 210, 1908.

have been intruded by igneous rocks. Undoubtedly the older rocks have been metamorphosed locally by the younger intrusives, but apparently they were considerably metamorphosed dynamically before they were intruded. No definite determination of the age of the gneisses and amphibolites has been made. Judged by their physical character they seem to be much older than any of the known late Paleozoic rocks. Although their aspect may be due in large measure to the contact effects produced in proximity to the large intrusive masses, the impression gained in the field, and not dispelled by later investigations in the office, is that those rocks are probably at least as old as the middle or earlier part of the Paleozoic era.

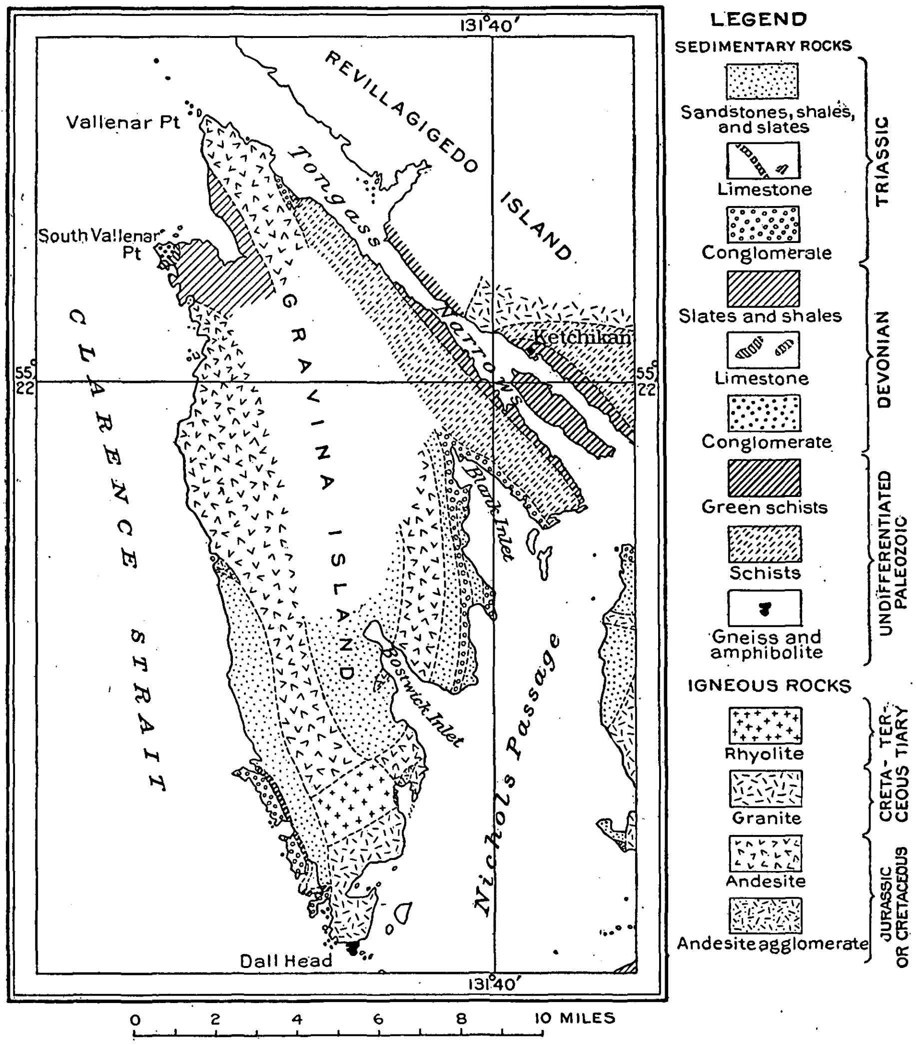


FIGURE 35.—Geologic map of Gravina Island, Alaska.

The relation of the old gneisses and amphibolites to the other sedimentary rocks of the region is indefinite, because they occupy only a small area at the extreme end of the island and are surrounded on all sides by sea or by a large area of younger igneous rock. No other rocks on Gravina Island are correlated with these rocks near Dall Head.

ROCKS NEAR VALLENAR BAY.

Near the north end of Gravina Island, in the vicinity of Vallenar Bay, sedimentary rocks are exposed which lithologically simulate other rocks on the island, but which paleontologically are apparently quite distinct. These rocks are considerably deformed and their relations are not everywhere evident. At the base, apparently, they consist of a small amount of conglomerate composed of pebbles few of which are over an inch in diameter. The pebbles are dominantly of schist or of quartz. The strike of the conglomerate ranges from northwest to northeast and the dip from northeast to southeast. Apparently the structure is that of a steep eastward-pitching anticline.

Overlying the conglomerate is a thin limestone, and this is succeeded by black slates and sandy beds. The rocks are not much metamorphosed and in the field were correlated with the Triassic rocks on the southwest coast. This correlation, however, is not confirmed by fossils found at a locality about a mile east of South Vallenar Point. According to the Wrights [1]—

Fossils were first found at this locality by Brooks in 1901 and were determined by Charles Schuchert to be Devonian. In 1905 a collection was made at this place by E. M. Kindle, and in 1906 more material was gathered by the writers. Kindle reports as follows:

"One mile west of Vallenar Bay, Gravina Island.—The material from this locality, while generally insufficient for specific determination, is much better than that obtained last year (1905), and leaves no doubt as to the Devonian age of the beds west of Vallenar Bay. Several specimens of *Atrypa reticularis* are present. This fixes the horizon as not later than Carboniferous, while the association of Chonetes cf. *manitobensis*, Spirifer sp., Proetus sp., and Cyclonema sp. indicate a horizon of Devonian age, probably middle Devonian."

The finding of Triassic fossils in rocks of similar lithologic character in the central part of Gravina Island suggested the need of a review of this early determination, and Mr. Kirk reexamined the collections from this locality. In an informal communication he states that the rocks from the vicinity of Vallenar Bay are clearly of Paleozoic age and that he sees no reason to question their assignment to the Devonian, as was originally suggested by Schuchert.

There seems to be no reasonable room for doubt that Paleozoic rocks, in part of Devonian age, occur in the vicinity of Vallenar Bay. The relation of these rocks, however, to the other sedimentary rocks is unfortunately obscured by the presence of later effusive rocks which unconformably overlie them and mask their contacts with the other rocks.

SCHISTS ON NORTHEAST COAST.

East of the eastern entrance to Blank Inlet and extending in a belt about a mile wide nearly to Gravina Point are metamorphic rocks consisting of schists and schistose limestones. The rocks of this belt trend dominantly northwest and dip apparently eastward at steep angles. As will be shown later in more detail, the major structure of Gravina Island is believed to be that of an overturned syncline. Therefore, although the dominant dip of the schists appears to be eastward, the geologic sequence is believed to be reversed, so that the top of the schist member is toward the west and the bottom toward the east.

The schists are considerably faulted, and the sequence of the individual beds is by no means constant. The contacts of the schist with the fossiliferous beds on Gravina Island are not such as to show definitely the relations of these rocks, and consequently interpretation of their age is based more on general features than on specific details. Apparently the schists are much more metamorphosed than the Devonian rocks already described. This difference in amount of metamorphism does not seem to be due to the proximity of the schists to the great intrusive masses of the Coast Range batholith, for apparently the rocks both at Vallenar Bay and on the northeastern coast of Gravina Island are about equally distant from the known large areas of intrusive rock. The difference in the amount of metamorphism therefore seems to be best explained by assuming that the rocks on the northeastern coast of Gravina Island have been affected by dynamic metamorphism to which the other rocks were not subjected. If this interpretation is correct it seems probable that the schists are older than the Devonian rocks. Inasmuch, however, as this suggestion is not confirmed by other facts it must be regarded as only a tentative correlation, and further data must be sought. Although definite correlation is not now made, little doubt is felt that these schists are of Paleozoic age, and they have consequently been represented on the accompanying map as belonging to the group called, for brevity, the undifferentiated Paleozoic rocks.

[1] Wright, F. E. and C. W., op cit., p. 50.

GREEN SCHISTS NEAR KETCHIKAN.

East of the belt of schists just described is another schist which forms the coast line for about 7 miles northwestward from Gravina Point. This is a light-green, thinly cleaving rock that seems distinct from the other schists. It has been variously interpreted as a schistose tuff, a sheared intrusive or extrusive igneous rock, or a sedimentary rock. No conclusive proof of its origin has yet been adduced. Its general appearance under the microscope suggests that it may have been a tuff, but in the specimens examined metamorphism had obliterated the diagnostic features.

This rock occurs not only on Gravina Island but also on the east side of Tongass Narrows, in the vicinity of Ketchikan, and it is the rock on which Brooks based the formation entitled on the map accompanying his report[1] "greenstone schist, Paleozoic." If this rock underlies the water-covered area which separates Gravina Island from Ketchikan it must occupy a belt nearly 2 miles wide. Apparently it has considerable longitudinal extent, for it has been recognized to the southeast at Foggy Bay and near Cape Fox, the latter place distant nearly 50 miles in an air line, and to the northwest on Cleveland Peninsula, a distance of at least 20 miles.

The continuity of the belt of green schists, the preservation of a semblance of tuffaceous composition, and the physical appearance of the rocks suggest that the green schists are younger than the schists to the west. This conclusion is further supported by the general eastward dip of the rocks, but, as has already been pointed out, this dip is not believed to be conclusive, for part of the structure is believed to be overturned. Probably an undetected fault or an unconformity separates the green schists from the schists to the west.

TRIASSIC ROCKS.

