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The Hydrogeology Of The Central Monroe County Karst, West Virginia.

ALBERT EDWARD OGDEN

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THE HYDROGEOLOGY

OF THE

CENTRAL MONROE COUNTY KARST,

WEST VIRGINIA

DISSERTATION

Submitted To The Graduate School
of
West Virginia University
In Partial Fulfillment Of The Requirements For
The Degree of Doctor Of Philosophy

by

Albert Edward Ogden, B.S.

Morgantown
West Virginia
1976

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ABSTRACT

The purpose of this hydrogeologic study was to define the number and nature of major aquifers of the Greenbrier Group and to chemically characterize both well and spring waters in central Monroe County, West Virginia. This was accomplished in four parts:
(1) detailed mapping of the structures and Greenbrier formations;
(2) identification of the major aquifers by well inventorying;
(3) investigation of the inorganic chemistry of aquifer waters;
(4) study of the seasonal and storm trends in spring-water chemistry.

The central Monroe County karst is developed on about 1100 stratigraphic ft (335 m) of Upper Mississippian Greenbrier Limestone. Within the 65 square mile (169 square kilometer) study area, there are nine major folds and several thrust faults. The nine formations of the Greenbrier Group were mapped in detail. The broad, low-plunge folds trend in a NE-SW direction.

Caverns are found primarily in the Union, Patton, and Sinks Grove limestones, whereas the areas of highest doline density are found on Union, Taggard, and Patton limestone surfaces. Cavern orientations are not statistically related to joints, stratigraphic strike, or photo-lineament orientations, although the cavern orientations may be influenced by combinations of these factors. Photo-lineaments show a nearly uniform density among all formations not cropping out on mountain slopes, and show little preferred orientation.

Three main confined aquifers were found within the Greenbrier Limestone: (1) the Hillsdale-Maccrady aquifer; (2) the Patton-Taggard aquifer; and (3) the Union-Greenville aquifer. The piezometric surface of each aquifer was mapped where there were sufficient data. Well productivity was found not to be statistically related to photo-lineaments.

Overall, the Hillsdale-Maccrady aquifer has the greatest hardness and sulfate concentrations. Some wells in this aquifer contain H_2S and as high as 990 mg/l of sulfate. The Union-Greenville aquifer has been contaminated by improper road salt storage in the recharge area causing chloride levels of up to 300 mg/l and high hardness due to the $CaCl_2$ in the road salt. The Patton-Taggard aquifer and the locally productive Sinks Grove aquifer produce water of intermediate quality and generally have higher nitrate levels.

The Union-Greenville and Patton-Taggard aquifers show seasonal variations with statistically significant increases in pH, SIc, and Pco_2 from fall to spring. The Ca-Mg ratio and calcium, chloride, and nitrate concentrations have overall increases in the spring season. The deeper Hillsdale-Maccrady aquifer waters have these same trends.

Eight springs and one insurgence were sampled either biweekly or monthly for 13 months to determine seasonal and discharge variations in water chemistry. Temperature, Pco_2, and nitrate show the most pronounced seasonal trends, while total hardness is related to discharge, Coefficients of variation of tested chemical parameters are highest for vadose conduit springs and become smaller moving downstream from insurgences.

The two Salt Sulphur springs appear to be "drying up" both chemically and physically, being mere seeps.

Dickson, Walters', and Cold Spring basins have measured karst denudation rates from 19.0 to 20.1 mm/1000 yrs.

Factor analysis of the springs and wells show common groupings of chemical variables under six factors given the following labels: (1) carbonate dissolution, (2) carbonate aggressivity, (3) dolomite dissolution, (4) nitrate, (5) chloride, (6) carbonic acid.

Spring-chemistry response to storms shows that, as basin size and average discharge increase, generally there are decreases in the range in pH, total hardness, chloride concentration, and a decrease in the ratio of peak to base discharge during storms. Large phreatic basins have longer "lag times" between peak discharge and minimum ion concentrations than small and/or vadose basins.

INTRODUCTION

Purpose of Study

The objective of this study was to identify and characterize the aquifers of the Greenbrier Group in the central Monroe County karst. This was accomplished in four parts: (1) detailed mapping of structures and Greenbrier formations; (2) determination of aquifer depths and piezometric surfaces for each aquifer by well inventorying; (3) investigation of the inorganic chemistry of aquifer waters; (4) study of seasonal and storm trends in spring water chemistry.

Location of Study Area

The study area is located in central Monroe County, West Virginia, in portions of the Gap Mills, Union, Fort Springs, and Ronceverte 7 1/2 minute quadrangles; it is approximately 65 square in size (Figure 1). It lies south of Second Creek, the northern border of Monroe County, and extends to the south to Indian and Turkey creeks. The western border runs along the top of the Swoopes Knobs, and the eastern border is along the western base of Little Mountain (Figure 2). These borders were chosen as close to hydrologic boundaries as possible for the area. The area is bounded by 37°42'30" and 37°32'00" north latitudes and by 80°35'00" and 80°27'00" west longitudes. For a more detailed description of the area the reader is referred to Reger (1926).

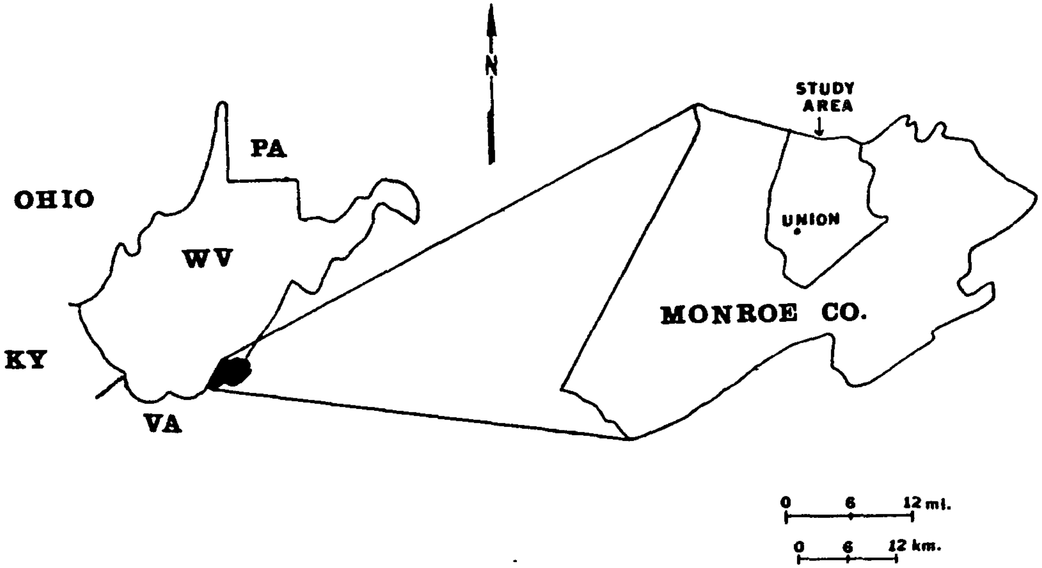

Figure 1. Location of the study area in central Monroe County.

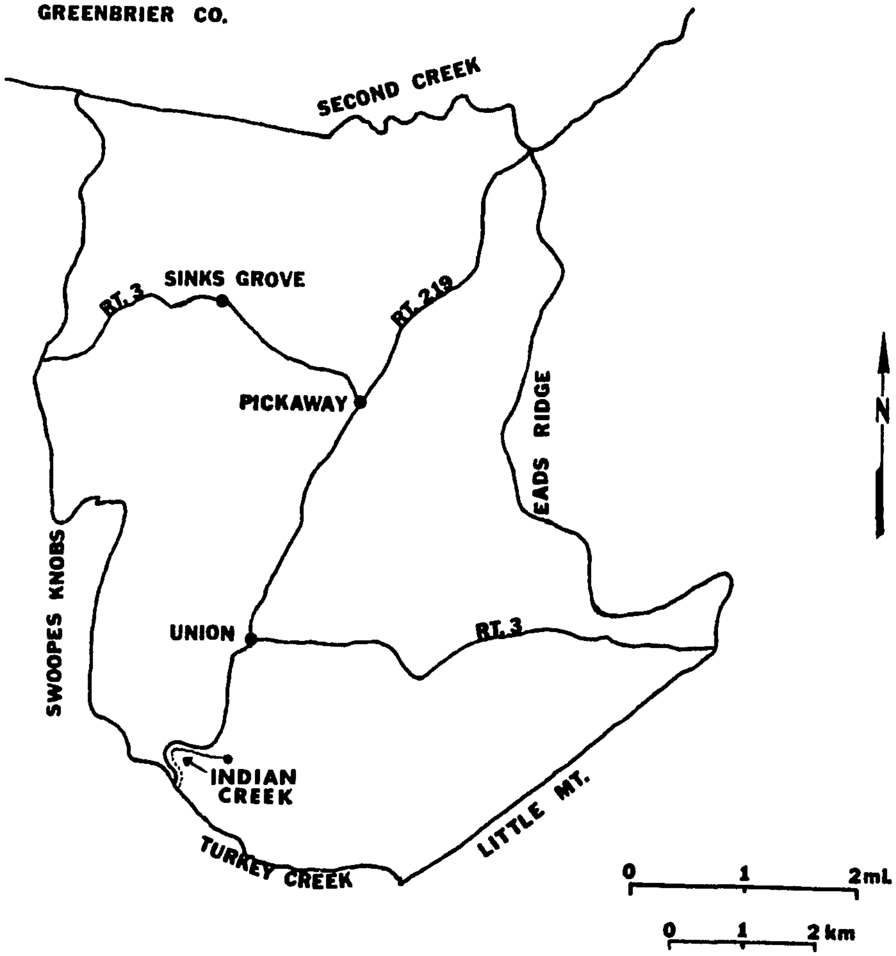

Figure 2. State roads and physiographic features in central Monroe County.

Physiography

The central area of Monroe County is a broad limestone valley that is situated between the Swoopes Knobs to the west and Eads Ridge and Little Mountain to the east and southeast respectively (Figure 2). Bickett Knob is the highest of the Swoopes Knobs with an elevation of 3328 ft. The Knobs are capped by the resistant sandstones within the Bluefield Group of the Upper Mississippian Mauch Chunk Series.

The study area is covered completely by the Greenbrier Limestone of Middle Mississippian age. Generally, the youngest formations of the Greenbrier crop out in the western area with the rocks becoming increasingly older to the east. The study area is intensely karstified with many dolines dotting the surface. Most of the study area is between 2000 and 2200 ft in elevation with much of the topographic relief resulting from dolines and uvalas that are commonly 100 ft deep.

Eads Ridge and Little Mountain are capped by the Lower Mississippian Pocono Sandstone. Little Mountain marks the structural boundary of the Allegheny Plateau to the west and the Valley and Ridge Province of the Appalachian Mountains to the east. Eads Ridge reaches an altitude of 2790 ft, with Little Mountain having a maximum elevation of 3036 ft.

