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SOLUTION DEPRESSIONS IN DIORITE IN NORTH CAROLINA*

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ABSTRACT. During 1950 more than 40 enclosed depressions, resembling sinks of limestone terranes, were observed by the writer in the igneous rocks of the Piedmont plateau of North Carolina. These depressions, averaging about 200 feet in diameter and about 3 feet in depth below the lowest possible overflow point, are restricted to upland areas of dioritic rocks.

That the agents of subaerial erosion are apparently incapable of forming these enclosed depressions suggests that ground water is the principal agent in forming them. The evidence indicates that soluble rocks underlie the depressions, that an appreciable amount of dissolved mineral matter is extracted from the dioritic rocks by ground water, and that surface subsidence is a consequence. More than three times as much mineral matter is extracted by circulating ground water from diorite as from granite, the most common rock of the Piedmont.

Solution subsidence is not confined to the enclosed depressions but is even more active in valley heads where the ground water circulation and the consequent solution are greater. Studies in the Piedmont of the occurrence and movement of ground water and an appraisal of data on the quantity and chemical quality of natural water reveal that ground water is a more significant agent in the erosion of igneous rocks than is generally believed.

INTRODUCTION

WHILE studying the ground water in a part of the Piedmont in North Carolina during the summer of 1950, as a part of investigations being made under a cooperative agreement between the U. S. Geological Survey and the North Carolina Division of Mineral Resources, the writer noticed several enclosed depressions in the upland areas. Since that time, as a result of casual observation rather than systematic search, he has seen more than 40 similar depressions in the Piedmont area of the state. They are similar in appearance to sinks in limestone, although those described are restricted to plutonic rocks of intermediate composition where limestone is absent.

The depressions are irregularly circular. A few are slightly elongated, the long axis of the depression being roughly in line with the nearest surface drainageway and appearing to be the discontinuous headward extension of it. The depressions range in diameter from about 100 feet to more than 300 feet,

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the average being about 200 feet. They range in depth below the lowest possible overflow point from a few inches to about 6 feet, averaging nearly 3 feet. More than a dozen depressions are at least 3 feet deep. The inner slopes are not steep but are typical of those of the upland areas. Rock is nowhere exposed in the depressions. A topographic sketch of a depression on the Ford property, 2 miles north of Cleveland, Rowan County, is shown in figure 1. Most of the depressions in Rowan County cannot be seen on the aerial photographs examined; however, photographs made during the late winter, when water is reported to accumulate in them, may reveal their presence. Despite moderately heavy rains of summer, infiltration of precipitation is generally rapid enough to allow the growth of crops within the depressions. Attempts have been made in several cases to drain them. For example, on the Misenheimer farm 5 miles southeast of Cleveland, Rowan County, a ditch several feet deep was excavated to drain a large depression.

The depressions are in nearly flat upland areas underlain by intrusive rocks of intermediate composition. They are found in one or more extensive areas of diorite or gabbro-diorite in each of the following counties in North Carolina: Rowan,

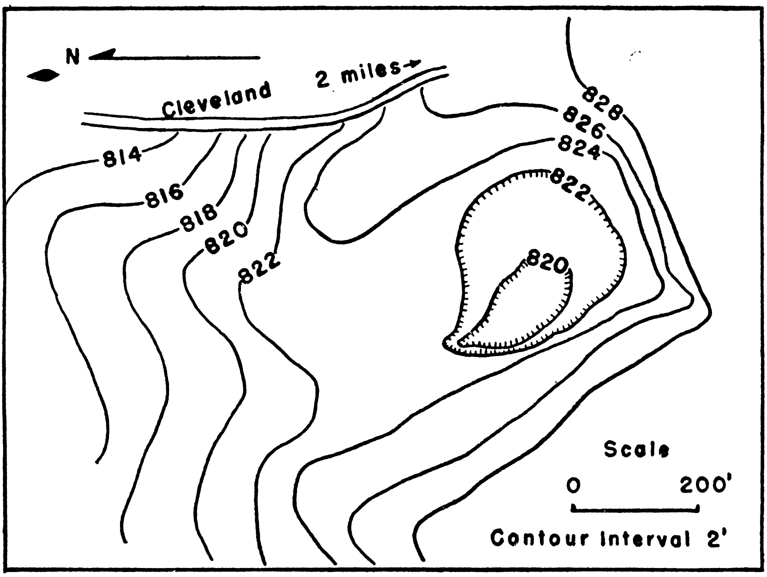

Fig. 1. Topographic map of a depression on the Ford property, 2 miles north of Cleveland, Rowan County.