WEST COAST OF GRAVINA ISLAND.

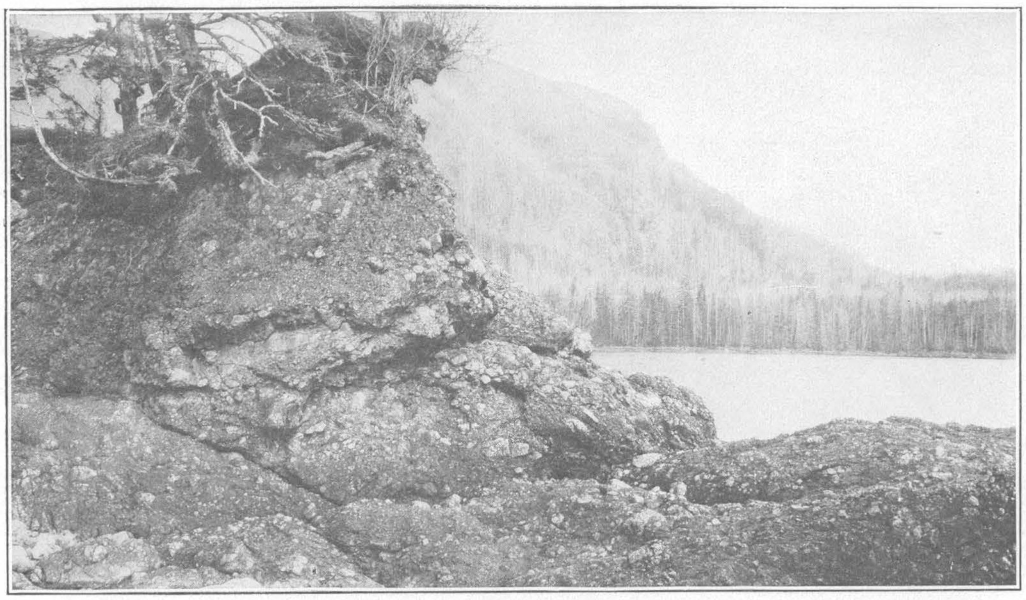
On the west coast of Gravina Island, about 1½ miles north of Dall Head, a conglomerate is exposed. South of this place the coast line is formed of granitic rocks. The relation of the southernmost conglomerate exposure to the granitic rock was not observed. None of the granite was recognized in the pebbles of the conglomerate, and the presumable age of the granite suggests that the contact relation is either that of intrusion or of faulting. At this place the conglomerate trends nearly east and stands nearly vertical. Thin sandstone beds alternate with beds of pebbles and cobbles, all thoroughly indurated so that the rocks fracture across the grains. Little or no cleavage has been developed, and the jointing is rather widely spaced.

A short distance to the north a small bay indents the coast, and on the islands in the bay a gray, reddish-weathering gritty limestone crops out. The strike of this rock swings abruptly from a general easterly trend on the southern islands to a northerly trend on the northern islands. The structure is that of an appressed fold pitching east. On the northern headland of this bay the conglomerate again appears, having apparently passed seaward of the limestone islands. This interpretation is further suggested by the presence of a submerged rocky shoal in the position that projection of the structure of the limestone would indicate should be occupied by the conglomerate. On the northern point of the bay the conglomerate and limestone dip 30° E. and strike about N. 25° W. Plate VII, *A*, shows a characteristic view of the conglomerate at this place. The conglomerate apparently is conformably overlain by the limestone.

A collection of fossils from this bay was made in 1906, but the precise locations of the outcrops from which the collections were obtained were not recorded. The lithology of the matrix containing the fossils, however, leaves no room to doubt that the collections came from this rather narrow band of limestone. The fossils were not diagnostic, but they were provisionally referred by the Wrights to the lower Carboniferous, though they stated that they might represent a Triassic horizon. G. H. Girty,[2] who examined the collections, reported:

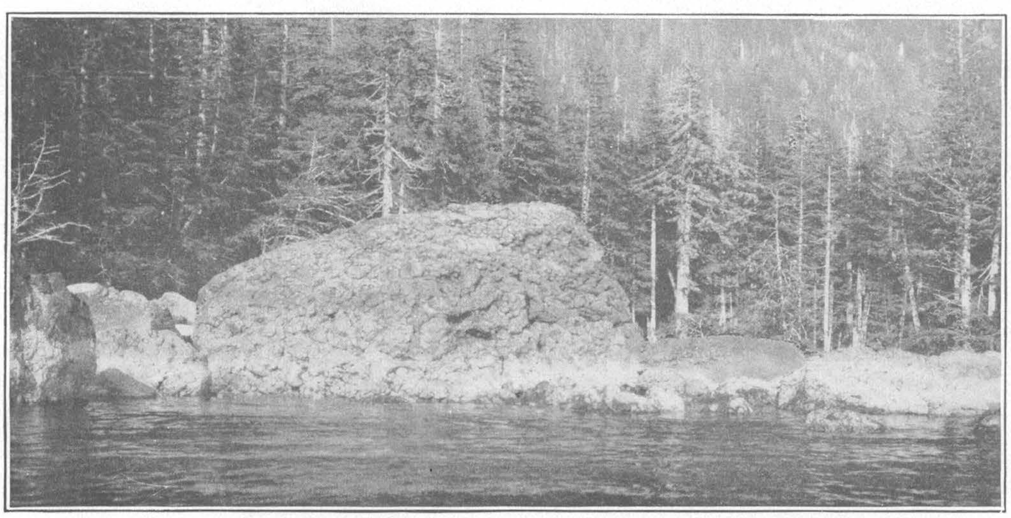
[1] Brooks, A. H., op. cit., pl. 2.

[2] Cited by Wright, F. E. and C. W., op. cit., pp. 52–53.



A. TRIASSIC CONGLOMERATE 3 MILES NORTH OF DALL HEAD, GRAVINA ISLAND, ALASKA.

B. TRIASSIC SANDSTONES AND SHALES ON WEST COAST OF GRAVINA ISLAND, ALASKA.



C. ANDESITIC AGGLOMERATE ON WEST COAST OF GRAVINA ISLAND, ALASKA.

Zaphrentis sp.
Lithostrotion sp.
Martinia? sp.
Dielasma? aff. bovidens Tschern. non Martin.
Dielasma? aff. millepunctatum.
Aviculipecten? sp.
Halobia? sp.
Pteria? sp.
Tetinka? cf. bellula Barrande.
Loxonema? sp.
Euomphalus? sp.
Pleurotomaria sp.
Naticopsis sp.
Several undetermined forms.

By the presence of Halobia (?), which is very similar to if not identical with that which occurs in lot 17 on the Yukon [now considered Triassic], as well as by certain other particulars, a correlation of the two horizons is suggested, and perhaps for the present that is the best disposition that can be made of this very ambiguous collection. At the same time the two faunas are rather widely different.

East of the limestone and separated by a short interval in which no rocks are exposed are outcrops of shales, slates, and thin sandstones. These beds apparently trend parallel to the conglomerate and limestone. Thus at the northern part of the bay they strike nearly north and dip at moderate angles to the east; in the central part they form a closely appressed synclinal fold pitching east, cut by small faults; still farther south they trend nearly east and dip steeply north. Cleavage rather steeply inclined to the bedding has been induced in the weaker members to such an extent that the rock fractures into small angular slaty bits. Owing to this structure, bedding that would be easily recognizable in outcrop is extremely obscure in the small cleavage flakes into which the rock breaks. This precludes hasty search and doubtless accounts for the lack of success earlier geologists have had in obtaining fossils. Where good bedding planes are found fossils are abundant. All the forms seen consisted of one genus, but doubtless further search would reveal others. These forms are so numerous that the imprint of their shells forms an almost unbroken surface. No shell material remains. The fossils are simply imprints of the shells in the shale, and their presence usually is not determinable in sections of the rock other than those parallel to the bedding.

The collections of fossils obtained north of the center of the small bay on the northern limb of the appressed pitching syncline (8704), and also from the cove 6 miles north of Dall Head (8705) were submitted to T. W. Stanton, who reported upon them as follows:

The only fossil species recognized in these two lots is a Halobia, which is closely related to if not identical with *H. superba* Mojsisovics, an Upper Triassic species. The rocks from which these collections came are therefore referred to the Triassic.

The exposures on this bay were examined in 1914 by G. C. Martin, who obtained several collections of Triassic and one of Devonian fossils. It is Mr. Martin's opinion [1] that—

the Triassic conglomerate rests unconformably upon Devonian rocks, like those of Vallenar Bay, at the north end of Gravina Island, and the Devonian fossils which have been collected near the Triassic fossil localities on the "cove 3 miles north of Dall Head," were obtained either from Devonian bowlders in the Triassic conglomerate or from unrecognized Devonian rocks occurring in complex structural association with the Triassic beds.

The fossils collected by Mr. Martin were determined by T. W. Stanton, as follows:

8829 (G. C. M. No. 1). Gravina Island, north arm of cove 3 miles north of Dall Head. Float on outcrop of shale and thin limestone beds of localities 8834 and 8835.
Undetermined corals. Possibly Triassic.

8830 (G. C. M. No. 2). Gravina Island, south arm of same cove as 8829. Massive limestone outcrop near anchorage behind wooded island.
Undetermined corals of Mesozoic type—two or three genera represented.
Ostrea? sp.
Pseudomelania? sp., internal cast.
Arcestes?? sp., fragment; may not even be an ammonite. Probably Triassic.