The area is drained ultimately to the New River to the west via two separate drainage systems. Figure 3, showing the drainage of Monroe County, clearly indicates the karts regions by their lack of

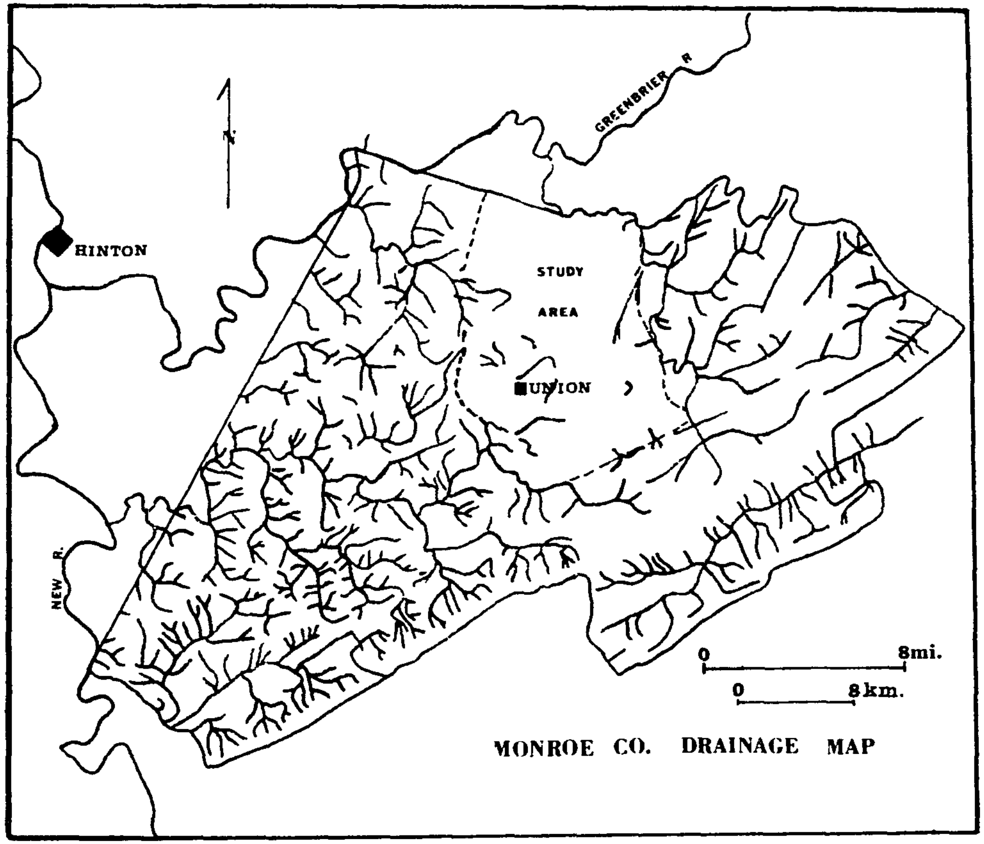

Figure 3. Drainage of Monroe County after Reger (1926).

surface drainage. Second Creek, which originates from a spring on the west flank of Peters Mountain, flows through a water gap in Little Mountain and runs along the eastern and northern boundary of the study area. Many of the sinking streams in the area eventually discharge into Second Creek, with Dickson Spring draining the largest of the karst basins (W. Jones, oral communication, 1976). Second Creek enters the Greenbrier River in Greenbrier County and then flows west to Hinton and joins the New River. During drier periods, Second Creek sinks in its bed before reaching this river.

The southern section of the study area drains into Turkey and Indian creeks which join and flow west into the New River. The spring at Steeles Cave forms the head of Indian Creek, but this is actually the resurgence of two small creeks that enter the cave and flow underground for less than 2000 ft. Walters' Spring is a major tributary of Indian Creek.

GEOLOGY OF MONROE COUNTY

Selected Literature Review

Previous geologic literature for central Monroe County is limited. The earliest reference found for the area was Grimsley (1908) on the limestones of West Virginia. White (1921) produced a map of limestone areas of West Virginia for economic purposes. The first geologic map of the region was published by the West Virginia Geological and Economic Survey (Reger, 1926). In this report Reger first divided the Greenbrier Group into formations, choosing type localities from various places in the county. The Greenbrier Group was not mapped on the formational level. McCue, et al. (1939) described several sections in the study area. Other articles dealing with the Greenbrier Limestone have been written by Price and Lucke (1942), Rittenhouse (1949), and Hall (1949). Wells (1950) worked with the stratigraphy of the lower Greenbrier Limestone trying to distinguish the lower formations described by Reger (1926) based on fossil assemblages. Leonard (1968) studied the stratigraphy and sedimentation of the upper Greenbrier Limestone; he described two detailed stratigraphic sections in the study area.

One of the first comprehensive reports of the caverns in the area was by Davies (1949). Later reports on new caves have appeared in many of the National Speleological Society's publications (Werner, 1974). A very detailed compilation of cavern locations and descriptions was made by Hempel (1975).

Mapping Methods

Formational contacts were mapped on black and white, USGS, aerial photographs of a 1:20,000 scale. Coverage of the 65 square mile area was from 1970 and 1971 flights. These photographs were also used for the production of doline and lineament maps. Solid contact lines represent walked contacts or short distances between walked contacts on the geologic map (Plate 1). The dashed lines represent covered areas of greater than approximately 1000 ft between two mapped contacts. Fold axes drawn on the map are controlled by many more bedding orientations than have been plotted on it.

Stratigraphy

The Greenbrier Group of Middle Mississippian age crops out in all parts of the study area. The Lillydale Shale of the Mauch Chunk Series overlies the Greenbrier Limestone and the Maccrady Shale is found below it (Figure 4). Both shales are also Mississippian in age. Minor amounts of alluvium are found along Second Creek, Indian Creek, and a few of the dry valleys.

The Greenbrier Group is about 1100 ft thick in the area, but ranges from 900 ft in the northern section to 1200 ft in the south (Wells, 1950). The Greenbrier Group was divided into nine formations by Reger (1926) with the type locality for each being in Monroe County. Wells (1950) suggested from paleontological evidence that the Patton and Sinks Grove formations be lumped together as the Denmar Formation. The writer feels that for Monroe County, these

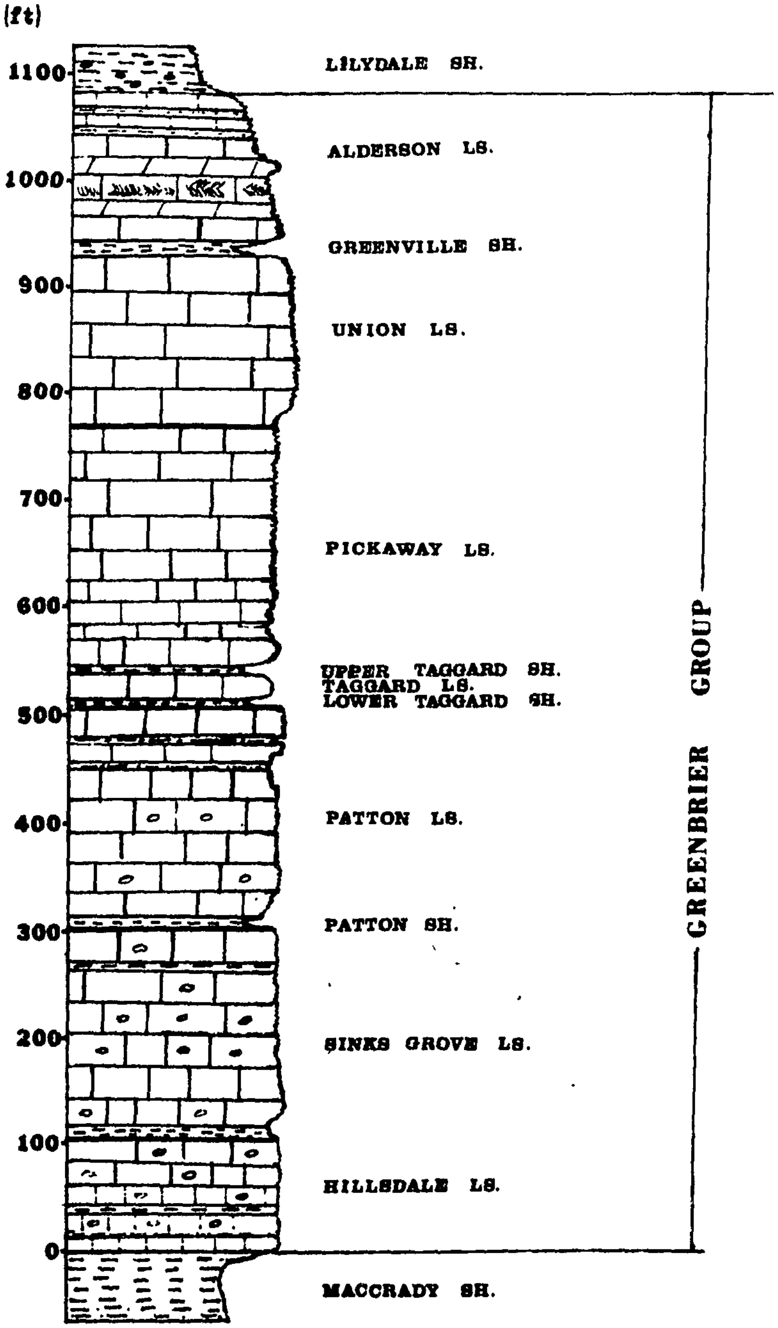

Figure 4. Generalized stratigraphic section of the Greenbrier Limestone in central Monroe County.

formations are distinct and should remain separated. The Patton Shale and Greenville Shale are thin units throughout the area and are occasionally absent. For mapping purposes these units were combined with the Sinks Grove and Alderson limestones respectively. Leonard (1968) combined the Greenville Shale with the Alderson Limestone in his stratigraphic study. A geologic road log (Ogden, 1976) suggests places where several of the contacts of the lower Greenbrier can be found.

Maccrady Shale

The Maccrady Formation represents the oldest rocks dealt with in this report (Reger, 1926). This formation is situated just below the Greenbrier and right above the Pocono. Characteristically, they are red, purple, and green shales, and mudstones. Near the contact with the Greenbrier, the Maccrady Formation commonly contains yellow and calcareous shales and yellow earthy limestones. At places there are black coatings of manganese minerals on bedding surfaces. Thin beds of sandstone and siltstone are found throughout the formation.

The Maccrady is practically barren of fossils with the calcareous beds generally containing most of the marine fossils. Fossil plants are found occasionally in the shales and siltstone.