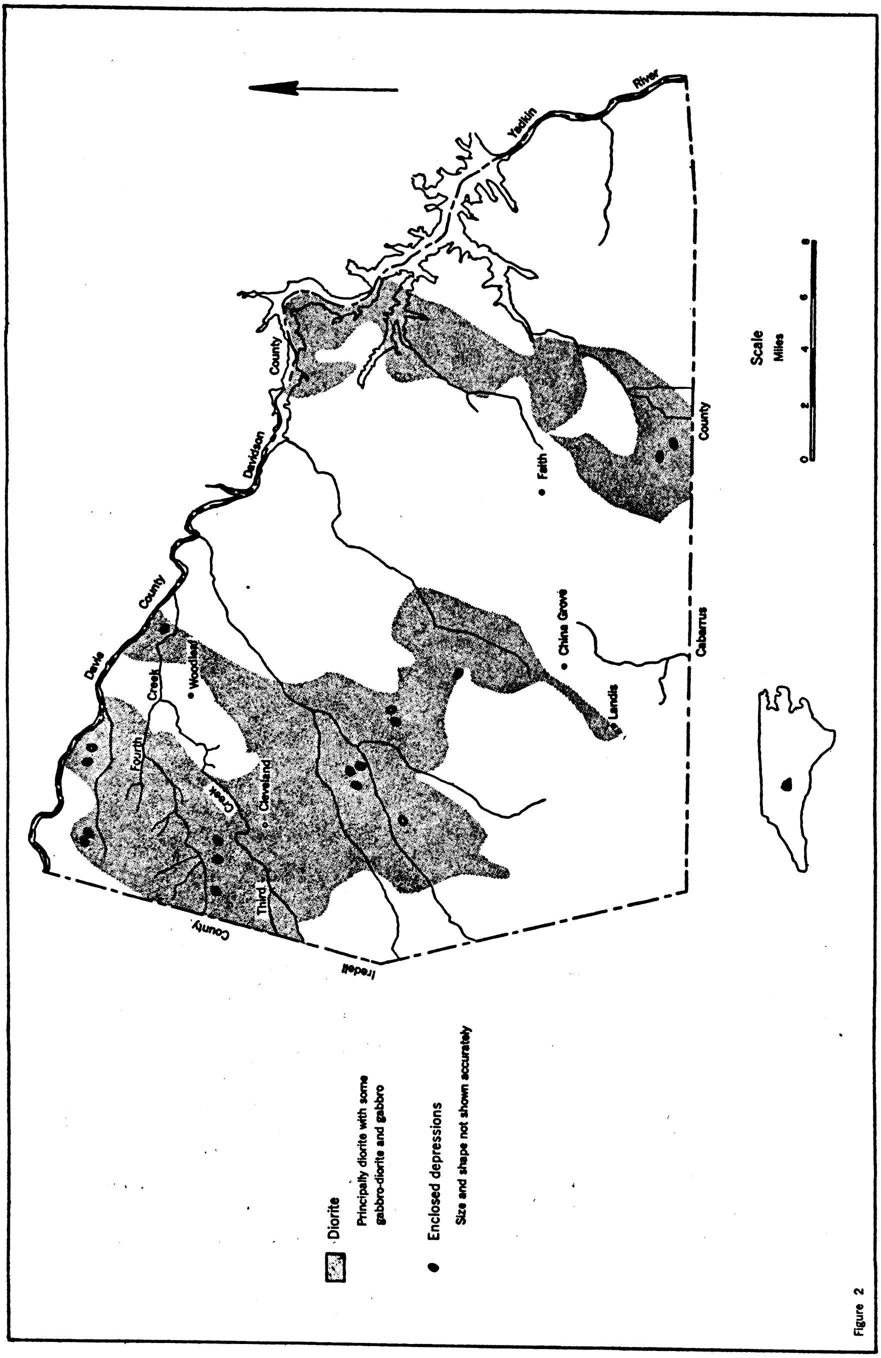

Fig. 2. Map of Rowan County showing relation of enclosed depressions to areas of diorite and gabbro-diorite.

Davidson, Cabarrus, Iredell, and Alamance. Figure 2 shows the location of many of the depressions in Rowan County.

Although the depressions have been recognized by the owners of the tracts of land on which they are situated, they apparently have received no attention scientifically. So far as genesis is concerned they are abnormal land forms on igneous rocks; the normal destructive processes depend on running surface water, producing fully drained, rather than enclosed, depressions wherever slopes converge. The apparent inability of subaerial erosion to account for the depressions (erosion by wind action seems quite out of the question) requires that consideration be given to ground water as an agent that causes subsidence of the land surface through solution. To test the hypothesis of solution subsidence it is necessary to show that soluble rocks occur beneath the depressions, that appreciable mineral matter in solution is extracted from the rocks, and that there is subsidence of the surface as a consequence. The requirements needed to satisfy this hypothesis are discussed in the following pages.

PHYSIOGRAPHY

All depressions noted in the present study are on the Piedmont plateau, or Piedmont as it is generally called. It is a plain so thoroughly dissected by streams that its plainlike features are noticeable only by comparing the tops of interstream areas. The drainage is of fine texture, and consequently an undulating or hill-and-valley type of topography prevails. The larger streams flow southeast in consequence of the regional slope. Many tributaries flow northeast or southwest, parallel with the most prominent rock structures; some of those streams are controlled by structure, whereas others merely follow the most direct surface slope which coincidentally is parallel with the structure.

The depressions most thoroughly studied are in northwestern Rowan County in an area of almost typical Piedmont topography. The depressions are in nearly flat but narrow upland areas where the local relief is about 100 feet. In addition to the depressions there are slight undulations on the uplands which appear to follow no particular pattern, and in this respect the local topography is not typical of that in the Piedmont. In fact, the local topography on the nearly flat uplands resembles that on many limestone terranes. Many small springs flow from the valleys which form reentrants into the upland areas.