8831 (G. C. M. No. 3). Gravina Island near 8830. Large limestone nodule in conglomerate.
The whole nodule is a nautiloid with deeply lobed suture, possibly referable to Cosmonautilus. On the back is a Rhynchonella (?).
Probably Triassic.

8832 (G. C. M. No. 4). Gravina Island, near south foreland on arm of cove 3 miles north of Dall Head, near contact with conglomerate.
Undetermined coral fragment.
Pentacrinus sp., segment of column.
Probably Triassic.

[1] Martin, G. C., The Mesozoic of Alaska (in preparation).

8833 (G. C. M. No. 5). Gravina Island, south arm of cove 3 miles north of Dall Head. Near zone of nodular masses of limestone in conglomerate.

This lot appears to be Devonian. [See Kirk's report, below.]

8834 (G. C. M. No. 6). Gravina Island, north arm of cove 3 miles north of Dall Head. Massive limestone in reef west of cabin. Probably about 100 feet below 8704.

Corals, probably several genera.
Cassianella sp.
Myophoria?? sp.
Natica sp.
Murchisonia? sp.
Triassic.

8835 (G. C. M. No. 7). Gravina Island, near 8834, from thin-bedded limestone interbedded with shale about 20 or 30 feet below 8834.

Corals—several genera represented.
Spiriferina? sp.
Myophoria? sp.
Natica sp.
Turritella? sp.
Pseudomelania? sp.
Trachyceras? sp., small fragment.
Triassic.

The fossils from locality 8833 have been examined also by Edwin Kirk, who submitted the following report on them:

Devonian (Middle).

No. 5. South arm of "cove 3 miles north of Dall Head." Near zone of nodular masses of limestone in conglomerate.

Cladopora sp.
Diaphorostoma sp.

These fossils are clearly of Devonian age. P. S. Smith collected corals identical with those in this lot from Kasaan Bay, Long Island, in 1913 at locality 13AS49.

The conglomerate is exposed continuously along the coast for 3 miles north of this bay and throughout this distance strikes nearly parallel to the coast and dips at low angles eastward. Deformation then causes the strike to swing more to the northwest, or seaward, and the conglomerate disappears from the coast, probably being covered by water. Overlying it, however, appears the small limestone band, and this in turn is overlain by shales and sandstones similar to those farther south. Halobia is found in the shales at this place (8705) also.

The shales and sandstones were traced northward almost continuously for about 5 miles. Throughout this distance the rocks are approximately parallel to the coast, dipping eastward, but here and there showing a small amount of deformation such as that illustrated by Plate VII, *B*. Although folding of the sort shown by the picture complicates measuring the thickness of the formation and introduces minor irregularities, it is evidently of a relatively simple type and on a broad scale.

EAST COAST OF GRAVINA ISLAND.

On the east side of Gravina Island the structure is somewhat more involved and the several lines of evidence lead to somewhat antithetical conclusions. The conglomerate on the west coast at the southernmost locality trends nearly east. Its direct continuation on this trend is apparently interrupted by granite and other igneous rocks which form the country rock on the east coast as far north as Bostwick Inlet.

On the headland northeast of the entrance of Bostwick Inlet a conglomerate trending nearly north and dipping 70° E. is exposed. It is somewhat finer grained than the conglomerate on the west coast, but lithologically resembles and seems to be equivalent to the western conglomerate. If this correlation is valid the structure of the island as a whole is that of a somewhat overturned synclinorium whose western limb dips about 25° E. and the eastern limb about 70° E. This fold is not simple, for its general synclinal structure is complicated by subordinate anticlinal flexures. This is well shown by the numerous folds observed along Blank Inlet, where small anticlines separated by minor synclines give the formation a much greater areal extent than the steep dip and normal thickness would otherwise admit. Faulting on a small scale has also produced some duplication of strata and some apparent anomalies of distribution.

To the west of the conglomerate on Bostwick Inlet are black sandstones and thin impure limestones, in general striking north and dipping east at high angles. Fossils were collected in 1913 by the writer from these rocks on the west shore of Bostwick Inlet and submitted to Mr. Girty for examination. The following is his report to Mr. Stanton:

Three lots from Bostwick Inlet, Gravina Island, contain round crinoid stems (13AS170) and a single compressed pelecypod (13AS169), suggesting the genus Posidonomya. The third lot (13AS171) contains a pelecypod fauna interesting and varied but entirely new to me. As these fossils at best show only the shapes and some of them the sculpture, and as pelecypods of similar external appearance may belong to widely different genera, the identifications made here are offered with doubt. Though similar doubt tacitly surrounds many pelecypod identifications in faunal lists and elsewhere, I have expressed it in this case by the use of question marks because the age of the whole fauna is involved in such uncertainty. In lot 171 five types are represented more or less abundantly and by specimens more or less good. These are Glossites? cf. *G. lingualis*, Schizodus? cf. *S. appressus*, Paracyclas? cf. *P. ellipticus*, Crenipecten? cf. *C. crenulatus*, Elymella? cf. *E. nuculoides*. Besides these, however, there are a good many indeterminate forms, some of which suggest the genera Leda, Chonetes??, Pseudomonotis??, Aviculipecten, and Nucula. The age of the fauna is quite uncertain. You declined for the time being to admit it into the Triassic, and nothing resembling it has thus far been brought in from the Alaskan Carboniferous. The generic and specific resemblances suggested above might indicate a Devonian fauna, but neither has any Devonian fauna related to this been obtained from Alaska. The genus Chonetes, if definitely present, would at least limit the geologic age to the upper Paleozoic, but the specimen is so imperfect that even the identification as a brachiopod is doubtful.

Thus the age of this, the best fauna in the collection, must for the present remain undesignated. It would be highly rash to attempt any definite age determination or conclusion for the other lots, containing as they do, for the most part, only crinoid stems (even that being doubtful in some cases), though they may tentatively be placed in the Paleozoic.

As Mr. Girty points out, this fauna is entirely unlike any other from Alaska. It therefore affords little aid in solving the stratigraphic position of the beds on Gravina Island. Certain significant deductions, however, suggest themselves. In general in southeastern Alaska the known Carboniferous rocks are limestones and not lithologically similar to the rocks of Gravina Island. The rocks here discussed are much less dynamically metamorphosed and are less intensely deformed than the known Devonian or Carboniferous rocks of the region. Their relation to the andesitic agglomerates and flows fits in better with an assumed Mesozoic age than with a Paleozoic age. The almost uninterrupted succession of beds from a basal (?) conglomerate to shales containing unquestioned Triassic fossils on the southwestern coast suggests that the doubtfully determined genera from that locality, provisionally assigned to the Carboniferous, justify the suggestion made by Mr. Girty at that time that they may mark a Triassic horizon. No Lower Triassic is known in Alaska. Is it not possible that this fauna from Bostwick Inlet, which is unknown elsewhere in Alaska, fits into this as yet unfilled gap?

The fossils represented in the following list were obtained by G. C. Martin at or near this same locality. These fossils were determined by T. W. Stanton as follows:

8836 (G. C. M. No. 8). Gravina Island, Bostwick Inlet, west shore near entrance. From angular nodules in a brecciated(?) nodular limestone.

Terebratula sp.	Myophoria sp.
Spiriferina? sp.	Myophoria or Trigonia sp.
Pecten sp.	Nucula sp.
Plicatula? sp.	Astarte? sp.
Cassianella sp.	Arcestes? sp.

Triassic. This assemblage suggests the fauna of the lower part of the Modin formation in California, which was tentatively assigned to the Jurassic.

The eastward-dipping structure which is dominant on Gravina Island indicates that the beds of Bostwick Inlet are equivalent to or higher rather than lower than the definitely determined Triassic beds on the west side of the island. An interpretation of the structure as that of an overturned anticline, in which the beds in the central part of the island are the oldest, is possible, but is opposed by the observed dips and by the broader correlations already pointed out. The interpretation that these conglomerates, thin limestones, shales, and sandstones may be of early Mesozoic age seems to be a reasonable working hypothesis. Further stratigraphic and paleontologic evidence should be sought and the field relations carefully scanned to test this interpretation, but until work of this character presents data more in accord with another view the rocks on the west coast of Gravina Island and on the east coast as far northeast as Blank Inlet should be regarded as of the same age.

In this connection it may be interesting to note that Brooks long ago grouped these rocks together and regarded them as of Mesozoic age. He included these rocks in his Gravina series, which he described as follows: [1]

> This is a series of massive conglomerates overlain by black shales or slates and closely infolded with the rocks of the Vallenar series. * * * It is thus probable that the placing of the Gravina series in the Cretaceous is correct.

Subsequently,[2] however, he said:

> The Gravina was correlated with Dawson's Queen Charlotte group (Cretaceous), but on reviewing the evidence its identity with the Vancouver series (Triassic) seems equally probable.

About 2½ miles southeast of Vallenar Point, immediately beyond the belt of undifferentiated Paleozoic schists, is a conglomeratic rock. This differs from the conglomerate noted on Bostwick and Blank inlets in that it is somewhat more schistose. Like the conglomerate at those places it is rather fine grained, few of the pebbles being more than an inch or two in diameter, and it thus appears quite different from the very coarse phase seen on the west coast of the island. The relations of this northernmost conglomerate are obscured, as the beds have been considerably disturbed by faulting subsequent to the deposition of the next overlying formation. Inasmuch, however, as this conglomerate is essentially in line with the conglomerate on Blank Inlet, has a corresponding strike and dip, and is not more than 7 miles distant, and as the general relation at the two places are essentially the same, the two are correlated.

IGNEOUS ROCKS.

ANDESITIC EFFUSIVE ROCKS.