In the county, the Maccrady is up to 350 ft thick but only the upper 50 ft were usually observed, since the Greenbrier-Maccrady boundary defined the lower extent of the mapping. This upper contact with the Greenbrier is gradational in Monroe County and does not appear to be an erosional disconformity as has been seen in Greenbrier County. One of the best exposures of the Maccrady can be seen to the east along State Route 3, 7.8 miles east of Union, at the base of Little Mountain where the rocks are nearly vertical or overturned. The best exposure of the contact between the Greenbrier and Maccrady is found on the axis of the Harts Run anticline, 6.0 miles east of Union along State Route 3. This zone has been shown to be a high yielding aquifer at depth in Monroe County.

The Maccrady shale generally forms topographic lows. Stream valleys often occupy this zone between the more resistant rocks of the Pocono and Greenbrier. Second Creek (along the eastern border of the area) is a good example of this. Smaller streams on top of the Maccrady shale will commonly sink along the Greenbrier contact into either the upper Hillsdale or lower Sinks Grove Limestone, forming blind valleys.

Hillsdale Limestone

The Hillsdale Formation (Reger, 1926) is the oldest unit of the Greenbrier Group occurring just above the red Maccrady shales. Generally it is a blue-gray, massive limestone at the top, but is shaly towards the base. A detailed stratigraphic section of the basal portion is shown in Figure 5 where its gradational nature into the Maccrady Shale is also indicated (Figure 6). Both nodular and layered chert are found in the upper and middle portion of the Hillsdale, but these are absent in the lower layers. Chert nodules are sometimes large in size, being up to a foot in diameter.

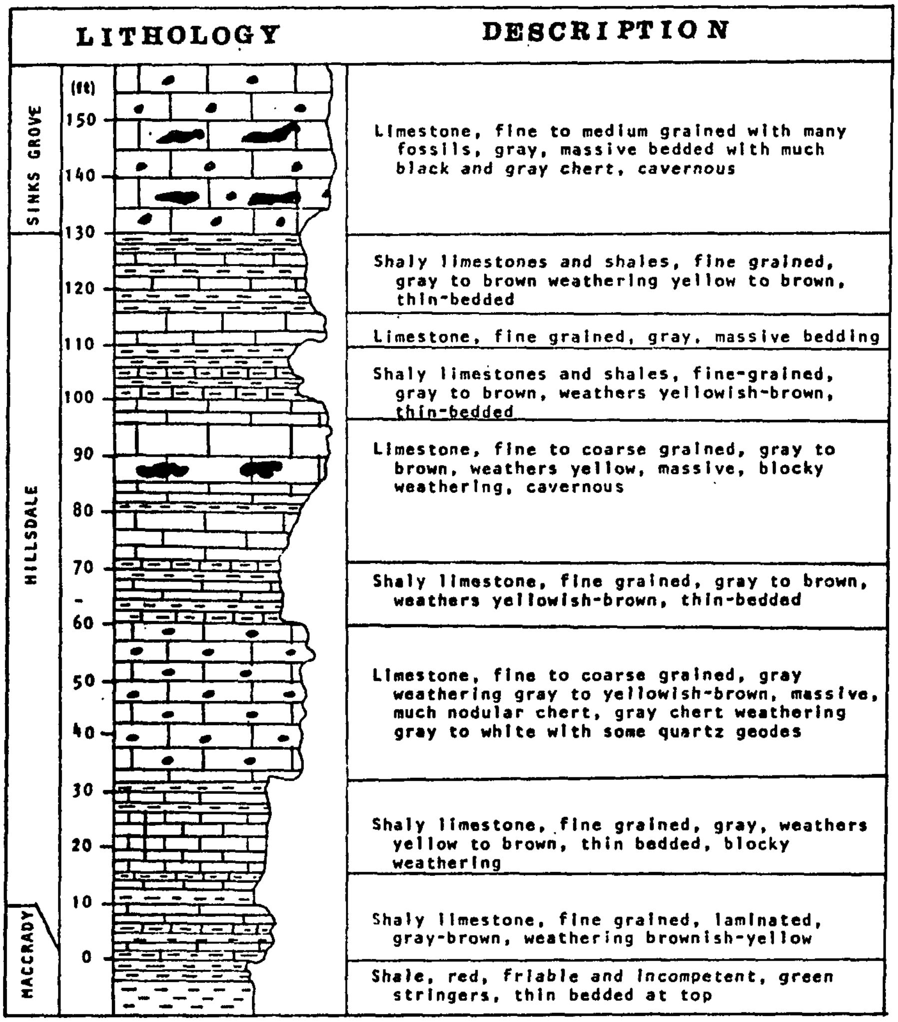

Figure 5. Measured section of the Hillsdale Limestone, located 6.0 miles east of Union on State Rt. 3, near the axis of the Harts Run anticline.

Figure 6. Outcrop photograph showing contact between the Hillsdale Formation (above) and the Maccrady Shale (below).

Opalized banded chert and quartz geodes are found in the Hillsdale but not in the Sinks Grove. Nodules of gypsum are also found in the Hillsdale Limestone. This helped to distinguish the two formations during field mapping. At the top of the Hillsdale is an unnamed shaly limestone that is generally 10-15 ft thick. This zone is the most recognizable unit in separating these two formations but was not described as such by Reger (1926).

Fossils are scanty in the chart but are abundant in the limestone matrix. Corals, gastropods, bryozoa, crinoids, and brachiopods were observed. Wells (1950) studied the fossil assemblages in the Hillsdale Limestone, but never in Monroe County.

The thickness of the Hillsdale in the study area is commonly only 70 ft and rarely over 100 ft. Reger (1926) described several sections in Monroe County that included the Hillsdale. His type locality, 0.1 mile east of the town of Hillsdale, is now covered; however, the Bickett Knob section, 1.8 miles north of Sinks Grove on the Nickells Mill, proved more useful.

Sinks Grove Limestone

The Sinks Grove Limestone Formation (Reger, 1926) occurs just above the Hillsdale Limestone. It is usually a massive, hard limestone throughout, except near the top where it is occasionally sandy or shaly. Where the limestone is purer it weathers blue or blue-gray, but weathers yellow with increased impurities. In Monroe County, the Sinks Grove commonly exhibits both layered and nodular black chert that sometimes weathers gray or brown. Sinks Grove chert was never observed to be as large as that found in the Hillsdale. Fossils are found both in the chert and in the matrix. Common fossils are brachiopods, bryozoa, crinoids, horn corals, and blastoids.

In the northeast section of the field area the Sinks Grove was observed in two measured sections by Reger (1926) to be 115 ft (at Patton Section, 1/2 mile south of Patton) and 167 ft thick (at Bickett Knob Section). This writer has found from several drilling records and geologic mapping that the Sinks Grove varies from 200 to 300 ft in thickness in the southeastern section of the study area. This southeastward thickening appears to be in accordance with the isopach map drawn for the Greenbrier Group (Wells, 1950).

The type locality for the Sinks Grove was defined by Reger (1926) in the vicinity of the village of Sinks Grove, Monroe County, in the Bickett Knob Section. The writer used that exposure, plus the presence of the Patton Shale above and the unnamed shale below, in mapping this limestone unit. The massive beds of the Sinks Grove contain an abundance of solution features and a significant percentage of the cavern footage in the area.

Patton Shale

The Patton Shale is a lenticular deposit separating the Patton Limestone from the Sinks Grove Limestone (Reger, 1926). It appears as gray or yellow, and is highly calcareous to the point of being a shaly limestone at most places. Its shaly nature distinguishes this unit from the massive beds of the Patton and Sink Grove limestones above and below. The author has observed occasional marine fauna in this unit, although Reger (1926) describes this shale as having "somewhat abundant plant fossils."

The Patton Shale varies from 0 to 25 ft in thickness in the study area. Due to its lenticular nature, it was mapped in combination with the Sinks Grove Limestone. It can be seen easily along road outcrops in two places: 0.8 miles southeast of Pickaway on the Pickaway-Hillsdale road and 4.7 miles east of Union on Route 3 just east of a roadside quarry.

Patton Limestone

The Patton Limestone occurs just below the Lower Taggard Shale, and weathering is usually massive, gray to blue-gray. Generally it is shaly and sandy at the top and very porous in nature. The massive beds sometimes contain black nodular chert that commonly weathers to a gray color. The massive beds are commonly oolitic. The thickness of this formation was measured by Reger (1926) as 210 ft and 275 ft in two of his sections. Records from drilled water wells indicate that in the southeastern section of the mapping area, it can be up to 350 ft thick. The Patton Limestone is very fossilliferous, containing brachiopods, crinoids, horn corals, bryozoa, and many blastoids. Reger (1926) has noted the presence of a few plant zones, but these were never located by the writer. The Patton lends itself readily to dissolution with a large variety of karst solution features developed on outcrops. Caves and pits are also abundant in this limestone.

The type locality is south of the now abandoned village of Patton in Reger's (1926) Patton Section. His description of this formation proved to characterize it well and was used for mapping purposes. The Patton Limestone was combined with the Sinks Grove by Wells (1950) and called the Denmar, but the author was able to distinguish between these two units due primarily to the presence of the Patton Shale, lesser amounts of chert in the Patton Limestone, and the greater thickness of the Patton Limestone.

Taggard Formation

The Taggard Formation (Reger, 1926) is divided into three members: The Upper Taggard Shale Member, Taggard Limestone Member, and Lower Taggard Shale Member. A detailed description of this formation is found in Figure 7, while a photograph of this unit is shown in Figure 8. Its type locality is 2.8 miles southeast of Union on a now abandoned portion of the Willow Bend Road. A better exposure of this formation is found 2.2 miles south of the Greenbrier-Monroe County line along State Route 219.