SUMMARY OF GEOLOGY

The geology of the areas where depressions occur is imperfectly known. Many depressions occur in Rowan County, where the writer had previously made a reconnaissance geologic map in connection with systematic ground water studies. The geologic map of Rowan County prepared by the writer is shown as figure 3 and the geology of the county is described briefly below. The extreme eastern part of Rowan County is underlain by slates and volcanic rocks. Depressions do not occur in them, and they need not be discussed further. The remainder of the county is underlain chiefly by felsic to mafic plutonic rocks, predominantly granite, diorite and gabbro-diorite. In some places the diorite and gabbro-diorite show a northeast structural trend. Homogeneous masses of both granite and diorite are found, although for the most part these two types of rocks are profusely interlayered or interpenetrated. The subordinate rock, which may be granite in one place and diorite in another place, appears to vein the predominant rock, so that changes in rock type generally occur every few feet. Although the individual rock bodies are generally not gradational, the predominance of diorite in one place and granite in another is a gradational feature. The intrusive complex of granite and diorite is the most outstanding feature of the geology.

Neither the age nor the age relationship of the rocks is clearly known; all are of Paleozoic age or older.

In the field study, special attention was paid to the diorite in order to determine its relation to the depressions. Almost nowhere is the diorite free of granitic bodies, although in the area mapped as diorite less than 5 per cent of the aggregate rock appears to be granitic. The diorite varies in composition from place to place, the most mafic varieties actually being gabbro. Watson and Laney (1906, p. 20), who examined thin-sections of the diorite from several places in western Rowan County, say that the diorite is composed largely of hornblende and plagioclase feldspar, the typical accessory minerals occurring in very subordinate amounts.

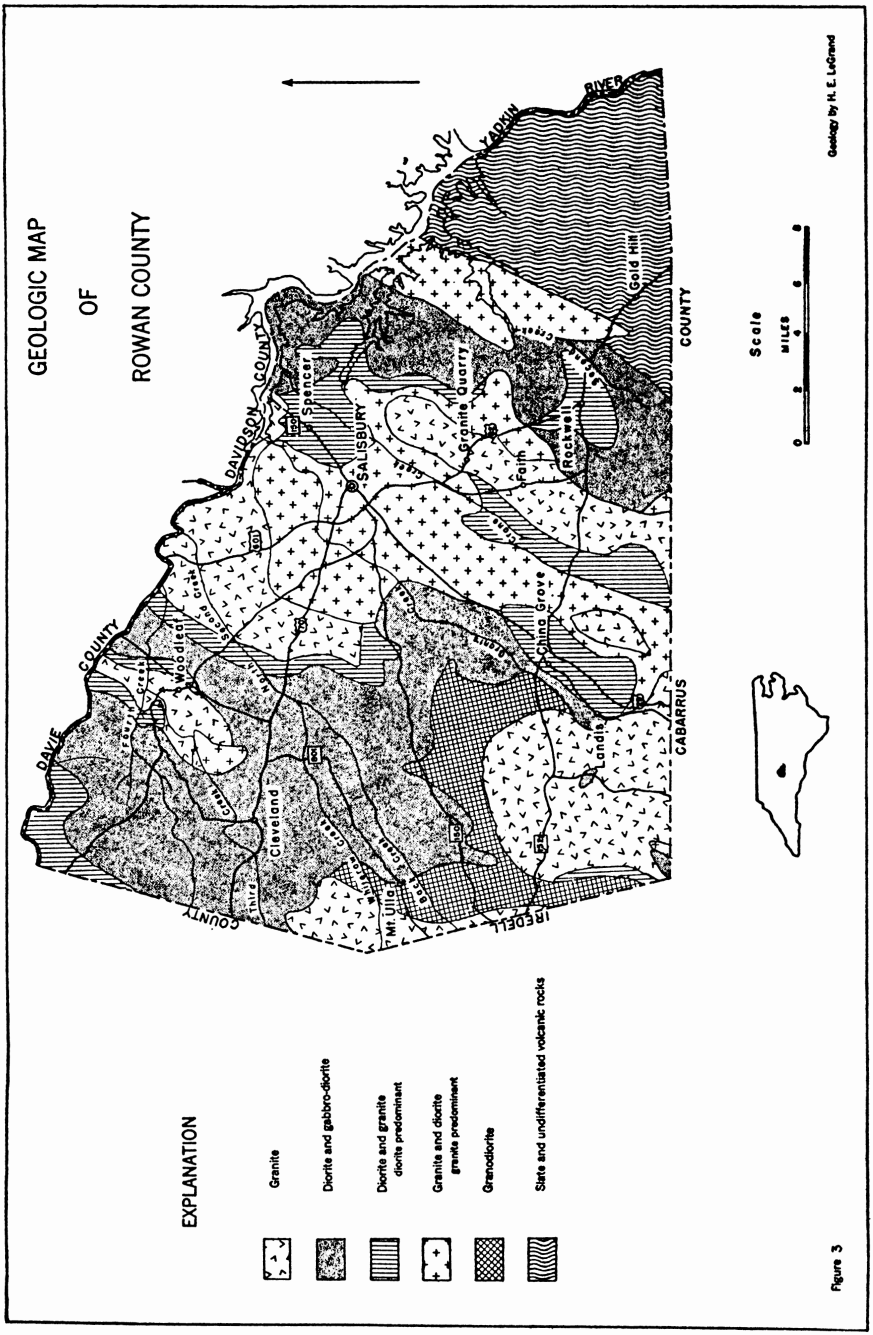
GEOLOGIC MAP
OF
ROWAN COUNTY
EXPLANATION
Granite
Diorite and gabbro-diorite
Diorite and granite
diorite predominant
Granite and diorite
granite predominant
Granodiorite
Slate and undifferentiated volcanic rocks
Figure 3
Scale
MILES
0 2 4 6 8
Geology by H. E. LeGrand
DAVIE COUNTY
DAVIDSON COUNTY
CABARRUS COUNTY
IREDELL COUNTY
YADKIN RIVER
Spencer
SALISBURY
Granite Quarry
Faith
Rockwell
Gold Hill
China Grove
Landis
Cleveland
Woodleaf
Mt. Ulla
Third
Fourth Creek
Second Creek
Crane Creek
Grants Creek
Back Creek
Withrow Creek