Immediately north of the Triassic shales on the west coast is a volcanic breccia of andesitic composition. Large bowlders of this formation had been recognized along the beach farther south and had apparently fallen from the hills that rise steeply from the coast. Plate VII, *C*, shows some of these large bowlders at a point 1 mile north of the Triassic fossil locality that was noted as 6 miles north of Dall Head. The detrital character of the rock and the distribution of the float indicate that it has a distinct stratigraphic position above the Triassic rocks. Just what the relation is was not determined, as the contacts were not well exposed and the depositional structure was not evident, but marked discordance was apparent. The andesitic breccia or agglomerate was recognized also on the east coast of Vallenar Bay and at Seal Bay, on the east coast of the island.

Stratigraphically overlying the andesite agglomerate or breccia is a considerable thickness of andesitic flows, with here and there a relatively small amount of interbedded sedimentary material. These rocks are strikingly similar to those in the region north of Juneau, described by Knopf as augite melaphyres and referred by him to the Upper Jurassic or Lower Cretaceous. According to Knopf,[3] these melaphyres were earlier than the great period of Coast Range intrusion. This age determination is based on the fact that though the melaphyres are nowhere cut by the Coast Range igneous rocks they belong to the sequence of formations that have been metamorphosed by contact with the igneous masses which were injected at that period.

On the west coast of the island the andesites form the shore line for about 6 miles, occupying that part between the Triassic and Devonian exposures. On the north end of the island, extending along the coast for 2 to 3 miles, both south and east of Vallenar Point, the andesites form the country rock. In most exposures they are rather massive and heavily jointed, but at several places thinly laminated phases occur. The rock is dark green, and some of it is amygdaloidal.

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[1] Brooks, A. H., op. cit., p. 45.
[2] Brooks, A. H., The geography and geology of Alaska: U. S. Geol. Survey Prof. Paper 45, p. 226, 1906.
[3] Knopf, Adolph, The Eagle River region, southeastern Alaska: U. S. Geol. Survey Bull. 502, pp. 18-20, 1912.

Andesites correlated with the andesites at the north end of the island were seen also on Bostwick Inlet. Presumably the andesites at Bostwick Inlet and at Vallenar Point are continuous inland between the two places. The andesite exposed on the west coast probably also extends southward for a considerable distance. The andesite inland from the coast was not examined by the writer but is indicated on the map (fig. 35), on the basis of the Wrights' map, on which the igneous rock on the north side of Bostwick Inlet and east of the head of Vallenar Bay is shown as continuous in the hills, locally known as the California Range, between the two places. The Wrights, however, considered the igneous rocks on Bostwick Inlet as belonging to the group of Coast Range intrusives and the rocks of Vallenar Point as belonging to the group described in the legend accompanying their map as "greenstone lava flows interstratified with volcanic tuffs and black slates."

Although, as has already been pointed out, the andesite agglomerate and andesite nowhere appear to be unconformable with the underlying rocks, the fact that they are in juxtaposition with rocks of different ages and kinds clearly indicates that the relation is either one of faulting or an unconformity. From the facts at present known the interpretation that the andesites unconformably overlie the sedimentary rocks previously described seems to be most probable.

COAST RANGE INTRUSIVE ROCKS.

Few new facts were obtained bearing on the age and broader relations of the Coast Range intrusive rocks. Some new details were obtained as to the distribution of these rocks, but as these facts are most clearly displayed on the accompanying map specific description will be omitted. The following excerpts from the Wrights' report [1] give the more important facts regarding the lithology of the Coast Range intrusive rocks:

> The Coast Range massif, as it has been defined by Dawson, is not of the same composition throughout, but is composed of different kinds of igneous rocks ranging from granite to diorite and even gabbro, quartz hornblende diorite or tonalite being the dominating type. The most noteworthy feature of the entire Coast Range mass of intrusives is their general uniformity in texture and their continuity. The variations across the range are apparently not so gradual as those along its trend. The Coast Range massif consists of many separate interlocking batholiths, or batholiths within batholiths, intruded at successive epochs but during the same general period of irruption.

Knopf [2] has shown that in the region north of Juneau—

> the diorite [part of the Coast Range massif] invades the rocks of the Berners formation and is consequently post-Jurassic in age. The upper limit is indicated by the fact that on Admiralty Island Eocene conglomerates are found to contain pebbles of the diorite, showing that the intrusion took place in Cretaceous time. The general history of southeastern Alaska suggests that the diorite is of early rather than late Cretaceous age.

RHYOLITIC LAVAS.

The high peak west of Seal Cove is formed of a light-colored igneous rock which has been determined to be a rhyolite. It has been somewhat faulted, but appears to overlie unconformably all the other rocks in the vicinity. This rhyolite was correlated by the Wrights with the Tertiary, and there seems to be no reason to doubt this correlation. The area occupied by this rock has been delineated mainly according to the map by the Wrights, as the exposures in the interior of the island were not visited by the writer. Some changes, however, have been made as to its eastern limits on the coast to conform with the new information obtained in 1913.

Rhyolites were also recognized by Brooks in 1901, for he states: [3]

> Rhyolites are not uncommon in the Ketchikan region. They were found as dikes and small flows in all parts of the district. * * * These rhyolites probably belong to the same general period of extrusion as the Kasaan greenstone.

The age of the Kasaan greenstone was thus stated by Brooks: [3]

> The Kasaan greenstone was extruded after the deformation of the Wales and Ketchikan series. It seems probable that it is of later origin than the Coast Range granite, for it shows evidence of having suffered during the crustal disturbances which accompanied this intrusion.

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[1] Wright, F. E. and C. W., op. cit., pp. 61–63.
[2] Knopf, Adolph, op. cit., p. 27.
[3] Brooks, A. H., Preliminary report on the Ketchikan mining district, Alaska: U. S. Geol. Survey Prof. Paper 1, p. 50, 1902.

THE AGE OF THE OCALA LIMESTONE.

By Charles Wythe Cooke.

INTRODUCTION.

In 1881 Eugene A. Smith [1] announced the presence, underlying large areas in both western and peninsular Florida, of limestone which he correlated with the Vicksburg limestone of Mississippi and Alabama and designated by the term Vicksburg limestone. Among the localities he mentioned specifically are Marianna, in Jackson County, and Ocala, in Marion County.

In the following year Heilprin [2] described a species of Nummulites from fragments of rock found by Willcox in Hernando County, on the west coast of Florida, and two years later Willcox discovered the nummulitic limestone in place not far away. Heilprin believed the rock to be the equivalent, in part, of the "Nummulitic" of Europe and, on account of the association of the Nummulites with *Orbitoides ephippium*, considered it to be of Oligocene age.

At the meeting of the American Association for the Advancement of Science in 1887 Johnson [3] said that the rocks mentioned by Heilprin "may be remnants of the Nummulitic limestone, which is really a stratum overlying the Vicksburg rocks" near Levyville and is apparently conformable with the "Vicksburg stage" but evidently not identical with it.

The term Ocala appears to have been first formally used by Dall, who described the formation under the heading "Nummulitic beds, Ocala limestone (Oligocene of Heilprin)." He says: [4]

> Among the rocks which until recently were not discriminated from the Orbitoides limestone and which appear in central Florida directly and conformably to overlie the latter, though no one has described their contact, is a yellowish friable rock containing many Foraminifera, conspicuous among which are two species of Nummulites, *N. willcoxii* and *N. floridana* Hp. This rock was first brought to notice by Mr. Joseph Willcox, and to Prof. Heilprin we owe a description of it which discriminates between it and the Vicksburg or Orbitoides rock. The rock was early recognized as Eocene, though not discriminated from the earlier beds. It is best displayed at Ocala, Fla., where it forms the country rock and has been quarried to a depth of 20 feet without coming to the bottom of the beds.

Besides Ocala, Dall mentions several localities where the same nummulitic rock is said to have been found by Willcox and Johnson.

At this time little was known of the fauna of the Ocala limestone, but Dall [5] remarks that "vertebrate remains belonging to the cetacean genus Zeuglodon or possibly to Squalodon were discovered by Mr. Willcox in the Nummulitic rock of the Ocala quarry, thus adding another indication of the close faunal relations of the Nummulitic with the preceding post-Claiborne beds." He adds:

> There is little doubt of the correctness of Prof. Heilprin's contention that these rocks are the analogue of the so-called Oligocene of the West Indies and of northern Europe. But, while this may be admitted, the propriety of regarding the group or series as constituting a distinct epoch, equivalent to or analogous in value to the Eocene, Miocene, or Pliocene epochs, which would be inferentially granted by adopting for them the term Oligocene, is a very different matter and in Florida receives no justification from the paleontological evidence.

Four years later, however, a more thorough study of the faunas led to the recognition of the correlation of the "Old Miocene," including the Vicksburg limestone, with the Oligocene of European geologists. The Oligocene was then accepted by Dall [6] as a separate epoch of the North American Tertiary, a view maintained in his subsequent publications.

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[1] Smith, E. A., On the geology of Florida: Am. Jour. Sci., 3d ser., vol 21, pp. 292-309, 1881.

[2] Heilprin, Angelo, On the occurrence of nummulitic deposits in Florida: Philadelphia Acad. Nat. Sci. Proc., vol. 34, pp. 189-193, 1883.

[3] Johnson, L. C., The structure of Florida: Am. Jour. Sci., 3d ser., vol. 36, p. 232, 1887.

[4] Dall, W. H., Correlation papers—Neocene: U. S. Geol. Survey Bull. 84, pp. 103-104, 1892.