The Lower Taggard Shale Member is a thin deposit of red shale usually 1 to 5 ft thick in central Monroe County. It grades downwards into the yellow calcareous shales (shaly limestones) of the Patton Limestone. South of Union it becomes sandy but is still red in color. Small calcite geodes are sometimes found in this unit. The thinness of this member made it very difficult to locate. The Taggard Limestone Member occurs between the two Taggard shales and

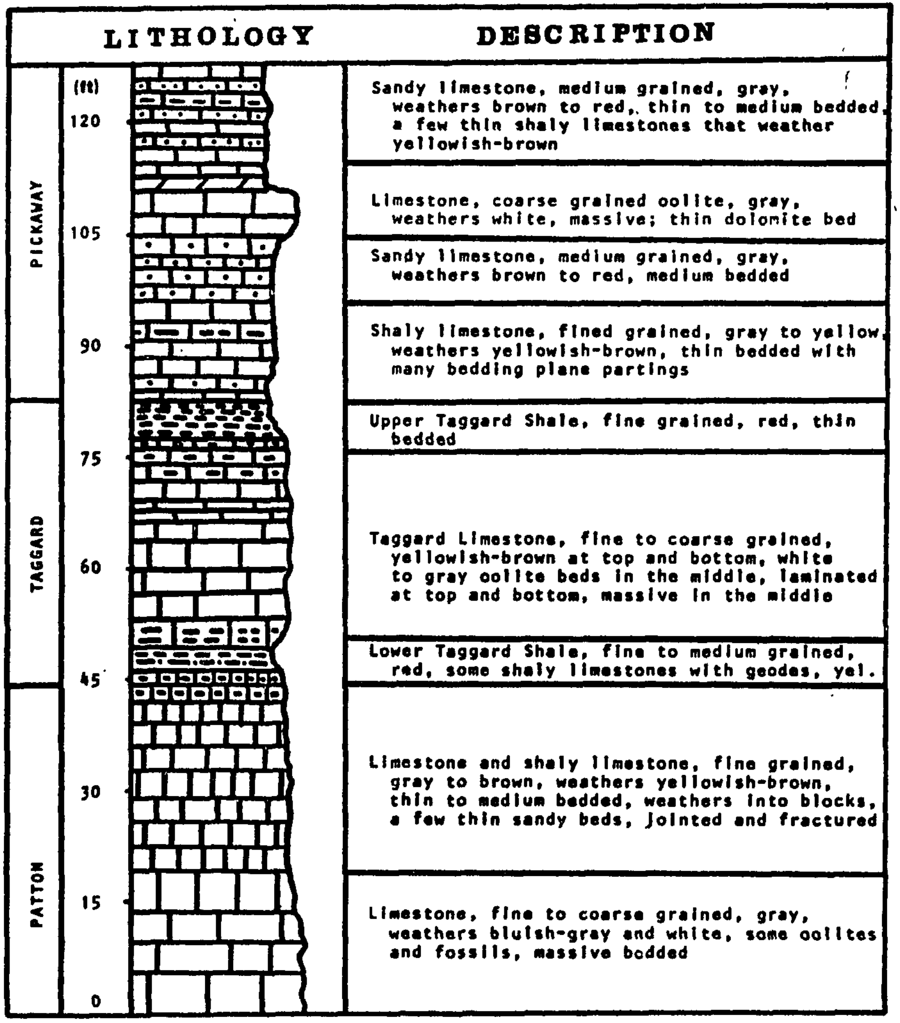

Figure 7. The Monitor measured section showing the Pickaway, Taggard, and Patton Formations, located 2.2 miles south of the Greenbrier-Monroe County line along State Rt. 219.

Figure 8. Photograph of Taggard and Patton strata along the Ft. Springs Road, 1 mile east of the Acme Quarry in southern Greenbrier County.

varies from 5 to 45 ft thick. It is found both as a massive oolitic limestone and as a massive clay-rich limestone. The upper and lower contacts of this member are generally laminated. Where it is oolitic it weathers white, but it is yellow to yellowish-brown when occurring as a mudstone. Marine fossils such as brachiopods, crinoids, bryozoa, and blastoids can be found.

The Upper Taggard Shale Member consists of red siltstones and mudstones and is found stratigraphically above the Taggard Limestone, and below the Pickaway Limestone. It is generally 5 ft to 10 ft thick. No fossils were found in this unit. The Upper Taggard Shale proved extremely useful in mapping by separating the upper and lower portions of the Greenbrier Group.

Pickaway Limestone

The Pickaway Limestone (Reger, 1926) is a dark, impure limestone formation occurring immediately above the Upper Taggard red shale. This formation has a stylolitic structure known as "Pickaway jointing" (Figure 9). This jointing is usually a guide in mapping this formation. The Pickaway is sandy near the bottom, weathering dark red to rust-brown. Near the top it is laminated and blue-gray in color. In Monroe County its thickness ranges from 200 to 275 ft. Fossils are not as common as in other Greenbrier formations. Fossil assemblages present are mainly brachiopods, gastropods, crinoids, blastoids and bryozoa. Reger's (1926) type locality for this formation is located along the road from Pickaway to Union, West Virginia. His Bickett Knob Section and Leonard's (1968) Union

Figure 9. Photograph of vertical Pickaway jointing, as seen on a horizontally bedded outcrop of Pickaway Limestone.

Section (1.7 miles west of Union on the Knobs Road) offer better exposures of this unit.

Leonard (1968), in his detailed petrographic study of the Pickaway, divided it into three distinct members: a lower fossiliferous calcilutite member, a middle superficial oolite member, and an upper laminated calcilutite member. This upper laminated member is very persistent and was a good mappable zone in separating the Pickaway and Union formations in the field.

Union Limestone

The Union Limestone (Reger, 1926) is a gray, massive limestone that weathers bluish-gray and white. It is extremely pure and is both oolitic and fossiliferous. Leonard (1968) divided the Union into an upper white-oolite member and a lower-oolitic calcarenite member. He also notes a minor amount of dolomite. In Monroe County, this formation is 155 ft to 250 ft thick with the upper half having many blastoids, a few bryozoa, and brachiopods, horn corals, crinoids, and a few gastropods throughout.

The type locality for the Union Formation is outside of Union, Monroe County, where it crops out in many of the fields, but Reger (1926) does not suggest a type section. Reger's (1926) Bickett Knob Section and Leonard's (1968) Union Section were used to familiarize the writer with the Union Limestone. In contrast to the gray, jointed Pickaway and the laminated, bioclastic Alderson Formation, the oolitic, massive structure, and white color of the Union enables easy identification of this formation in the field. The

Union Limestone also has numerous caves as well as minor and major karst solution features developed on it.

Greenville Shale

The Greenville Shale (Reger, 1926) is a black, fissile, and carbonaceous formation that occurs just above the Union Limestone. It often weathers to a white, greenish, or black color. The Greenville Shale is a highly lenticular deposit that can range from zero to 100 ft in thickness. It contains marine fossils of which pelecypods, cephalopods, gastropods, and brachiopods predominate. In northern Monroe County the Greenville is absent: going southward, this unit changes from a thin black shale to a five foot thick sandstone unit and then to a thick black shale.

The type locality for the Greenville Shale is in Monroe County, 1.6 miles southeast of Greenville along Indian Creek. Here it is 100 ft thick. Leonard (1968) combined the Greenville Shale with the Alderson Limestone during field mapping and the writer did likewise.

Alderson Limestone

The Alderson Limestone (Reger, 1926) occurs directly over the Greenville Shale when the Greenville is present and is the uppermost formation of the Greenbrier Group. It is an impure deposit throughout most of its thickness, being arenaceous, dark gray, and commonly weathering yellowish-brown. At the bottom and top it is an impure deposit rich in calcareous mud that breaks into small shaly blocks along finely spaced joints. These shaly areas are also rich in dolomite. The middle section of the Alderson is purer with alternating beds of oolites, dolomite, and fossil hash. The fossil and oolite beds are commonly cross-bedded. Leonard (1968) divided the Alderson into two lithologic divisions: a lower, laminated calcilutite member and an upper, biocalcarenite member.

The Alderson Limestone is a highly fossiliferous formation containing many brachiopods, horn corals, pelecypods, crinoids, and bryozoa. In two measured sections in the mapping area, the Alderson ranges from 130 ft to 208 ft thick. Leonard (1968) included the Greenville Shale in the Alderson Limestone which accounts for it being thicker than described by Reger (1926). The upper contact of the Alderson Limestone is gradational into the Lillydale Shale. The type locality for the Alderson Limestone is one-third mile south of the town of Alderson, on State Route 3, where it is only 95 ft thick.

Lillydale Shale

The Lillydale Shale of the Mauch Chunk Group was defined by Reger (1926) as a dark green to black, carbonaceous, fissile deposit occurring directly above the Alderson Formation. Siderite nodules are common near the gradational contact with the Alderson Limestone, and fossils are generally rare. This Shale varies from 80 ft to 125 ft thick and has its type locality four miles southwest of Union on the Lillydale Road. The Lillydale Shale was not examined in great detail by the writer but was used solely for defining the upper contact of the Greenbrier Limestone during mapping.

Structure

Introduction

Central Monroe County lies on the eastern boundary of the Alleghany Plateau province on the boundary separating the central and southern Appalachians. The Southeastern edge of the study area marks the beginning of the Valley and Ridge province where the St. Clair thrust fault, which trends NE-SW, has overturned Lower Mississippian and older rocks.

Gwinn (1964) suggested that folds in this area resulted from "steplike upward shearing of the detachment thrusts" from a Cambrian shale glide zone. This "thin-skinned" hypothesis has received much support in recent years. Wheeler et al. (unpublished manuscript) have described in detail the "Ronceverte Lineament" a few miles north of Monroe County. They have shown statistically that along this lineament there is a cross-trend "zone of unusually intense, along-trend changes in major structures."

Winslow and Baroody (1976) have produced a draft of a structural map of a portion of Greenbrier County north of the study area. Fold axes of this map and of central Monroe County (Plate 1) line up. Minor folds and many of the small faults in the Pocono Group near the Monroe County-Greenbrier County line do not appear to extend upward into the Greenbrier Limestone of Monroe County. The writer feels that the competency of the massive, dense rocks of the Greenbrier Limestone has prevented the development of the same number of minor structures exhibited in less competent rocks of the Pocono. It may also be possible that stylotites in the Greenbrier Limestone account for the same amount of shortening.

Folds

The predominant structures of the map area are northeast trending folds. Generally the folds are broad and of low plunge (Plate 1). Most of the major folds trend between due north and N25°E. A frequency distribution of much of the bedding strike data is shown in Figure 10. Those folds along Little Mountain near the St. Clair fault trend about N55°E (Plate 1). There are both symmetrical and asymmetrical folds, with two northwestward-overturned synclines in the eastern portions of the Maccrady and Pocono outcrop areas.