Fig. 3

That depressions do not occur in rocks higher in silica content than diorite indicates that the chemical composition of the underlying rock is a factor in their development.

OCCURRENCE AND MOVEMENT OF WATER IN THE PIEDMONT

Despite intensive studies of the physiography of limestone terranes, there is a prevailing disagreement concerning the sequence of events that lead to solution subsidence. This is largely due to a general lack of attention to the basic principles of the occurrence and movement of ground water and the effects these principles have on land forms. To understand the extraction of mineral matter, whether from limestone or igneous terranes, requires consideration of ground water behavior.

The igneous rocks of the Piedmont are commonly mantled by 10 to 50 feet of soil and weathered rock in which water occurs between the individual mineral particles. In sharp contrast is the occurrence of water in the underlying bedrock, where water is restricted to fractures. These fractures are generally not evenly distributed, so that they may be an inch or two or several feet apart. Many are interconnected sufficiently to allow ground water to circulate through them. In many places fracture openings are only a fraction of an inch wide, although there is a great variation in size of openings. In so far as the yields of water wells indicate the degree of fracturing, the size and number of fractures appear to decrease with depth, at a rate that appears to be approximately logarithmic. As a result, most ground water occurs at a depth of less than 125 feet—much of it within the uppermost 30 feet of the bedrock—and perhaps less than 5 per cent of the ground water occurs below 175 feet. Hence, the lower limit of the underground reservoir is not a sharp boundary but a thick, indefinite zone; the top, however, is a definite though fluctuating surface known as the water table. The water table is absent in a few places because of the absence of fractures, but it is present almost everywhere. The water table lies in the residuum in some places and in the bedrock in other places. It is generally at least 30 feet below the surface beneath the uplands. The water table stands higher beneath the upland areas than beneath the adjacent valleys, although it lies farthest below the land surface in the uplands; in other words, it slopes much like the land surface but less steeply.

Water is discharged from the underground reservoir as seeps and springs which produce the base flow of streams, and by evaporation and transpiration. Evaporation and transpiration are not pertinent to solution subsidence because they are not considered capable of transporting mineral matter to any degree, they are not localized to depressions, and they operate largely in the residuum where most soluble material has already been removed. A spring occurs at a point of convergence of the surface slope and water table, generally at the base of a steep valley head. The flow of a spring is dependent on the amount of water supplied by precipitation and subsequent infiltration, on the topography, and on the ability of the rocks to transmit water underground to the spring. More than 45 inches of precipitation distributed rather evenly throughout the year recharges the underground reservoir and thus prevents its depletion. After each rainy period the water table beneath the uplands rises, steepening the hydraulic gradient and thereby increasing the flow of springs.

After infiltrating downward through the residuum, as a relatively continuous body or sheet, water circulating in the bedrock is restricted to fractures. Most of the natural circulation is confined to a zone extending no lower than the upper 30 feet of bedrock because the number and size of water-bearing fractures below that zone decrease greatly. Unlike homogeneous and isotropic water-bearing rocks in which much water moves at considerable depth below the level to which it ultimately rises to discharge, the igneous rocks of the Piedmont constrict the downward movement of water and shunt it laterally to discharge points above the base of the perennial streams. Thus, the movement of ground water in the Piedmont from the recharge or interstream areas to the discharge or stream areas follows in general an almost direct path, although locally, of course, the water flows through devious interconnecting fractures. Evidence that most of the circulation takes place near the top of the bedrock is found in the facts that the yields from deep wells are not appreciably greater than the yields from shallow wells and that, with few exceptions, there is no significant difference in temperature in water from wells of various depths. If, in the average deep well, a substantial part of the water came from the lower part of the hole, its temperature and the average temperature of all the water from the well would be higher than that from shallower wells, which is not the case.

In terms of the water table, the greatest circulation at any given place occurs in the zone between its highest and lowest stages, the circulation being most active just below the water table at all times. From the direct relation which appears to exist between circulation and solution it can be concluded that the greatest solution is in this zone. From studies of ground water in the limestones of Florida, Stringfield[1] reached a similar conclusion—that the greatest solution occurs in the zone between the highest and lowest stages of the water level.