[5] Idem, p. 105.

[6] Guppy, R. J. L., and Dall, W. H., Descriptions of Tertiary fossils from the Antillean region: U. S. Nat. Mus. Proc., vol. 19, No. 1110, pp. 303-304, 1896.

In 1903 appeared the concluding volume of Dall's monumental work on the Tertiary fauna of Florida,[1] in which is incorporated a brief account of the Ocala limestone, together with a list of 59 species of mollusks and foraminifers. The formation is supposed to overlie conformably the "Peninsular" limestone, which is believed to represent a higher horizon than the typical Vicksburg limestone.

The next report on the geology of Florida embodying the results of additional field work appeared in 1909 and was written by Matson and Clapp,[2] who employed the term Vicksburg group to include both the Ocala and "Peninsular" limestones of Dall as well as the limestone of western Florida, to which they gave the definite formation name Marianna limestone. The Marianna, which they considered the stratigraphic equivalent of the upper part of the bluff at Vicksburg, Miss., they believed to represent a horizon below the "Peninsular" limestone, but they were in doubt as to the stratigraphic relations of the two. They stated that the Ocala limestone conformably overlies the "Peninsular" limestone. The geologic conclusions of Matson and Clapp were republished with little change in 1913.[3]

The most recent contribution to the geology of Florida appeared in January, 1915, from Dall's pen.[4] Although presenting no new information in regard to the Ocala limestone, he gives an account of the geologic exploration of the region and repeats his former summary of the Ocala fauna.

The accompanying correlation table shows the present state of knowledge of the sequence of Eocene and lower Oligocene formations in Mississippi, Alabama, and Florida. For purposes of comparison the sequence for Florida as published by Matson in 1913 is given in a column parallel to the one presenting the changes proposed in this paper.

Correlation table of the Eocene and lower Oligocene formations of Mississippi, Alabama, and Florida.

	Mississippi.		Alabama.	Florida.			
				Matson, 1913.			This paper.
Oligocene.	Vicksburg limestone.		St. Stephens limestone.[6]	Vicksburg group.	Ocala limestone.	Exact correlations doubtful.	
					"Peninsular" limestone.		
		Upper bed at Vicksburg.[5]			Marianna limestone.		
		Lower bed at Vicksburg.			(Buried.)		
		Red Bluff clay member.			(Buried.)		Marianna limestone.
Eocene.	Jackson formation.			(Buried.)			Ocala limestone.
							(Buried.)
	Claiborne group.		Claiborne group.	(Buried.)			(Buried.)
	Wilcox group.		Wilcox group.	(Buried.)			(Buried.)
	Midway group.		Midway group.	(Buried.)			(Buried.)

[1] Wagner Inst. Trans., vol. 3, pt. 6, 1903.

[2] Matson, G. C., and Clapp, F. G., Preliminary report on the geology of Florida: Florida Geol. Survey Second Ann. Rept., 1909.

[3] Matson, G. C., and Sanford, Samuel, Geology and ground waters of Florida: U. S. Geol. Survey Water-Supply Paper 319, 1913.

[4] Dall, W. H., Fauna of the *Orthaulax pugnax* zone: U. S. Nat. Mus. Bull. 90, 1915.

[5] Distinctive names have not been applied to the different beds at Vicksburg.

[6] Vaughan's statement that the Vicksburg and Jackson formations can be discriminated in Alabama (U. S. Geol. Survey Prof. Paper 71, pp 738, 739, 1912) has been fully confirmed by my own unpublished studies, which show that the St. Stephens limestone is susceptible of division into several lithologic and faunal units.

RELATIONS OF THE MARIANNA LIMESTONE TO THE OCALA LIMESTONE.

During a recent investigation of the stratigraphy and paleontology of the St. Stephens limestone of Alabama I discovered a startling similarity between the fauna of the beds which are considered to represent the upper part of the Jackson formation (the "Zeuglodon bed" of Mississippi and western Alabama) and that of the Ocala limestone of Florida. It became apparent not only that many species of the Ocala are present in the Jacksonian deposits of Alabama but that they are restricted to that horizon and are not present in the overlying Vicksburgian members of the St. Stephens limestone. This conclusion is the more surprising in view of the fact that the Ocala limestone has been correlated with the very top of the Vicksburg limestone and, if present at all in Alabama, should overlie the Vicksburgian "chimney rock" of the St. Stephens limestone.

As the work progressed, more and more species of mollusks and echinoids were found to be common to the two faunas, and in 1913 a portion of the jaw of *Basilosaurus cetoides*[1] (the Zeuglodon), which had hitherto been thought to be exclusively of Jackson age, was obtained at the type locality of the Ocala limestone.

The obscurity in regard to this similarity of faunas was illuminated by the discovery at Marianna, Fla., of soft nummultic limestone containing an abundance of *Amusium ocalanum* and lying unmistakably beneath the Marianna limestone, which is the equivalent of the lower Vicksburgian "chimney rock" of Alabama and carries the exclusively Vicksburgian *Pecten poulsoni*,[2] as well as many Orbitoides. The section at Marianna is as follows:

Section on the west bank of Chipola River at the wagon bridge one-half mile east of Marianna, Fla.

	Feet.
Marianna limestone:	
5. Alternating hard and softer beds of light-colored limestone, very hard and compact in places, locally semicrystalline. The lower portion contains a considerable amount of glauconite. The upper portion has been quarried for building stone and contains Orbitoides, *Pecten poulsoni* (var.?), *Clypeaster rogersi*, and casts of other fossils. The floor of the bridge is 9 feet above the base of this bed	33
Ocala limestone:	
4. Concealed	3
3. Hard creamy-white semicrystalline limestone, apparently a more indurated phase of bed No. 1. Contains Orbitoides (stellately marked species), Arca, Glycymeris, *Amusium ocalanum*, Plicatula (Ocala species), Venericardia	1⅓
2. Concealed	4
1. Soft cream-colored porous limestone or marl, composed largely of Foraminifera loosely packed together. Contains Nummulites, Orbitoides (stellately marked species), Bryozoa, *Amusium ocalanum*, Cardium. Extends beneath water in the river	5

The intervals concealed at the bridge are exposed near the mouth of a cavern about 200 yards below the bridge, where the following supplementary section was observed:

Section 200 yards below the wagon bridge east of Marianna, Fla.

	Feet.
Marianna limestone:	
5. White limestone, the same as bed No. 5 of the section at the bridge	33
Ocala limestone:	
4. Soft cream-colored limestone with several species of Orbitoides and some Bryozoa	1
3. Hard semicrystalline pinkish limestone with large Orbitoides, Flabellum, and *Amusium ocalanum*	6½
2. Soft granular cream-colored limestone much like No. 1 of section at bridge but with fewer Foraminifera. Contains Orbitoides (stellately marked species), Flabellum, Bryozoa, *Terebratulina lachryma*?, Natica, Arca, *Pecten indecisus*, *Amusium ocalanum*, and Plicatula (Ocala species)	3
1. Concealed to water level in Chipola River	3

[1] Identified by J. W. Gidley.

[2] Erroneous statements regarding the stratigraphic range of *Pecten poulsoni* and of *Pecten perplanus* have from time to time appeared in the literature. Contrary to the general opinion, the two species cited do not occur together. *Pecten poulsoni* is exclusively Vicksburgian, whereas *Pecten perplanus* is restricted to deposits older than the Red Bluff clay member and is probably confined to the Jackson formation, though it may range down into the upper Claiborne. As these two pectens have a narrow stratigraphic range and a wide areal distribution and flourished in great abundance under very dissimilar conditions of sedimentation, they form exceptionally good index fossils. Moreover, they may readily be distinguished from each other and are not likely to be confused with other species.

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Bed No. 5 of these sections is the Marianna limestone, the lower portion of which is the stratigraphic equivalent of the Red Bluff clay member of the Vicksburg limestone of Mississippi and western Alabama. Beds 1 to 4, inclusive, belong to the Ocala limestone, as is shown by the included fossils.

The lower bed of the Marianna limestone forms a hard projecting ledge which in several places in the vicinity serves as the roof to small caverns excavated in the softer Ocala limestone. I could detect no evidence of unconformity between the two formations.

The same nummulitic limestone crops out along Flint River in the vicinity of Bainbridge, Ga., where it is almost identical in lithologic appearance and fossil content with the exposure at Marianna. In 1900 the identity of the rock near Bainbridge with the Ocala limestone was recognized by Vaughan,[1] and 11 years later his notes on the geology of this region were incorporated in a report by Veatch and Stephenson.[2] My own observations, made during a two-weeks' stay at Bainbridge, have confirmed in every respect Vaughan's account of the stratigraphic relations of the rocks exposed along Flint River.

The lowest rock exposed in the vicinity of Bainbridge is a white to yellow, partly consolidated foraminiferal limestone like that of the lower bed at Marianna. It is separated by a well-marked erosional unconformity from the overlying series of irregularly bedded sands and variegated clays with chert blocks carrying corals and mollusks of earliest Chattahoochee age.

At Red Bluff,[3] 7 miles above Bainbridge, the following fossils were obtained from the Ocala limestone:[4]

Orbitoides papyracea (Boubée).
Orbitoides n. sp. (stellately marked form).
Nummulites willcoxi Heilprin.
Echinolampas sp.
Cassidulus sp.
Clypeaster sp.
Pecten suwaneensis Dall.
Pecten indecisus Dall.
Amusium ocalanum Dall.