Dip of bedding is generally less that 15 degrees. Steeper dips are found near the axes of several folds and along thrust faults. Most of the folds plunge to the southwest. Reger (1926) mapped eight folds and no faults in the study area. He found the Sinks Grove anticline and the Hurricane Ridge syncline to be the two most dominant folds. Reger's (1926) interpretation of the axial trend and number of mapped folds were modified by the writer (Figure 11). The number of major folds mapped remains the same, but there are a few newly mapped smaller folds longer than one mile in length. Several of the major folds (Patton syncline, Maple Grove anticline, and Hurricane Ridge syncline) were found not to make sharp axial bends to the northeast as suggested by Reger (1926); they instead

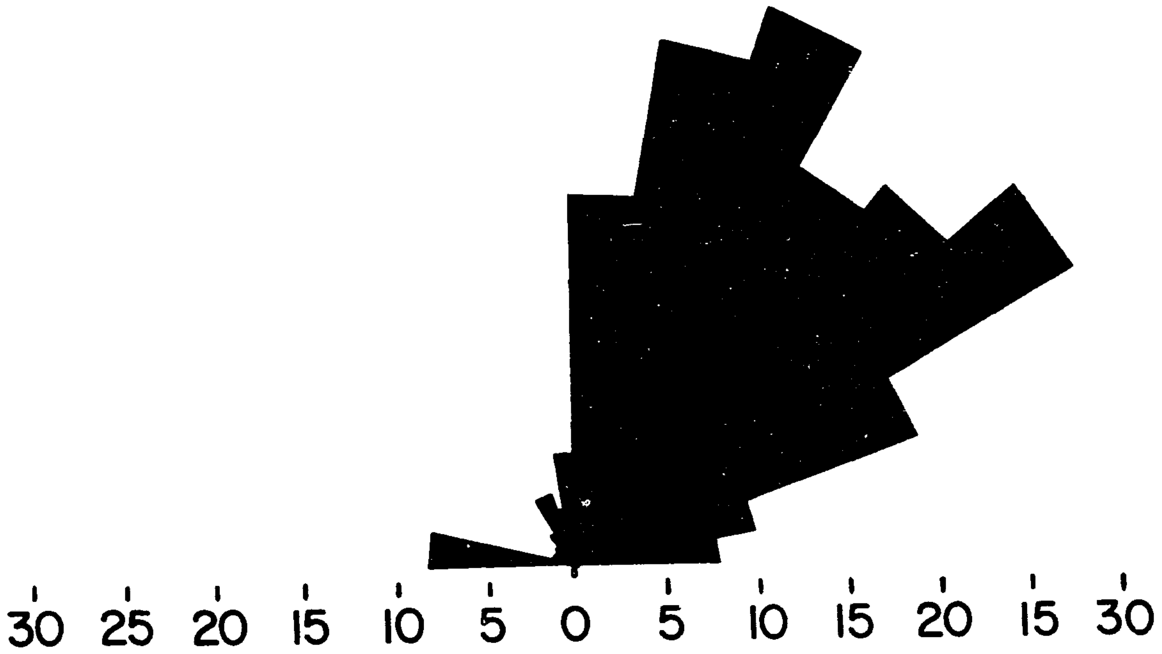

Figure 10. Orientation rosette of 229 strike measurements taken from outcrops of the Greenbrier Limestone through the field area. Scale is in number of strike measurement values and 10 degrees class intervals are used.

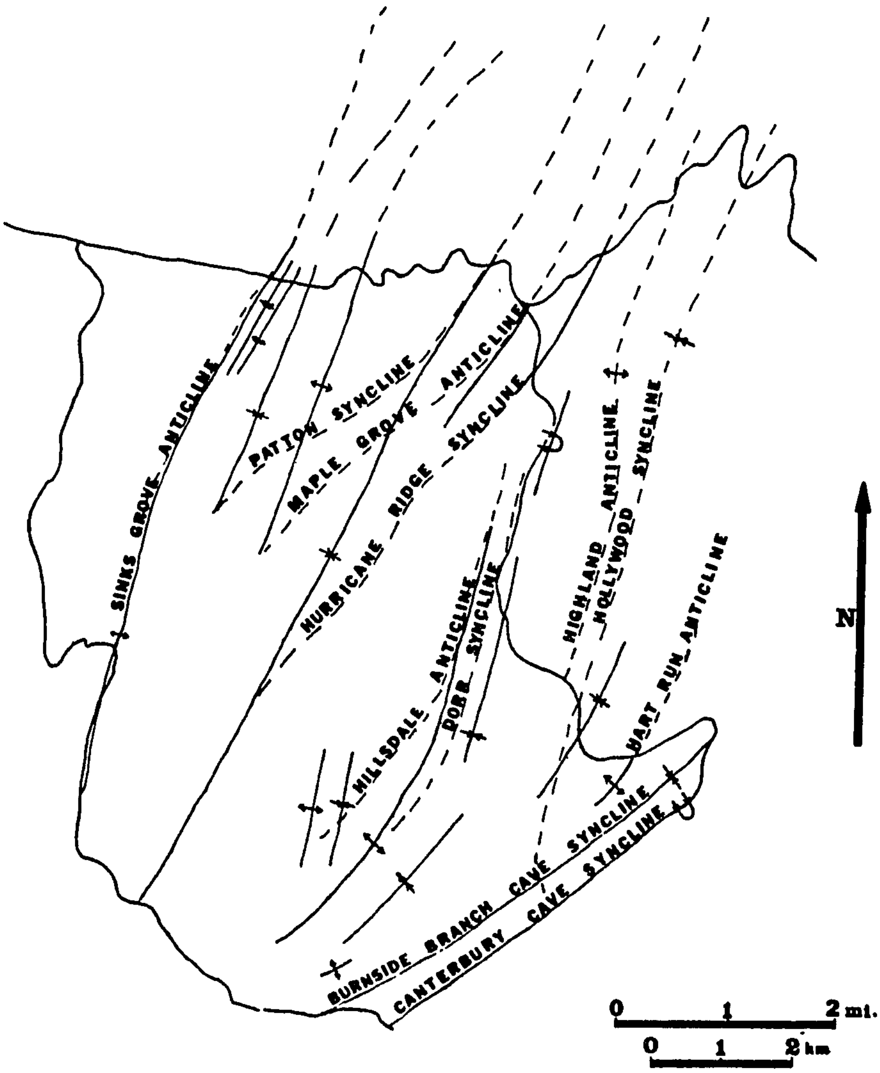

Figure 11. Map of fold axes in the study area. Dashed lines show positions of axial traces mapped by Reger (1926) and Price and Heck (1939). Solid lines represent the position of axial traces mapped by this author.

continue northeastward into Greenbrier County Geologic Map (Price and Heck, 1939). The Patton syncline and Maple Grove anticline connect northward with unnamed folds while the Hurricane Ridge syncline of Greenbrier County (Figure 11). The Hillsdale anticline and Dorr syncline were found to have their axial traces more eastward than originally mapped.

A major overturned syncline, henceforth referred to as the Canterbury Cave syncline, borders the southeastern portion of the mapped area. A newly mapped fold named the Burnside Branch Cave syncline parallels this overturned syncline to the west. These two folds, whose orinetations differ markedly from those of the formerly described folds, are probably closely related to the St. Clair fault of similar orientation to the southeast.

Joints

Joint orientations were measured at eleven stations or outcrops throughout the study area on different formations of the Greenbrier Limestone. Each rosette station had more than 30 joint readings taken, but all station readings were combined together since there were only minor differences between stations. Figure 12 shows a rosette of the 873 joint measurements. Four sets of joints exist. Longitudinal joints trend around N37°E, while diagonal joints trend about N27°W and N85°W. The NW-SE-facing acute angles formed by the intersection of the two northwest diagonal sets are consistent with NW-SE shortening implied by trends of folds and thrust faults. A

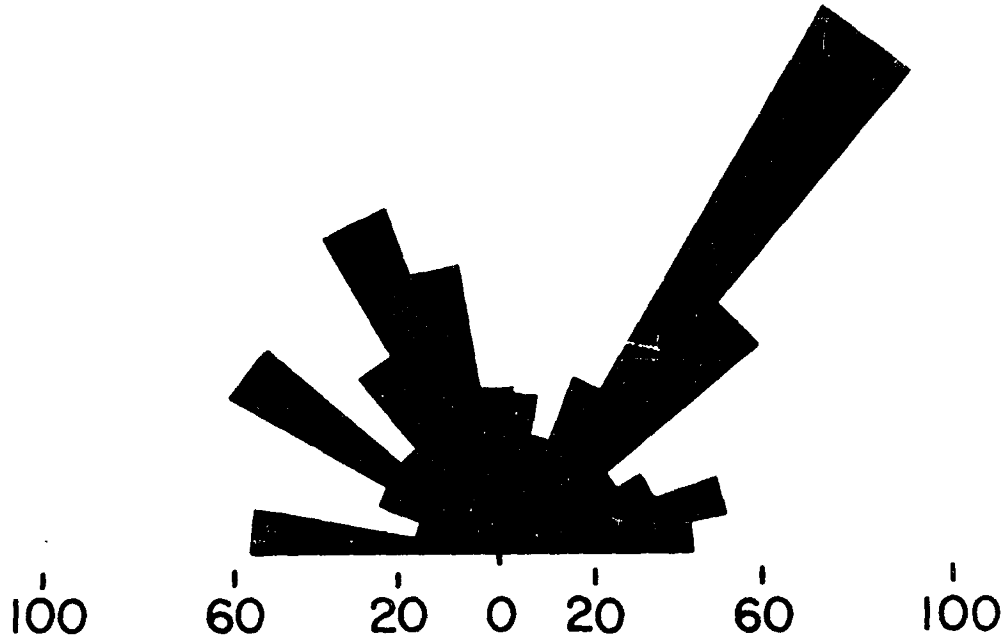

Figure 12. Orientation rosette of 873 joints taken from Greenbrier Group Limestone outcrops in central Monroe County. Scale is in number of joints, and 10 degree class intervals are used.

fourth set of joints are developed around N58°W and are interpreted as cross joints. Most of the joints are perpendicular or nearly perpendicular to bedding.

The unusual jointing found in the Pickaway Limestone (Figure 9) was measured at four stations between Willow Bend and Monitor. The rosette patterns were nearly identical to each other, being especially similar in the direction of strike of bedding. This may suggest that the Pickaway joints are not related to folding and may have been formed before major folding.

Faults

There were no major faults found in the study area. Two low-angle thrust faults, including one back thrust fault, were located (Plate 1). One thrust fault near Salt Sulphur Springs involving the lower Alderson Limestone and Greenville Shale, has an estimated 20 to 30 ft of repeated section. The second small thrust fault north of the village of Pickaway, involves the Pickaway Limestone and is believed to repeat at least 30 ft of Pickaway Limestone. It could not be followed laterally so was not mapped on Plate 1. A third high angle reverse fault near Willow Bend appears to thin the section by as much as 100 ft, but no exact measurement could be made. Several small thrust faults were observed in caves with displacements of a few feet, but none of these could be located on the surface. Slippage along bedding planes as indicated by slickensides in recrystalized limestone are common, but appear to be extremely localized. Other small faults may exist in the area, but there is little chance of observing them with the few limestone outcrops that are present.

Lineaments

Photo-lineament maps were prepared for central Monroe County from 1:20,000 scale, black and white, U.S. Geological Survey photographs. Photo-lineaments were defined in stereo coverage to be any linear alignment of dolines, valleys, stream segments, or soil tonation of over one-quarter mile in length. These photo-lineament maps are on open-file with the West Virginia Geological Survey. Two orientation rosette diagrams were made of the 749 mapped lineaments: one for percent lineament frequency, and the other for accumulated lineament length (Figures 13 and 14). Both plots show preferred orientation trends for lineaments at about N65°E ± 20° and N60°W ± 20°. A chi-square test comparing the percent lineament frequency distribution to a rectangular distribution indicates the existence of preferred lineament orientations at the 0.05 alpha probability level ($0.05>p>0.025$).