REMOVAL OF MINERAL MATTER IN SOLUTION

A part of the systematic study of ground water in the igneous and metamorphic rocks in North Carolina deals with chemical character of water discharged from these rocks. Some of the analyses that have been made are given in the accompanying tables. These analyses show clearly that the rocks are somewhat soluble, as pointed out in general terms by Clarke (1924, p. 484):

> "The evidence, both as found by experiment in the laboratory and by field observations, shows that practically all minerals, certainly all of the important ones, are attacked by water and carbonic acid. The pyroxenes and amphiboles yield most readily to waters, then follow the plagioclase feldspars, then orthoclase and the micas, with muscovite the most resistant of all. Even quartz is not quite insoluble . . ."

The total amount of mineral matter dissolved and later discharged by ground water depends on the length of time water is in contact with the soluble rock and on the solubility of the mineral constituents. The amount of dissolved mineral matter in water contained in the rocks increases with time of contact, although this is not a simple relation. Other factors being equal, the rate of increase in mineral content of water contained in a rock appears to lessen with approximately logarithmic regression as time passes. Thus, if water is in contact with a soluble rock long enough it will become

[1] Stringfield, V. T., oral communication, 1947.

saturated with dissolved mineral solids, and the water will be powerless to extract more mineral matter from the rock. It follows that stagnant water is not an important solutional agent. Circulating ground water, on the other hand, is important because water laden with mineral matter moves out of the rocks and water containing little or no mineral matter moves in to replace it. Thus, mineral matter is continuously being extracted from the rocks. Many of the rocks of the Piedmont show no great variation in degree of fracturing, so that there appears to be a nearly equal rate of circulation of water through each type of rock; however, the circulation seems to be slower at depth, as would be expected, so that the water is in contact with the rocks for a longer period and the mineral content of water from deep wells is higher than that in water from shallow wells. If the water level in the deep wells is lowered considerably by pumping the mineral content of the water appears to increase. This, too, can be expected because it means that water is being drawn from depth in greater quantities than if the water level were lowered only slightly.

Where the circulation of water in different kinds of rock is equal, the chemical quality of the water reveals the general solubility of the source rock.

Table 1 shows the chemical quality of some well waters derived from rocks in the environs of the depressions. Not all features of the analyses can be explained easily. Nevertheless, it is evident that the amount of dissolved solids in water from diorite is three or four times greater than that in water from granite. In fact, the diorite contains water which, except for a higher silica content, is comparable in dissolved solids and mineral constituents to many waters in limestone in the Atlantic Coastal Plain.

Table 1 also shows the character of water from four wells tapping residual material above bedrock. That none of these contained more than 50 parts per million of dissolved solids indicates that solution is more active in bedrock than in the residual material.

The quality of spring water also reveals the solubility of the source rock, but to a lesser extent than well water. Many spring waters flowing partly or entirely through residuum have very little mineral matter, whereas other spring waters

TABLE 1

Analyses of water from selected wells in the Piedmont area of North Carolina

Analyzed by the U. S. Geological Survey

Parts per million

County	Location	Owner	Silica SiO_2	Iron Fe	Calcium Ca	Magnesium Mg	Sodium & potassium Na+K	Bicarbonate HCO_3	Sulfate SO_4	Chloride F	Fluoride F	Nitrate NO_3	Dissolved solids	Total hardness as $CaCO_3$	Depth of well (feet)	Geologic source
Rowan	Kannapolis	T. H. Powers	24	0.14	4.1	1.5	4.0	24	1.6	2.2	0.0	0.9	52	16	161	Granite
Rowan	Rockwell	Town of Rockwell	27	.09	9.1	1.4	7.0	48	1.7	1.6	.1	.2	71	28	144	Granite
Rowan	Landis	Town of Landis	37	.40	9.4	.6	12	54	3.6	2.2	.2	.1	92	26	406	Granite
Cabarrus	Kannapolis	Ben Aycock	27	.03	4.3	.9	5.2	26	.9	2.0	.0	.8	58	14	180	Granite
Cabarrus	Kannapolis	J. G. Love	..	...	...	...	...	44	...	...	...	...	...	24	160	Granite
Cabarrus	Kannapolis	S. W. Cline	..	...	...	...	...	20	4	10	.1	...	...	26	...	Syenite
Cabarrus	Concord	Cannon Mlils	..	...	...	...	...	216	36	128	.3	...	...	279	612	Granite and diorite
Cabarrus	Concord	Odell School	..	...	...	...	...	90	2	5	.1	...	...	63	200	Granite and diorite
Rowan	Landis	Town of Landis	23	.06	54	2.0	17	100	86	2.5	2.2	.1	246	143	604	Granite and diorite
Rowan	Landis	Town of Landis	35	1.6	37	1.7	9.9	63	59	2.8	.6	2.7	185	99	1009	Granite and diorite
Cabarrus	Concord	City of Concord	..	.22	...	...	...	270	26	24	.2	...	...	258	135	Diorite
Rowan	Landis	Town of Landis	31	.49	174	3.5	15	82	391	2	1.8	.2	696	449	1108	Diorite

TABLE 1 (Cont.)