From the Ocala limestone at a bend in the river near the old factory three-fourths of a mile north of the Atlantic Coast Line Railway station at Bainbridge, the following species have been recently collected:

Orbitoides sp.
Nummulites sp.
Bryozoa, many species.
Ostrea sp.
Oligopygus haldermani Conrad.
Agassizia conradi (Bouvé).
Eupatagus sp.
Pecten perplanus Morton.
Amusium ocalanum Dall.

REVIEW OF DALL'S LIST OF SPECIES FROM THE OCALA LIMESTONE.

In order to find out whether the fossils which are known to occur at the type locality of the Ocala limestone justify the reference of the formation to the high stratigraphic position which is assigned to it in all accounts of the geology of Florida, I have undertaken a critical analysis of the Mollusca enumerated in 1903 by Dall[5] in his list of species from the Ocala limestone. Dall's summary of the list is as follows:

> The total is about 59 species, of which about 25 appear to be peculiar, 15 are inherited from the Vicksburgian, and 11 persist as far as the silex beds of Tampa. Two Ocala species are present in the Eocene, four as far up as the Chipola, one reaches the Miocene, and one survives to the present day.

Inspection of the list brings to light the fact that among "those also known from Vicksburg" are mentioned *Papillina dumosa*, *Cassis globosa*, *Cyprædia fenestralis*, *Pinna quadrata*,

[1] Vaughan, T. W., A tertiary coral reef near Bainbridge, Ga.: Science, new ser., vol. 12, p. 873, 1900.
[2] Veatch, Otto, and Stephenson, L. W., Preliminary report on the geology of the Coastal Plain of Georgia: Georgia Geol. Survey Bull. 26, pp. 321–322, 329–333, 1911.
[3] Not to be confused with the type locality of the Red Bluff clay member of the Vicksburg limestone, which is on Chickasawhay River, Wayne County, Miss.
[4] Veatch, Otto, and Stephenson, L. W., op. cit., p. 320.
[5] Dall, W. H., Tertiary fauna of Florida: Wagner Inst. Trans., vol. 3, pt. 6, pp. 1557, 1558, 1903.

Pecten perplanus, *Pecten indecisus*, *Amusium ocalanum*, and *Plicatula densata*, none of which have ever been found at Vicksburg. It is evident that Dall intended to imply the "Vicksburg or Peninsular limestone" rather than the specific locality Vicksburg, Miss.

Species from Ocala.—By excluding the Foraminifera, which require study by a specialist on that group, and eliminating those species which are not credited to Ocala, the number is reduced to 32 mollusks, of which three (*Serpulorbis granifera*, *Turritella gatunensis*, and *Pecten centrotus*) appear to have been referred to Ocala by mistake. The abbreviated list is given below.

Those marked O are from Ocala; M, from Martin station. Those also known from Vicksburg are marked V, while those followed by S are also known from the silex beds of Tampa. An asterisk denotes the survival of the species to the recent fauna.

Aturia (near alabamensis Morton), O.
Helix (Cepolis?) sp., O.
Scaphander grandis Aldrich, O; also Jacksonian.
Eucymba ocalana Dall, O; also Eocene.
Caricella sp., O.
Lyria musicina Heilprin, O, S.
Turbinella polygonata Heilprin, O, S; also Chipola?
Mitra like millingtoni Conrad, O, V?
Fusus (Papillina) dumosus Conrad, O, V.
Cassis globosa Dall, O, V.
Transovula multicarinata Dall, O, M.
Cypræa heilprini Dall, O, S; also Tampa limestone.
Cypraedia fenestralis Conrad, O, V.
Rimella smithii Dall, O, M.
Cerithium ocalanum Dall, O, M.
Cerithium sp., O.
Turritella var. martinensis Dall, M, O.
*Xenophora conchyliophora Conrad, O, S, V.
Amauropsis ocalana Dall, O.
Leda multilineata Conrad, O, M, V.
Pinna quadrata Dall, O, V?
Pecten (Æquipecten) perplanus Morton, O, V.
Pecten sp., O.
Amusium ocalanum Dall, O, M, V, S.
Plicatula densata Conrad, O, M, V, S.
Crassatellites sp., M, O.
Diplodonta sp., M. O.
Cardium sp., O.
Fistulana ocalana Dall, O.

Of the 29 species in this list, seven are not named specifically and seven others appear to be peculiar to the Ocala limestone. The peculiar species are *Ovula multicarinata*, *Rimella smithii*, *Cerithium ocalanum*, *Turritella martinensis*, *Amauropsis ocalana*, *Pinna quadrata*, and *Fistulana ocalana*. Two species, *Eucymba ocalana* and *Cassis globosa*, are apparently elsewhere restricted to the Claiborne group. Seven, *Aturia alabamensis*, *Scaphander grandis*, *Mitra millingtoni*, *Papillina dumosa*, *Cypræa fenestralis*, *Pecten perplanus*, and *Amusium ocalanum*, are restricted to the Jackson or have their closest affinities in that formation. Four, *Lyria musicina*, *Turbinella polygonata*, *Cypræa heilprini*, and *Plicatula densata*, have not been found in beds older than the "silex beds" of the Tampa formation. One, *Xenophora conchyliophora*, is supposed to range from the Cretaceous to the Recent, and one, *Leda multilineata*, occurs in the Claiborne group of Mississippi and Georgia, is very abundant at Jackson, Miss., and is doubtfully reported from Vicksburg.

Presenting the preceding statement in tabular form, we have:

Generic name only	7
Peculiar to Ocala	7
Peculiar to the Claiborne	2
Peculiar to the Jackson	7
"Silex beds" of Tampa formation or later	4
Cretaceous to Recent	1
Claiborne to Vicksburg	1
	29

An examination of the specimens on which the determinations of the four species from the "silex beds" were based showed that all were identified from poor material and that the correctness of the identifications appears doubtful. Two of them apparently occur also in the Castle Hayne limestone at Wilmington, N. C., which is of Jackson age.

The summary may now be restated as follows:

Undetermined and peculiar species	14
Known to occur in the Jackson or earlier	13
Supposed to occur also in the Vicksburg	2
Post-Vicksburg (2 doubtful)	3
	32
Counted twice	3
	29

The foregoing analysis shows that the molluscan fauna of the Ocala limestone at the type locality is decidedly Jacksonian in its affinities. The testimony of the mollusks is amply corroborated by that of the vertebrates, echinoids, and bryozoans,[1] and the foraminifers, which are now being studied, apparently point to the same conclusion.

Species from Martin.—Those species in Dall's list which are not from Ocala come, with one exception, from Martin, Fla. In addition to some species of undoubted Ocala age, the fossils listed from Martin include three Vicksburg species, *Drillia servata*, *Fusus mississippiensis*, and *Pitaria astartiformis*, and four "silex beds" species, *Conus planiceps*, *Latirus floridanus*, *Serpulorbis granifera*, and *Ostrea mauricensis*. These Vicksburg and "silex beds" species are represented in the collection by siliceous pseudomorphs which may have come from a different horizon; the oyster certainly did not come from the Ocala limestone but is probably from the Alum Bluff ("Hawthorn") formation, which overlies the Ocala limestone at many localities in peninsular Florida. Until further investigations have been made these doubtful species had better be eliminated from lists of the Ocala fauna.

RELATION OF THE "PENINSULAR" LIMESTONE TO THE OCALA LIMESTONE.

Regarding the relation of the "Peninsular" to the Ocala limestone, it may be said that the name "Peninsular" is a general term, without type locality, applied to the "Orbitoidal limestone which forms the mass of the Floridian plateau and which has been * * * generally called the Vicksburg limestone" but which "may really form a different [higher] horizon altogether from the typical Vicksburgian and be intermediate between the latter and the nummulitic Ocala limestone."[2] "The two are distinguishable only by their contained fauna, the nummulites, a great profusion of other Foraminifera, and a certain number of mollusks being characteristic of the Ocala limestone."[3]

The presence of nummulites in the Ocala limestone appears to have been the chief reason for the separation of that formation from the "Peninsular" limestone and the presence or absence of nummulites to have been the essential criterion for distinguishing between the two formations. Inasmuch as nummulites are known to occur at several different horizons, the mere presence of the genus, when not specifically determined, can have very little bearing on the correlation of the strata containing it, and its apparent absence from strata whose fauna has been insufficiently explored seems scarcely sufficient cause for discriminating between formations which in other respects appear identical. Whether the "Peninsular" limestone or any part of it can be distinguished from the Ocala remains to be ascertained. It is certain that at many localities in north-central Florida, which are cited in the following section of this paper, the two appear to be identical. It is quite possible, however, as Dall has suggested, that more than one horizon may be represented in the "Peninsular" limestone, and I have seen places where the fauna has a different aspect from that of the Ocala. However, the discrimination of these beds must await further investigation.

[1] Since the above was written the study of the typical Ocala bryozoan fauna of north-central Florida has been completed by F. Canu and R. S. Bassler, who have identified accurately the same fauna in the vicinity of Bainbridge and at Rich Hill, Crawford County, Ga. Dr. Bassler authorizes the statement that this assemblage of Bryozoa shows a marked resemblance to upper Jacksonian faunas, especially those of the "Zeuglodon bed" of Alabama, the Castle Hayne limestone of North Carolina, and the corresponding strata at Eutaw Springs, S. C. The result of these studies shows that the Bryozoa of the Ocala limestone are quite distinct from typical Vicksburgian faunas and can be correlated only with faunas of upper Jacksonian age.

[2] Dall, W. H., Tertiary fauna of Florida: Wagner Inst. Trans., vol. 3, pt. 6, p. 1554, 1903.