Photo-lineament maps were prepared for comparing lineament orientations with joint, strike, and cavern orientation data, and for determining the effect of lineaments on water well yields. Figure 15 shows an aerial photograph of perhaps the most outstanding and controversial topographic lineament in Monroe County. This lineament, which has been named the "Monitor lineament" (Werner, 1975d), is represented by a five mile chain of doloines bearing

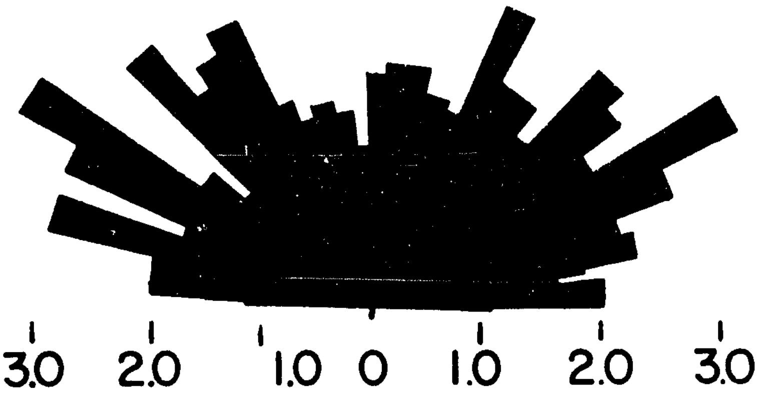

Figure 13. Frequency percent plot versus orientation for 749 lineaments mapped from photographs of central Monroe County, W. Va. Scale is in percent of total, and 5 degree class intervals are used.

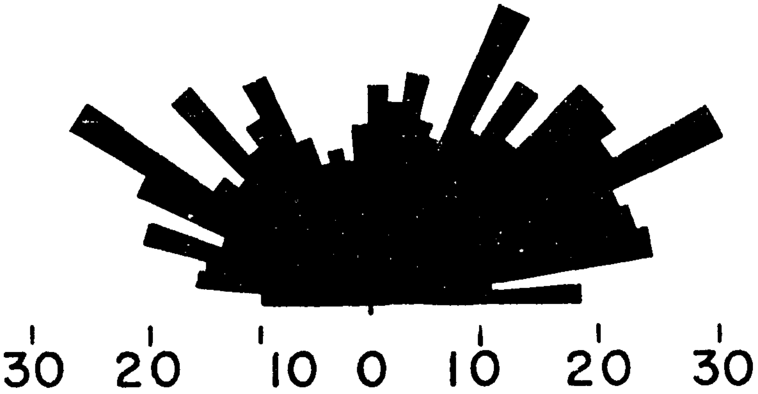

Figure 14. Accumulated lineament length versus lineament orientation for the 749 mapped lineaments. Scale is in thousands of feet and 5 degree class intervals are used.

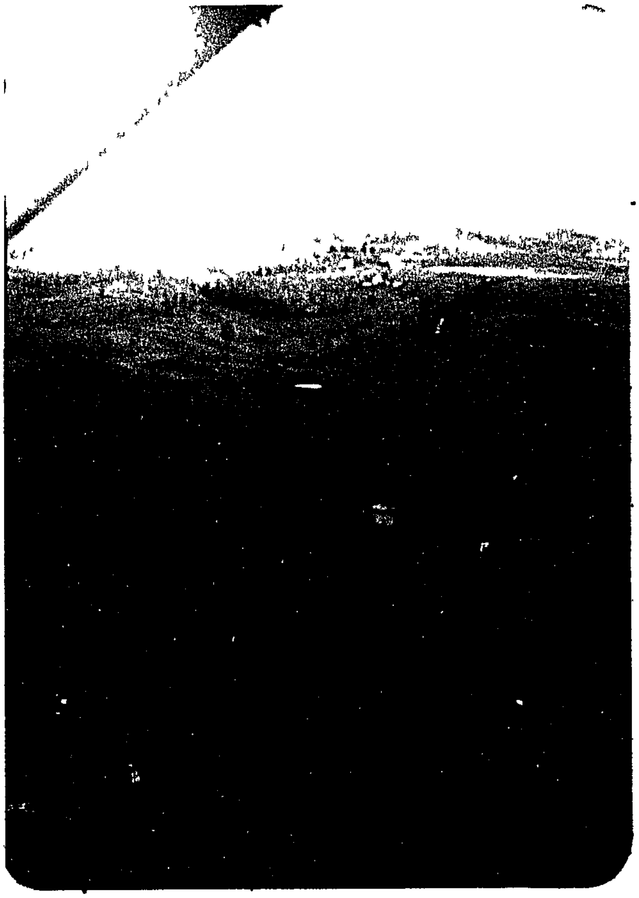

Figure 15. Aerial photograph of the Monitor Lineament, a five mile long feature bearing N76°E across the Monroe County karst.

N76°E near Monitor. The lineament probably resulted from increased fracturing and not faulting, since there were no faults mapped on it. Wheeler et al. (unpublished manuscript) suggest that lineaments such as the Monitor Lineament may be fracture systems having little or no slippage. This major surface feature captures two sinking streams that have been dye-traced to Dickson Spring, but the lineament appears to have no effect on subsurface water flowing across it.

Dolines and Ground Subsidence

Introduction

A common problem in carbonate terranes is subsidence. This may occur at varying rates and often results in costly damage to property owners. Much of the surface of central Monroe County has been karstified with both recent and ancient dolines dotting the surface.

Several authors have discussed the factors affecting doline formation. Cramer (1941) related the size and density of dolines to climate and lithology (limestone, dolomite, and gypsum). He found that temperate climate regions have the least density of dolines. In Mendip, England, Ford (1964) found the highest density of dolines to occur in dry valleys despite the limestone lithology. Structural effects of doline formation have been discussed by Williams (1966), LaValle (1967), and Kemmerly (1976). Williams (1966) found little tendency for preferred orientation of dolines in New Zealand. LaValle (1967) and Kemmerly (1976) found significant elongation of dolines along joints and faults. LaValle (1967) has shown that the structural alignment increases with limestone purity, and that doline density increases with greater karst relief. The formation of dolines due to dewatering effects by excessive pumping has been discussed by Quinlan (1974) and Nutter (1973).

A cursory inspection of possible factors affecting doline subsidence was necessary to determine the best approach to take for subsidence prediction. In the study area there are seven major limestone formations with varying lithologic characteristics. Initial observations of the doline density showed a relationship to the various Greenbrier Limestone formations. Caves also appeared to be more common in certain formations suggesting a stratigraphic control. Joint measurements showed nearly the same orientation among all formations so were believed to offer little help in determining subsidence prone areas. Joints density may increase with limestone purity as LaValle (1967) has shown, but this was not measured. Lineament length in each formation was to be tested which could shed some light on joint density. Pumping effects were not deemed important in influencing subsidence since the ground water in the study area is obtained from high yielding confined aquifers with a peizometric surface generally greater than 150 ft below the surface. Also there is too low a population density in the area for excessive ground water use. The approach taken here to evaluate doline formation and future subsidence therefore emphasizes lithologic controls.

Methods

The problem of predicting ground subsidence required that several variables be measured in the area and expressed quantitatively. Both cave location information for Monroe County (Hempel, 1975), and observation from cave exploration by the author, were used to accurately determine the principle geologic formation in which each cave was developed. Cave locations were plotted on 7-1/2 minute topographic maps and on the detailed geologic map. Only caves over 100 ft in length were used.

A map of dolines for the area was prepared by outlining dolines on U.S. Geological Survey aerial photographs and transferring these to 7-1/2 minute topographic maps. Most dolines smaller than about 30 ft in diameter were not located by this method, but aerial photographs are superior to using topographic maps alone for detailed doline coverage. Lineaments were drawn on the aerial photographs and transferred to the topographic maps containing plotted dolines.

Next, eleven points on the base topographic maps were selected at random by using a grid system and a random numbers table. Gridded squares one mile by one mile in size were centered over them as shown in Figure 16. Overlapping squares were rejected and new points were selected. The number of dolines per formation, the area of each formation, the total area of dolines for each formation, and the total length of photo-lineaments for each formation were determined for each sampled square. For each formation in each of the eleven square samples, the morphometric parameters of doline density, percentage limestone area in dolines, and

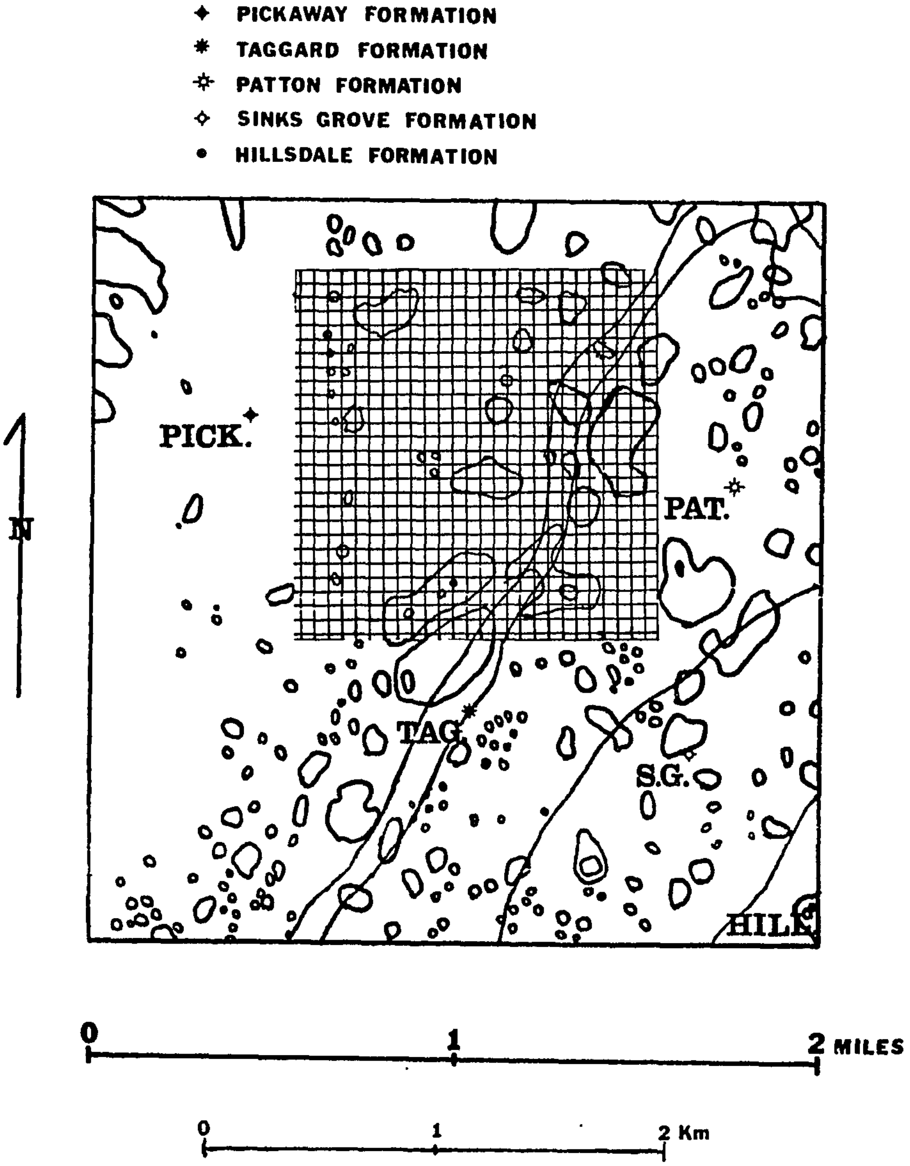

Figure 16. Demonstration of method for measuring percentage area of dolines from each Greenbrier formation, using a one mile square grid superimposed on the doline and geologic map.

photo-lineament density (miles of photo-lineaments per square mile of limestone) were calculated. Area determinations for dolines and formations in each square were determined by counting the number of blocks or partial blocks within the grid.