Analyses of water from selected wells in the Piedmont area of North Carolina

Analyzed by the U. S. Geological Survey

Parts per million

County	Location	Owner	Silica SiO_2	Iron Fe	Calcium Ca	Magnesium Mg	Sodium & potassium Na+K	Bicarbonate HCO_3	Sulfate SO_4	Chloride F	Fluoride F	Nitrate NO_3	Dissolved solids	Total hardness as $CaCO_3$	Depth of well (feet)	Geologic source
Rowan	China Grove	Town of China Grove	26	.21	47	4.9	11	111	63	2.5	.2	.0	219	137	714	Diorite
Rowan	China Grove	Town of China Grove	30	.17	57	5.4	12	103	98	3.2	.1	.3	268	164	319	Diorite
Rowan	China Grove	Town of China Grove	35	.06	57	5.3	13	123	84	2.5	.3	.1	259	164	750	Diorite
Rowan	Cleveland	Town of Cleveland	47	.30	38	16	9.5	127	23	25	.1	22	260	161	187	Diorite
Cabarrus	Roberta	Roberta Mfg. Co.	51	.80	53	21	17	146	103	19	.3	1.6	366	219	276	Gabbro-diorite
Rowan	1 mi. S. of Cooleemee	T. C. Hendrix	50	.20	23	11	8.1	87	26	12	.2	5.5	191	103	49	Gabbro-diorite
Rowan	2 mi. N. of Cleveland	Ira Hodge	..	...	...	...	...	...	...	...	...	...	30	13	45	Residuum of diorite
Rowan	2 mi. N. of Cleveland	Ross Wood	..	...	...	...	...	...	...	...	...	...	50	22	40	Residuum of diorite
Rutherford	....	Alexander Mfg. Co.	13	.10	3.3	1.7	3.8	13	1.4	6.8	.1	2.0	41	15	25	Residuum of mica schist
Rutherford	....	Alexander Mfg. Co.	12	.11	2.6	1.6	3.2	18	1.2	1.8	.1	1.7	32	13	25	Residuum of mica schist

circulate through granite or other relatively insoluble rocks yet are high in mineral content, showing that the circulation is slow. Spring waters generally circulate more rapidly through the rocks than do well waters, and, consequently, the dissolved-solid content of spring waters is considerably less than that of well waters.

It can be seen from table 2 that springs emerging from diorite near the depressions have more dissolved solids than the average of the springs listed. In a report[2] on some mineral springs in the state, the mean dissolved-solids content of water from 22 springs in the Piedmont was 150 parts per million. The average flow of these springs was only 1.0 gallon a minute, suggesting that their high mineral content may be owing, in part, to poor circulation of water through the rocks. The majority of these springs, selected for their mineral properties, are not typical. Of the thousands of springs in the Piedmont of North Carolina, the median concentration of dissolved solids is probably less than 45 parts per million.

The geologic source of water from large streams is obscured, owing to the mixture of water flowing over and through diverse rocks. On the other hand, the mineral content of water from a short stream may reveal much information on the geology of its small drainage area.

Table 3 shows miscellaneous analyses of water from some small streams in the Piedmont. Those which have diorite as the principal source rock drain the areas in which some depressions occur. In evaluating these analyses it should be noted that the concentration of mineral matter in a stream appears to vary inversely with the amount of its flow, so that an analysis made after a heavy rain will show less mineral matter than one made at the same place after a long period of fair weather. Samples for analysis were collected at different times, and consequently the relative stage of concentration of mineral matter was not the same for each analysis. Nevertheless, according to table 3 the dissolved solids in water flowing from diorite are considerably higher than that of water from granite, indicating that considerable mineral matter is being removed from diorite in drainage areas underlain by it.

[2] North Carolina Geol. and Econ. Survey, Econ. Paper 15, 1908.

TABLE 2

Analyses of water from selected springs in the Piedmont area of North Carolina

Analyzed by the U. S. Geological Survey

Parts per million

County	Location	Owner	Silica SiO_2	Iron Fe	Calcium Ca	Magnesium Mg	Sodium & potassium Na+K	Bicarbonate HCO_3	Sulfate SO_4	Chloride F	Fluoride F	Nitrate NO_3	Dissolved solids	Total hardness as $CaCO_3$	Yield (gal. per min.)	Geologic source
Gaston	2 mi. N. of Lowell at edge of road near Catawba River	....	23	0.21	4.9	2.2	5.3	31	4.3	1.9	0.0	0.2	59	21	½	Hornblende gneiss
Rowan	2 mi. N. of Cleveland	Ross Wood	..	....	...	...	...	...	...	...	...	...	74	34	2	Diorite
Rowan	2 mi. N. of Cleveland	Ira Hodge	..	....	...	...	...	...	...	...	...	...	89	39	1	Diorite
Cleveland	4 mi. W. of Shelby	T. P. Hamrick	11	.09	1.7	.9	3.5	11	1.2	2.2	.1	2.4	30	8	15	Granite and mica schist
Rutherford	....	Grady Withrow	15	.34	2.0	1.0	3.8	17	1.6	1.2	.0	.0	33	9	4	Granite gneiss
Stokes	Lawsonville County School	....	..	.04	...	...	...	13	2	2	...	...	...	12	5	Granite gneiss