[3] Idem, p. 1556.

LOCAL DETAILS OF THE OCALA LIMESTONE.

It may not be out of place here to anticipate a more comprehensive report by the insertion of a few notes on the Ocala limestone at the type locality and at other places in north-central Florida.

Ocala and vicinity.—At plant No. 1 of the Florida Lime Co., on the southwest edge of Ocala, the fresh face of the quarry exposed, at the time of my visit in 1913, 40 feet of white limestone, for the most part amorphous, soft, and porous, but containing scattered lumps of cherty limestone. Fossils are very abundant, especially Orbitoides and *Amusium ocalanum.* I collected also *Oligopygus haldermani, Laganum floridanum?*, Laganum sp., Mitra aff. *M. millingtoni, Cerithium ocalanum,* Turritella aff. *T. mississippiensis, Ovula multicarinata,* Fissuridea, *Pecten suwaneensis,* Cardium sp., Tellina n. sp., and many others. All are preserved only as casts except the sea urchins and the pectens. The rock contains many cavities which are filled with sand, clay, and fragments of small bones. On the southern face of the most recent working is a mass of sand and clay resembling fuller's earth which has evidently fallen to its present position by the collapse of a cavern roof. The clay resembles that of the Alum Bluff formation.

The quarry of the Oakhurst Lime Co. (plant No. 2, Florida Lime Co.) is south of the tracks of the Atlantic Coast Line Railway about 2 miles southeast of Ocala. The rock exposed consists of 52 feet of light cream-colored, very homogeneous limestone resembling the "chimney rock" of Alabama. The basal 9 feet is below the floor of the quarry but is visible in a small cavern. The overburden consists of 1 or 2 feet of dark sandy loam containing much vegetable matter. Several crevices and solution cavities, all except the cavern mentioned filled with sandy clay and humus, extend to the floor of the pit. They contain fragments of bones of living species of animals. The rock is exceedingly fossiliferous, containing several species of Orbitoides and other Foraminifera, several echinoids, and mollusks. Mr. G. C. Fraser, one of the proprietors, presented to me several large bones of *Basilosaurus cetoides* [1] which had been blasted from the rock. I obtained also Flabellum, *Oligopygus haldermani,* Conus, Cypræa cf. *C. fenestralis, Papillina dumosa,* Solarium, Spondylus, *Pecten suwaneensis, P. perplanus, Amusium ocalanum,* Cardium, Crassatellites, and other forms. This quarry contains very little chert, which is confined mostly, if not entirely, to residual blocks embedded in the clay of the cavity fillings.

A quarry in the Ocala limestone 1½ miles east of Ocala and 100 yards north of the Silver Springs road shows about 30 feet of massive porous white limestone with Orbitoides, *Amusium ocalanum,* and other species. The upper portion is cherty, and there are some thin vertical bands of chert filling crevices. The overburden consists of 2 or 3 feet of soil.

Zuber.—At plant No. 3 of the Florida Lime Co., at Zuber post office, 6½ miles north of Ocala, the quarry is 35 feet deep, exposing 33 feet of soft white porous limestone overlain by 2 feet of brown sandy soil. The limestone is remarkably homogeneous and free from impurities. Fossils are very abundant, the following being represented: Orbitoides, Flabellum, *Oligopygus haldermani, O. wetherbyi,* Laganum, 2 sp., *Agassizia conradii,* Polygyra, Conus, *Ovula multicarinata,* Xenophora, Ostrea, *Pecten perplanus,* Pecten sp., *Amusium ocalanum,* Spondylus, Cardium, and Tellina.

Martin.—About one-eighth of a mile southeast of Martin station, 9 miles north of Ocala, a small quarry exposes about 15 feet of soft white porous limestone, highly fossiliferous in places, with very abundant Foraminifera, *Oligopygus wetherbyi?*, and *Amusium ocalanum.* The upper portion of the rock is much weathered. In one place near the top is a mass of light-green siliceous clay or fuller's earth, and on the surface above are fragments of sandstone intermingled with limestone and chert. I was unable to determine whether the clay had been deposited in a hollow in the surface of the limestone or whether it had fallen to its present position by the collapse of a cavern roof. The latter supposition is the more probable.

[1] Identified by J. W. Gidley.

Newberry and vicinity.—In the vicinity of Newberry the Ocala limestone is well exposed in many phosphate mines of the "hard rock" type. The upper surface of the Ocala is very irregular, with high pinnacles projecting above the general level of the rock. In the process of mining, the ore, which in most places immediately overlies the limestone, is stripped off, leaving the uneven surface of the Ocala exposed to view. A photograph showing this feature may be found in Sellards's report on the Florida phosphate deposits.[1] The Ocala limestone in this region is soft, white, porous, and apparently very pure. It is very fossiliferous and in places is composed almost entirely of Foraminifera.

At plant No. 6 of the Cummer Lumber Co., 1¼ miles south of Newberry, the following fossils were collected: Orbitoides, Lunulites, Agassizia ?, *Amblypygus merrilli?*, Laganum, Olivula, Rimella cf. *R. smithii*, *Pecten suwaneensis*, Spondylus, Plicatula, and Cardium.

At plant No. 10, 1 mile northwest of Newberry, I obtained Orbitoides, *Pecten suwaneensis*, *P. perplanus*, Spondylus, Plicatula, Crassatellites, and casts of other fossils. Scattered among the phosphate rock and on top of the limestone are many lumps of chert that contain *Cassidulus gouldii* and are apparently residual from a younger formation. Similar chert with the same species of Cassidulus was found near the top of the pit in plant No. 11.

At the Franklyn phosphate mine, 1½ miles northwest of Newberry, the limestone contains Orbitoides, Bryozoa, *Oligopygus haldermani*, *Laganum floridanum*, Ostrea, *Amusium ocalanum*, *Pecten suwaneensis*, *P. perplanus*, Plicatula, and Crassatellites ?.

Clark station.—At Clark station on the Atlantic Coast Line Railway, 5 miles south of High Springs, there are many abandoned phosphate pits. The Ocala limestone is exposed in the bottoms of the pits and in places reaches the surface. The top of the limestone, as laid bare by the workings, contains high pinnacles separated by narrow channels from which the phosphatic ore has been extracted. The limestone is soft and white, as at the other mines visited. It contains Orbitoides, *Oligopygus haldermani*, and *Pecten perplanus*.

Fort White.—At the Fort White phosphate mine, now abandoned, a quarter of a mile northwest of Fort White, Orbitoides, Bryozoa, *Oligopygus haldermani?*, *Pecten perplanus*, *Amusium ocalanum*, and Cardium occur in the Ocala limestone. Lying loose in the quarry is an enormous bowlder of light-colored silicified limestone containing *Cassidulus gouldii*, Cylichna ?, Glycymeris cf. *G. lameyi*, and Modiolus cf. *M. grammatus*. The bowlder is of post-Ocala age.

SECTIONS IN MISSISSIPPI AND ALABAMA.

In order that the stratigraphic equivalents of the Ocala limestone in its western extension may be available for comparison, several sections from Mississippi and western Alabama are given below.

Jackson, Miss.—The following generalized section of the Jackson formation in the vicinity of Jackson, Miss., was published by Hilgard.[2]

Section of Jackson strata at Moody's Branch and McNutt Hills.

	Feet.
Yellowish-white marl, more or less sandy, sometimes indurate and forming a soft rock; gives rise to "bald prairies" in the McNutt Hills. Contains bones of Zeuglodon, vertebræ and teeth of fish, Echinus!, Scutella, Hemiaster?, and casts of univalves and bivalves of the Jackson group	30–45
Yellowish-white clayey marl, with few fossils—*Pecten nuperus*, Pinna, Ostrea	6–10
Coarse yellow sand, somewhat clayey, with "Jackson fossils" in a fine state of preservation	8
Blue sand with Jackson fossils, mostly detritus	2
Blue sandy clay, fetid, somewhat micaceous; its upper portion filled with oddly shaped ferrugino-siliceous concretions. No fossils	10
Earthy lignite	1
Gray laminated clay, interstratified with sand, with traces of stems and leaves	10

[1] Sellards, E. H., A preliminary paper on the Florida phosphate deposits: Florida Geol. Survey Third Ann. Rept., pl. 2, fig. 1, 1910.
[2] Hilgard, E. W., Agriculture and geology of Mississippi, p. 131, 1860.

Willow Branch, Ala.—An instructive section showing nearly the entire Jackson formation and much of the Claiborne group is exposed in the valley of Willow Branch, Choctaw County, Ala., about 4 miles from Silas on the road to Fail.

Section at Willow Branch, Ala.

	Feet.
Post-Vicksburg:	
13. Red sand to top of hill; about	50
Jackson formation:	
12. Drab calcareous clay with white calcareous concretions	25
11. Yellowish marl with *Pecten perplanus* and *Periarchus pileus-sinensis?*. Indurated in lower portion	11
10. Fine-grained yellow sand	21
9. Argillaceous yellow sandy marl with shells; grades into the underlying bed	9
8. Greenish-yellow clay with shells, forming a gentle slope; about	50
Claiborne group:	
7. Hard gray indurated marl with small grains of glauconite and a few fragmentary shells	1½
NOTE.—The measurements of the beds above No. 7 were made on the south side of the valley; of those below, on the north side.	
6. Reddish-brown ferruginous glauconitic sand containing casts of mollusks, with a 1-foot shell bed at bottom	7
5. Dark-gray to black sandy clay with shells	3½
4. Laminated gray sand and clay with *Oreodaphne inequilateralis* and *Mespilodaphne columbiana* [1]	7
3. Dark-green to black glauconitic sand loaded with Claiborne shells	2
2. Dark-green to black, somewhat sandy clay. Weathers with fissile parting resembling "coal blossom"	5
1. Reddish-brown ferruginous sand to stream bed (1 or 2 feet concealed at bottom)	10

Most of the fossils in the following list were collected by W. C. Mansfield from bed No. 9 of the section, but some came from bed No. 8.