Bar graphs were prepared, showing the distribution of these three parameters and cave length in the seven limestone units. Spearman-rank-correlation coefficients (Siegel, 1956) were calculated for all parameters in order to detect which parameters were most highly correlated with cave length. To test the equality of the seven limestone formations, the Kruskal-Wallis multi-sample test for identical populations (Siegel, 1956) was performed and tested for significance at the 0.10 probability level. Finally, by combining selected parameters with optimum slope steepness, a ground subsidence susceptibility map was prepared for the purpose of locating areas deemed most suitable for major man-made structures (Ogden and Reger, in press).

Results

Bar graphs showing stratigraphic distributions of doline density, percentage area in dolines, total cave length, and lineament density are shown in Figures 17, 18, 19, and 20 respectively. The Union, Patton, and Sinks Grove formations have the highest doline densities (Figure 17), and therefore are tentatively prime candidates for subsidence. The Taggard Formation has a higher-than-expected doline density, which can be explained by realizing that it is a

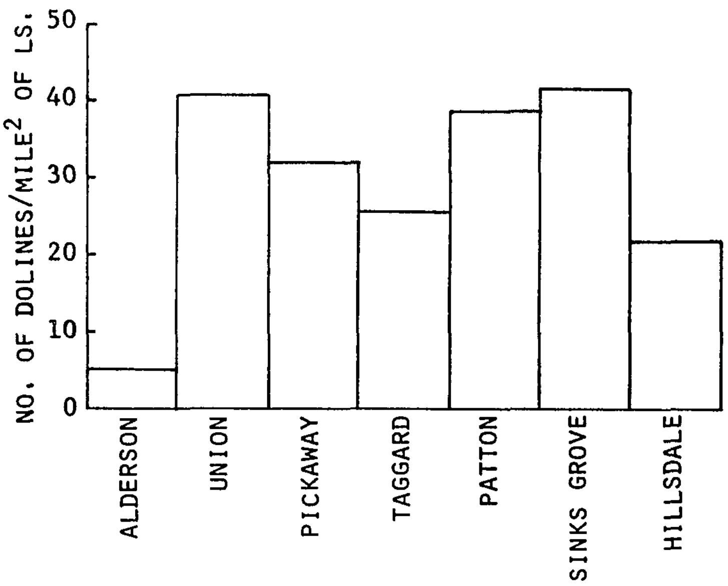

Figure 17. Distribution of doline density (number of dolines per square mile) among the Greenbrier Limestone formations.

fairly thin unit (with an average thickness of approximately 25 ft) and is underlain by the Patton Limestone. It is believed that many of the dolines on the Taggard are collapse dolines resulting from solution of the underlying Patton. In terms of actual percentage area of each formation exhibiting dolines (Figure 18), the Union, Taggard, and (to a lesser degree) the Patton formations are highest among the Greenbrier formations. The Union, Patton, and Sinks Grove formations also exhibit the greatest amount of cave development (Figure 19). Coupled with the doline densities of these formations, once again the Union and Patton formations present the most likely areas for subsidence, and the Taggard Formation is again interpreted as reflecting subsidence control by the underlying Patton Limestone.

A further comparison of the two doline distributions suggest another interpretation of the large area of the Taggard Formation in dolines despite the low doline density. Once a doline intersects the Taggard Shale members, erosion will take place at a faster rate, rapidly increasing the size of dolines while the number of dolines remains the same (Ford, 1964). Other differences in the doline distribution may reflect relative percentages of shales and shaly limestones.

The Alderson Limestone at first appears to be ideal for low subsidence risk, since it has the lowest doline density and the smallest percentage of area in dolines. However, the Alderson Limestone is exposed on steeper hillsides than are the other six formations. Therefore, this particular unit has topographic limitations for locating major man-made structures.

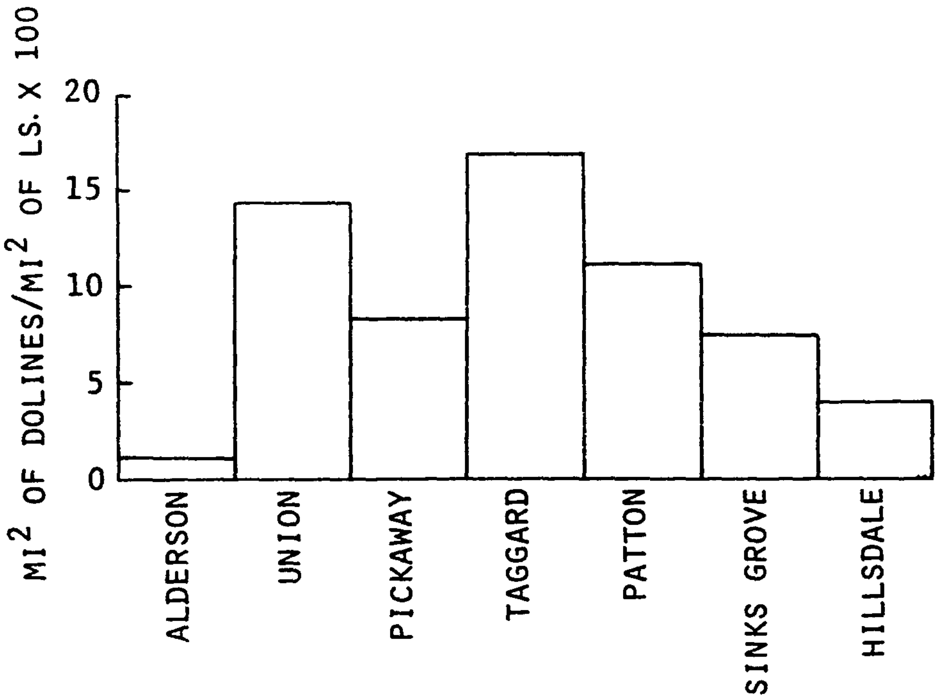

Figure 18. Distribution of percentage area in dolines among the Greenbrier Limestone formations.

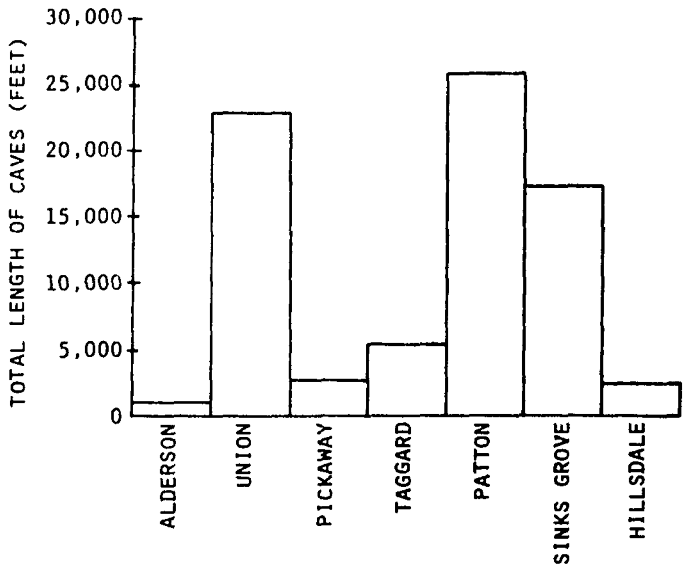

Figure 19. Distribution of cavern length among the Greenbrier Limestone formations.

Photo-lineament densities (Figure 20) show no clear relationship with respect to the different formations. The Alderson Limestone has the highest lineament density because it crops out near the top of Swoopes Knobs, which have many linear ephemeral stream valleys. Comparison of Figure 13 and Figure 14 indicates that photo-lineaments are approximately of the same length are are distributed with little preferred orientation. Photo-lineaments are therefore probably not a good regional indicator of subsidence among formations in the study area, and were not used in the preparation of a surface instability map.

The Spearman rank correlation coefficients were calculated and tested for significance (at the alpha level of 0.05) for each pair of parameters measured for the 11 sampled sections of the study areas. The results are summarized in Table 1. The coefficients for doline density versus cave length (0.86) and percentage area in dolines versus cave length (0.73) are significant at the 0.05 alpha level. No other correlations are significant at that level. The qualitative judgment to eliminate lineament density from use in constructing a surface instability map was thus substantiated by the lack of significant correlation between lineament density and the other measured variables.