TABLE 3

Analyses of water from selected streams in the Piedmont area of North Carolina

Analyzed by the U. S. Geological Survey

Parts per million

	Silica SiO_2	Iron Fe	Calcium Ca	Magnesium Mg	Sodium & potassium Na+K	Bicarbonate HCO_3	Sulfate SO_4	Chloride F	Fluoride F	Nitrate NO_3	Dissolved solids	Total hardness as $CaCO_3$	Date of collection	Geologic source
1. Forbush Creek near Yadkinville, at gage	13	0.04	3.1	1.3	4.3	22	2.0	1.4	0.0	0.3	37	13	8/11/44	Granite gneiss
2. Indian Creek at Crouse (Catawba Basin)	13	.04	3.2	1.3	3.7	19	2.1	2.1	.1	.5	36	13	8/10/49	Granite
3. Small creek in Rowan County, 2 mi. S. of Faith; ½ mi. N. of N. C. Route 152	..	....	...	...	...	...	...	...	...	...	71	20	10/12,50	Granite
4. Fourth Creek near Statesville	16	.5	5.4	1.6	2.6	19	1.9	4.8	...	.3	52	20	1/11/26	Granite gneiss
5. Davidson Creek near Cornelius (Catawba Basin)	26	.10	8.4	4.3	4.0	50	2.2	2.6	.1	.2	76	39	9/23/49	Granite and diorite
6. Abbotts Creek at Lexington, at gage	20	.02	9.9	3.4	19	59	5.8	18	.2	.8	109	39	8/12/44	Diorite and granite
7. Third Creek at Cleveland, at gage	20	.02	6.4	2.7	19	40	4.0	22	.1	.5	98	27	8/11/44	....
8. Third Creek, in Iredell County, on county road 1¼ mi. W. of Rowan County line and 2¼ mi. N. of Amity Hill	..	....	...	...	...	...	...	...	...	...	66	23	10/12/50	Predominantly granite — some hornblende gneiss

TABLE 3 (Cont.)

Analyses of water from selected streams in the Piedmont area of North Carolina

Analyzed by the U. S. Geological Survey

Parts per million

	Silica SiO_2	Iron Fe	Calcium Ca	Magnesium Mg	Sodium & potassium Na+K	Bicarbonate HCO_3	Sulfate SO_4	Chloride F	Fluoride F	Nitrate NO_3	Dissolved solids	Total hardness as $CaCO_3$	Date of collection	Geologic source
9. Third Creek at Cleveland, at gage	..	....	...	...	...	...	...	...	...	...	76	27	10/12/50	Granite, hornblende gneiss, and diorite
10. Small unnamed creek in Rowan County, ½ mi. south of Fourth Creek, 3 mi. N. of Cleveland	..	....	...	...	...	...	...	...	...	...	132	70	8/16/50	Diorite
11. Small unnamed creek in Rowan County, 1 mi. N. of 4th Creek, 3¼ mi. NW. of Woodleaf	..	....	...	...	...	...	...	...	...	...	134	76	10/12/50	Diorite
12. Small unnamed creek in Rowan Co., 2 mi. W. of its junction with S. Yadkin River and 3¾ mi. NW. of Woodleaf	..	....	...	...	...	...	...	...	...	...	140	77	10/12/50	Diorite
13.* Hypothetical stream in the Piedmont of North Carolina	16	0.81	5.2	1.9	5.2	1.9	5.9	4.6	...	0.8	62	20	....	....

* Represents average (mean) of 38 analyses of streams in the Piedmont of North Carolina, published in Preliminary report on the chemical quality of the surface waters of North Carolina, with relation to industrial use: North Carolina Dept. Cons. and Devel. Econ. Paper 61, p. 43, 1925.

The tables of chemical analyses show the concentration of mineral matter in waters of the Piedmont and the relative solubility of the source rocks. More pertinent than the mineral concentration of one or a large number of samples of water is the total mineral matter extracted by water from the rocks in a given time and area. This can be calculated if both quality and quantity of water discharged from the drainage areas are known.

Records of the quantity and quality of surface water compiled by the U. S. Geological Survey are chiefly for large drainage areas, the waters of which come from different types of rocks. The chemical character and amount of water yielded in a given area underlain entirely by a single rock type are not known, and consequently accurate calculations of the total amount of dissolved mineral matter removed from the environs of the depressions in diorite cannot yet be made. However, some speculation is worthwhile.

Drainage from the area of depressions in northwest Rowan County is largely into Third and Fourth Creeks. Some records are available for Third Creek at the gaging station about 2 miles north of Cleveland. On August 11, 1944, the dissolved-solid content of Third Creek was 98 parts per million. The discharge was 37 cubic feet per second, or 27 cubic feet below the yearly mean. The flow for that day, which was preceded by a long interval of nearly fair weather,[3] consisted entirely of discharge from the underground reservoir. About 20,000 pounds or 114 cubic feet of mineral matter, assuming an average specific gravity of 2.75, was extracted in solution in the 87-square-mile drainage area during the 24 hours of August 11, or 1.3 cubic feet per square mile.