Endopachys shaleri Vaughan.
Scala sp.
Turritella sp.
Natica sp.
Dentalium sp.
Nucula spheniopsis Conrad.
Leda mater Meyer?
Ostrea trigonalis Conrad?
Pecten aff. P. membranosus Morton.
Pecten (Pseudamusium) scintillatus Conrad.
Pteria limula (Conrad).
Corbula alabamiensis Lea?
Corbula wailesiana Harris?
Tellina aff. T. vicksburgensis Conrad.
Spisula sp.
Lucina sp.
Phacoides (Miltha) claibornensis (Conrad) var.?
Venericardia planicosta Lamarck.

The evidence afforded by these fossils is scarcely sufficient in itself to determine positively whether the beds from which they came are of Claiborne or of Jackson age, but as the beds lie above the horizon of the sand bed of the Claiborne and resemble more closely the Jackson in lithologic appearance, they are tentatively referred to the Jackson formation.

There can be no question as to the Claiborne age of the fossils in the following list, collected by W. C. Mansfield from beds Nos. 3 to 6 of the section:

Turbinolia pharetra Lea.
Endopachys maclurii (Lea).
Cylichna sp.
Ringicula sp.
Pleurotoma sp.
Olivula staminea (Conrad).
Marginella sp.
Ptychosalpinx altilis (Conrad).
Mazzalina inaurata Conrad.
Pseudoliva vetusta (Conrad).
Plejona petrosa (Conrad).
Fusus bellus Conrad, var.
Calyptraphorus velatus (Conrad).
Turritella, 2 sp.
Eulima sp.
Natica sp.
Teinostoma subrotunda Meyer.
Solariella lineata (Lea).
Crepidula lirata Conrad.
Dentalium sp.
Nucula sp.
Leda media (Lea).
Trinacria cunea (Conrad).
Corbula, 2 sp.
Lucina sp.
Myrtæa curta (Conrad).
Phacoides alveatus (Conrad).
Venericardia parva Lea.
Venericardia planicosta Lamarck.
Crassatellites protexta (Conrad), var.?
Meretrix, 2 sp.

[1] Identified by E. W. Berry.

Cullomburg, Ala.—The relation of the "Zeuglodon bed" to the Red Bluff clay member of the Vicksburg limestone is well shown on the road from Millry to Bladon Springs, Ala., 3 or 4 miles from Millry and about 3½ miles southeast of Cullomburg. The section extends from a small branch southward along the road.

Section 3½ miles southeast of Cullomburg, Ala.

	Feet.
8. Concealed to top of hill; about	50
Red Bluff clay member of Vicksburg limestone:	
7. Very plastic gray clay with crystals of gypsum. Contains *Pleurotoma plutonica*?, *P. congesta*, *Busycon spiniger*, *B. nodulatum*, *Phos macilentus*, *Ostrea vicksburgensis*, Pecten aff. *P. poulsoni*, *Spondylus dumosus*, *Corbula perdubia*	22
6. Green-gray or buff glauconitic marl, consisting of grains of green glauconite the size of bird shot, in a white calcareous clay matrix. In the upper portion are several discontinuous ledges, and at the top is a more persistent ledge. Contains *Balanophyllia caulifera*, *Ostrea vicksburgensis*, *Pecten cocoanus*, Pecten aff. *P. poulsoni*, *Spondylus dumosus*, Corbula sp., and *Astarte triangulata*. The Ostrea and Spondylus weather out of the lower 2 feet in great abundance but are difficult to see in the unweathered material	9
Jackson formation:	
5. Stiff calcareous clay, yellow or buff on weathered surface, bluish green on damp, fresh surface. Contains small irregular concretions. Merges into the overlying bed	8
4. "Zeuglodon bed," buff argillaceous marl, merging into the overlying bed. Forms a gentle slope. Contains Flabellum, *Schizaster armiger*, *Ostrea falco*, *O. trigonalis*, Gryphæostrea, Pinna, *Modiolus cretaceus*, *Pecten perplanus*, *Terebratulina lachryma*	9
3. Gray to yellow, very calcareous, argillaceous marl with some hard ledges. Forms steep slope. *Pecten perplanus*, *Ostrea trigonalis*, and Bryozoa abundant; other fossils represented by casts	6
2. Yellow calcareous sand with poorly preserved shells and casts of Leda. Some calcareous concretions at base	18
1. Steel-gray sandy calcareous clay; about	3

It is believed that beds 2 to 5 inclusive are the equivalent of beds 9 to 12 of the section at Willow Branch.

Cocoa, Ala.—Near the site of Cocoa post office, which was located on the road from Gilberttown to Melvin, Choctaw County, Ala., about 2¼ miles east of Melvin, the "Zeuglodon bed," No. 3 of the Cullomburg section, is very fossiliferous. The following section was measured at the place where the large Zeuglodon skeleton in the National Museum was obtained:

Section half a mile southwest of Cocoa, Ala.

	Feet.
4. Concealed. Exposures elsewhere in the vicinity show that above No. 3 is yellowish-brown argillaceous marl with *Spondylus dumosus* and *Ostrea vicksburgensis*, overlain by gray to yellow clay with crystals of gypsum and many Red Bluff fossils.	
3. Drab clay with irregular calcareous concretions in lower portion. Thickness seen, about	10
2. "Zeuglodon bed," gray or drab sandy and argillaceous marl with harder ledges and irregular calcareous concretions; very argillaceous in the upper part; about	11
1. Fine yellow sand with soft white calcareous lumps and large irregular lumps of hard yellow sandy marl. Grades upward into bed No. 2. Thickness seen	6

From bed No. 2 the following fossils were collected:

Flabellum sp.
Lunulites distans Lonsdale.
Many other Bryozoa.
Terebratulina lachryma (Morton).
Aturia alabamensis (Morton).
Scala ranellina Dall.
Turritella alveata Conrad.
Ostrea trigonalis Conrad.
Ostrea vicksburgensis Conrad (perhaps derived from higher bed).
Ostrea falco Dall.
Gryphæostrea sp.
Pecten perplanus Morton.
Pecten n. sp.?
Panopea oblongata Conrad?
Protocardia sp.
Schizaster armiger Clark.
Shark teeth.
Fish vertebræ.
Coprolites.

In addition to the species enumerated in the list, the old collections in the National Museum contain from this locality *Cypræa fenestralis* Conrad ?, *Crassatellites flexura* (Conrad), *Leda multilineata* Conrad, and *Venericardia planicosta* Lamarck.

Those species which the "Zeuglodon bed" has in common with the Ocala limestone, or which have near relatives in the Ocala, are the following:

Flabellum (perhaps not the same species; the genus is rare in the Vicksburgian beds).
Terebratulina lachryma (doubtfully at Marianna).
Aturia alabamensis.
Cypræa fenestralis.
Leda multilineata.
Pecten perplanus.
Basilosaurus cetoides.

That more species do not appear to be common to the two may be attributed partly to ecologic and geographic causes (Cocoa is more than 400 miles from Ocala) and partly to the unexplored state of the fauna.

From the hillsides near by the following Red Bluff fossils were collected:

Balanophyllia caulifera var. multigranosa Vaughan.
Conus protractus Meyer.
Pleurotoma congesta Conrad.
Pleurotoma plutonica Casey.
Pleurotoma tantula Conrad.
Pleurotoma (Drillia) caseyi Aldrich.
Pleurotoma (Gemmula) amica Casey.
Pleurotoma (Gemmula) sp.
Cancellaria mississippiensis Conrad var.
Mitra lintoidea Aldrich.
Latirus protractus (Conrad).
Busycon nodulatum (Conrad).
Triton conradianus Aldrich.
Phos macilentus Casey.
Murex mississippiensis Conrad.
Eulima sp.?
Turritella sp.
Lunatia sp.
Solarium hargeri Meyer.
Dentalium sp.
Glycymeris intercostata (Gabb).
Ostrea vicksburgensis Conrad.
Pecten aff. P. poulsoni Morton.
Spondylus dumosus Morton.
Corbula engonata Conrad.
Corbula perdubia Gregorio.
Astarte triangulata Meyer.
Myrtæa curta (Conrad)?
Cardium sp.

Toward the east the Red Bluff member thins, becomes calcareous, and merges into the Marianna limestone. The underlying beds also become more calcareous and can scarcely be distinguished from those of the Vicksburg group except by their fossils. In general, however, the lower beds are less pure and in many places contain a considerable amount of glauconite.

CONCLUSIONS.

It has been shown that the Ocala limestone is the equivalent in age of the upper part of the Jackson formation as defined in Alabama and Mississippi and that it underlies Vicksburgian limestone in western Florida. As the relations are conformable, the Ocala must represent at least the upper portion of the Jackson formation, but whether the lower portion of the Jackson in peninsular Florida is different from the Ocala, either lithologically or faunally, is at present unknown.

The "Peninsular" limestone is in large part identical with the Ocala, but further investigations are required to determine what other formations may be included in the "Peninsular."

The Vicksburg group is represented in western Florida by the Marianna limestone; although it may be present in peninsular Florida, it is of much less areal extent than has hitherto been supposed.

INDEX.

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