Because the daily mean discharge is greater, the daily mean extraction of mineral matter should be greater, though not in direct proportion to the increase in discharge. The upper three-quarters of the drainage area is underlain chiefly by granitic rocks, which supply much less dissolved mineral matter than the diorite. Thus the amount of mineral matter taken from the diorite is conservatively estimated as twice

[3] According to the U. S. Weather Bureau, 0.68 inch of rain occurred at the Salisbury station, Rowan County, during the first 11 days of August, of which 0.36 inch came on the 1st and 2nd days of the month and the remaining 0.32 on the 7th and 8th.

that of the average for the entire basin area, or about 2.7 cubic feet per square mile per day, or about 1,000 cubic feet per square mile per year. The removal of dissolved mineral matter is not equal in all parts of an area, even where the same rock prevails. It is greatest in the vicinity of, and up gradient from, springs or other discharge points, where circulation is greatest. The proximity of springs to the depressions and the steep hydraulic gradient from depressions toward springs indicate that circulation and consequent solution are great in the depression areas.

An estimate can be made of the rate of enlargement of a depression. The depression on the Ford property, for example, receives about 2,300,000 cubic feet of precipitation annually in its 620,000 square feet of internal drainage area. Within this area probably at least half the total precipitation infiltrates into the ground to become ground water. Although the mineral content of water discharged from the diorite may be several times greater, it is assumed that about 30 parts per million of the total dissolved-solids content of the water represent mineral matter dissolved from the diorite in the enclosed depression. Thus, it is estimated that about 13 cubic feet of rock is dissolved away each year in the Ford depression. In the enclosed depressions, the rate of solution should be almost directly proportional to the size of the internal drainage area. Hence, the rate of solution beneath small depressions is probably not as great as that beneath larger depressions. Solutions in the heads of valleys having large drainage areas is thought to be of considerable magnitude.

Plenty of time exists for the formation of the depressions, so long as the normal processes of subaerial erosion do not cause valleys to extend headward to them, in which case parts of the rims are lowered and the depressions become normal valley heads. Unquestionably many enclosed depressions are being destroyed by the headward extension of valleys. Some are destroyed before they reach a mature stage of development. However, many depressions situated on divides may escape destruction by subaerial erosion for thousands of years.

SURFACE SUBSIDENCE

In limestone terranes the removal of dissolved mineral matter creating voids does not necessarily lead to subsidence of the overlying rock and residual material. However, if caverns occur near the surface in the upper part of bedrock their roofs may collapse and the effect of this slumping may be observed at the surface. Ground water studies clearly indicate that, in the igneous rock of the Piedmont, mineral matter is dissolved largely in the upper part of the bedrock, but they do not reveal the nature of the voids produced. Data on wells in rocks of the Piedmont fail to show the presence of large air-filled or water-filled caverns, such as are found in some limestone terranes; however, many wells penetrate a zone of soft clay beneath a zone of bedrock, and it is possible that this clay may have moved downward through sizable openings; it is also possible that this clay represents the insoluble residue resulting from solution in this zone. Does removal of dissolved mineral solids occur at the top of bedrock, and minute but constant subsidence occur concomitantly? Water moving downward through the residuum reaches the top of the impervious bedrock where it is shunted down slope to fractures, which transmit it deeper into the rock or farther down the bedrock slope to surface discharge points. That much of the ground water discharge occurs at the contact between residuum and bedrock suggests that solution and, consequently, some subsidence occur in this zone. Whatever the nature of the voids produced, it is evident that solution occurs largely at, or near, the top of bedrock, where subsidence also is possible.

CONCLUSIONS

Depressions occur in the Piedmont of North Carolina in nearly flat upland areas of diorite. The relatively high solubility of these rocks, which appear to yield more than three times as much mineral matter to solution than does granite, is considered to be the cause of surface subsidence producing the depressions. The solubility of the rock and the degree of circulation of ground water through it are the factors that largely govern solution. Depressions develop on nearly flat interstream areas which so far have escaped the channel type of subaerial erosion, so active on adjacent slopes.

The greatest circulation and consequently the greatest solution occur near springs and along the steepest parts of the hydraulic gradient above them; in terms of surface topography this is in the steep headward parts of valleys. Although surface subsidence forming depressions is not noticeable on these slopes, there are numerous bulbous valley heads similar to depressions except that they have a surficial drainage outlet. Many of these valley heads are considered to have been formed in part by solution subsidence. Despite the lack of recognition by geologists of the role of solution in the production of land forms on igneous and metamorphic rocks, the evidence afforded by a study of the quantity and quality of our natural waters indicates that ground water is removing enough dissolved mineral matter in many places to alter the topography. Although running surface water is by far the dominant agent in carving landscapes in the southeastern Appalachian Piedmont, the circulation and discharge of ground water containing mineral matter in solution appears to constitute an important agent in the headward migration of valleys and the initiation of many slopes. By giving due consideration to subterranean as well as subaerial erosional processes, a more complete understanding can be reached of the sequence of events leading to a certain stage of degradation in igneous and metamorphic terranes.

The removal of dissolved mineral matter from the rocks, especially in valley heads, has resulted in the enlargement of fractures or voids through which circulating ground water moves relatively freely. The productivity of wells in the Piedmont, which is generally greater in valley heads than in any other topographic location (Mundorff, 1948, p. 31), supports this deduction, although several other factors enter into the productivity of wells.

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