The high positive correlation between total cave length and both doline density and percentage area in dolines suggests lithologic controls on doline and cavern development. Mapping has shown that the Union, Patton, and Sinks Grove limestones are

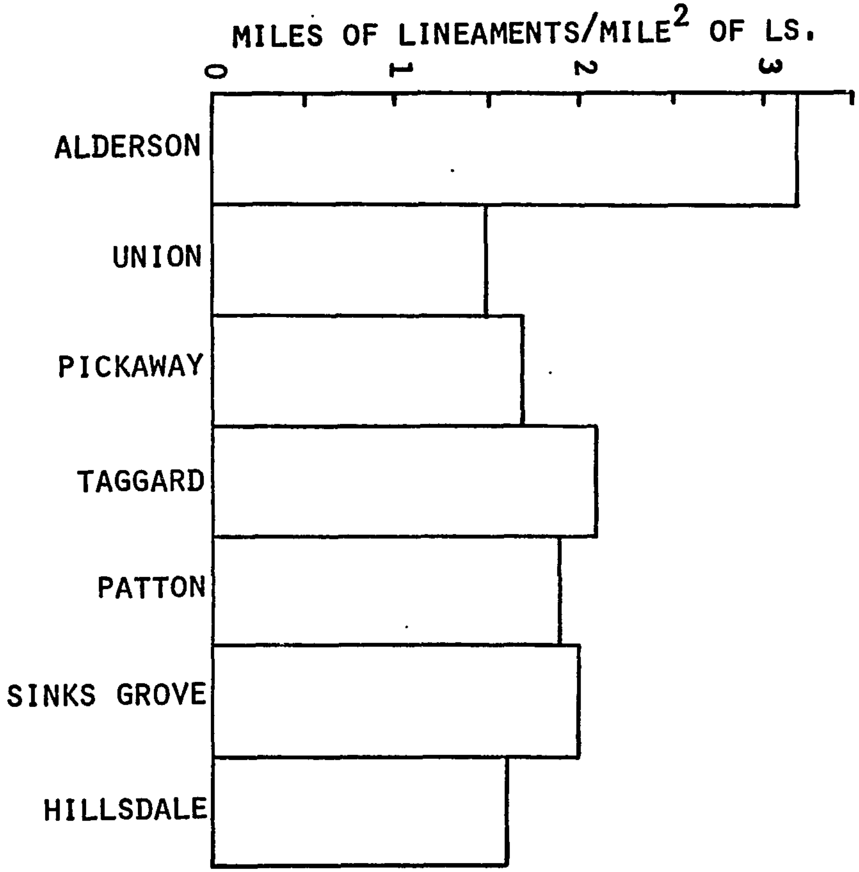

Figure 20. Distribution of lineament density among the Greenbrier Limestone formations.

relatively pure (lacking in insoluble impurities). These formations have the best cavern development and also the greatest doline densities. Once a doline has formed, lithologic differences should control continued area development as has been previously described.

To test the hypothesis that the various limestone formations have somewhat distinctive doline distributions (as measured by the three morphometric parameters), the Kruskal-Wallis multi-sample test for identical populations was performed. The results (Table 2) indicate that, at the alpha significance level of 0.10, the seven formations are not significantly dissimilar with respect to either doline density or lineament density, but that they are significantly dissimilar with respect to percentage area in dolines.

The test is essentially a nonparametric one-way analysis of variance. As such, when the null hypothesis is rejected, one can conclude that there is a "significant" difference in populations, but that the source of that difference cannot be determined from these results.

Surface Instability Map

For most karst terranes, there are topographic and surficial factors which constrain the building of major man-made structures with respect to subsidence susceptibility. Maps can be prepared that show each constraining factor separately. A generalized slope map, depicting classes of slope steepness, would represent topographic constraints. In the same way, maps could be prepared showing areas of similar percentages of limestone surfaces with

Table 1

Spearman Rank Correlation Coefficients for Ground Subsidence Parameters and Lineament Density

Parameter	(1)	(2)	(3)	(4)
(1) Doline density	+1.00	+0.54	-0.50	+0.86
(2) Percentage area in dolines		+1.00	-0.16	+0.73
(3) Lineament density			+1.00	-0.32
(4) Total cave length				+1.00

Table 2

Results of Kruskal-Wallis Tests Comparing Doline Distributions and Lineament Density among Greenbrier Limestone Formations

Parameter	H_t^+	Critical Value*	Decision
Doline density	7.22	10.63	Accept H_0
Percentage area in dolines	10.90	10.64	Reject H_0
Lineament density	4.68	10.64	Accept H_0

H_0: There is no difference among Greenbrier formations.

*Obtained from chi-square table for 6 d.f. at the 0.10 level of significance.

H_t^+ is the calculated "t" value.

dolines. Although it is beyond the scope of this differentation to map the study area in such a suggested manner, the process and preliminary general results are deemed important.

The suggested scheme is to categorize the various mappable factors into three classes, ranking the classes according to the subsidence risk and land-use limitations based on slope. Table 3 shows the classes adopted in this study. Classes and ranks of importance are arbitrary and may vary from area to area, depending upon actual conditions.

For the purpose of simplicity and illustration, hypothetical maps of the two factors, slope steepness and percentage area in dolines, are shown in Figure 21. The composite factor map, or surface instability map (Figure 21), can itself be coded by assigning degrees of importance to the various combinations of factors. For the two factors in this example (degree of slope and percentage area in dolines), a total of nine possible factor combinations were grouped into four classes of importance (I, II, III, and IV). The actual assignment of the various combinations of the two factors to their respective relative subsidence categories (Table 3) has been arbitrary, yet guided by experience and intuition. Further detailed study over much larger areas is needed in order to develop a more quantitative basis for the surface instability categorizations presented here.

Table 3

Factor and Composite-Factor Classes for Maps for Predicting Relative Surface Instability

Individual Factors			Composite		
Slope Steepness			Land Use Suitability		
A	Gentle	(0-15%)	I	Very Good	(Aa,Ba)
B	Moderate	(15-25%)	II	Good	(Ab,Bb)
C	Steep	(>25%)	III	Moderate	(Ca,Cb)
Percentage of Area in Dolines			IV	Poor	(Ac,Bc,Cc)
a	Low	(0-5%)			
b	Moderate	(5-15%)			
c	High	(>15%)			

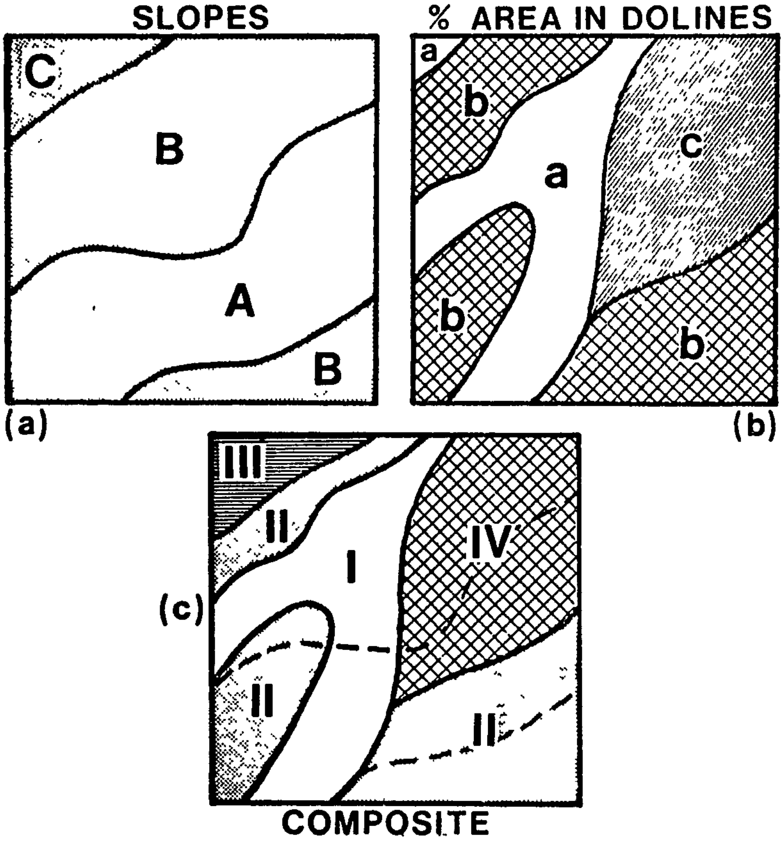

Figure 21. Hypothetical example showing the method by which a surface instability map could be made.

HYDROLOGY

Selected Literature Review

Carbonate aquifers have long been the concern of hydrologists because they do not lend themselves easily to the standard techniques of aquifer analysis (Hess, 1974). The presence of both concentrated flow via conduits and diffuse circulation is a problem not found in most non-karst terrains.

Early researchers (Grund, 1903; Cvijic, 1893) were concerned with the concept of a water table and trying to fit this to karst terrains. Cvijic (1918) suggested that three hydrological zones exist below the soil moisture zone. These were a vadose, upper zone; an intermediate, alternating wet and dry zone; and a phreatic zone in which all voids remained permanently full of water. The fact that dry holes can be drilled next to producing water wells caused Katzer (1909) and Martel (1910) to maintain that there is "no water table, only independent underground conduit systems operating like rivers. . . in three dimensional space" (Jennings, 1971).

Davis's (1930) two-cycle theory of the evolution of caves below the water table emphasizes the role of solution below a water table. Gardner (1935) and Malott (after Cullingford, 1953) added more to the controversy by supporting a vadose theory of cave origin. Bretz (1942) classified features in caverns to distinguish between vadose and phreatic caves. Lehmann (1932), Davies (1960), White (1960), Ford (1965), Thrailkill (1968) and others have proposed compromising views that have emphasized the dynamic nature of karst and have pointed towards Cvijic's "intermediate zone" as being the zone of most active solution. This intermediate zone includes the karst water table in low relief karst.

Carbonate hydrology has been reviewed by Burdon and Pupakis (1963). This work helped to "clarify the methods of studying, investigating, and developing the groundwaters held in karst limestone aquifers of the circum-Mediterranean countries." Effects of structure on ground water movement as well as quantitative methods for estimating karst denudation rates were discussed. These authors also review the geochemistry of karst waters in the Mediterranean countries. Stringfield and LeGrand (1968), Herak and Stringfield (1972), and Sweeting (1973) have also discussed carbonate hydrology in detail. Parizek, et al. (1971) has used hydrological, geological, and geochemical techniques to resolve many of the problems of the central Pennsylvania karst.

White (1969) has classified karst hydrogeologic systems of low to moderate relief. His classification divides carbonate ground water flow into three categories: (1) diffuse flow of relatively deep circulation and where few connected voids exist; (2) free flow with well integrated cave systems; and (3) confined flow with flow restricted by beds. He emphasized carbonate rock type and the presence or absence of capping beds in the role of ground water movement. In a later study Shuster and White (1971) attempted to classify diffuse and conduit flow on the basis of seasonal trends in spring chemistry. Hess (1974) has looked farther into seasonal trends of spring chemistry in central Kentucky and has analyzed spring chemistry response to storms. Nutter (1973) has studied ground water movement in the Cambro-Ordovician carbonates of Maryland and has found much of the recharge and discharge to be diffuse.

The style and rate of underground water movement in West Virginia has been studied by several authors. In Berkeley and Jefferson Counties, West Virginia, Hobba, et al. (1973) has found water movement to be mainly diffuse and slow moving. In the Greenbrier Limestone of Pocahontas County, West Virginia, Zotter (1965) and Medville (1976) found that water moves through conduits at an average rate of one mile per six hours where the relief is high. In Greenbrier County, where the relief is lower, Jones (1973a) found water to move through conduits in the Greenbrier Limestone at rates of about one mile per two days. Finally, Jones (oral communication, 1974) has traced insurgences in this author's study area and has found water to move at an average rate of about one mile per day.

Recharge and Discharge

Ground water in the carbonates of Monroe County is recharged by concentrated flow into dolines and caves and by diffuse infiltration of precipitation. Figure 22 shows most of the sinking streams

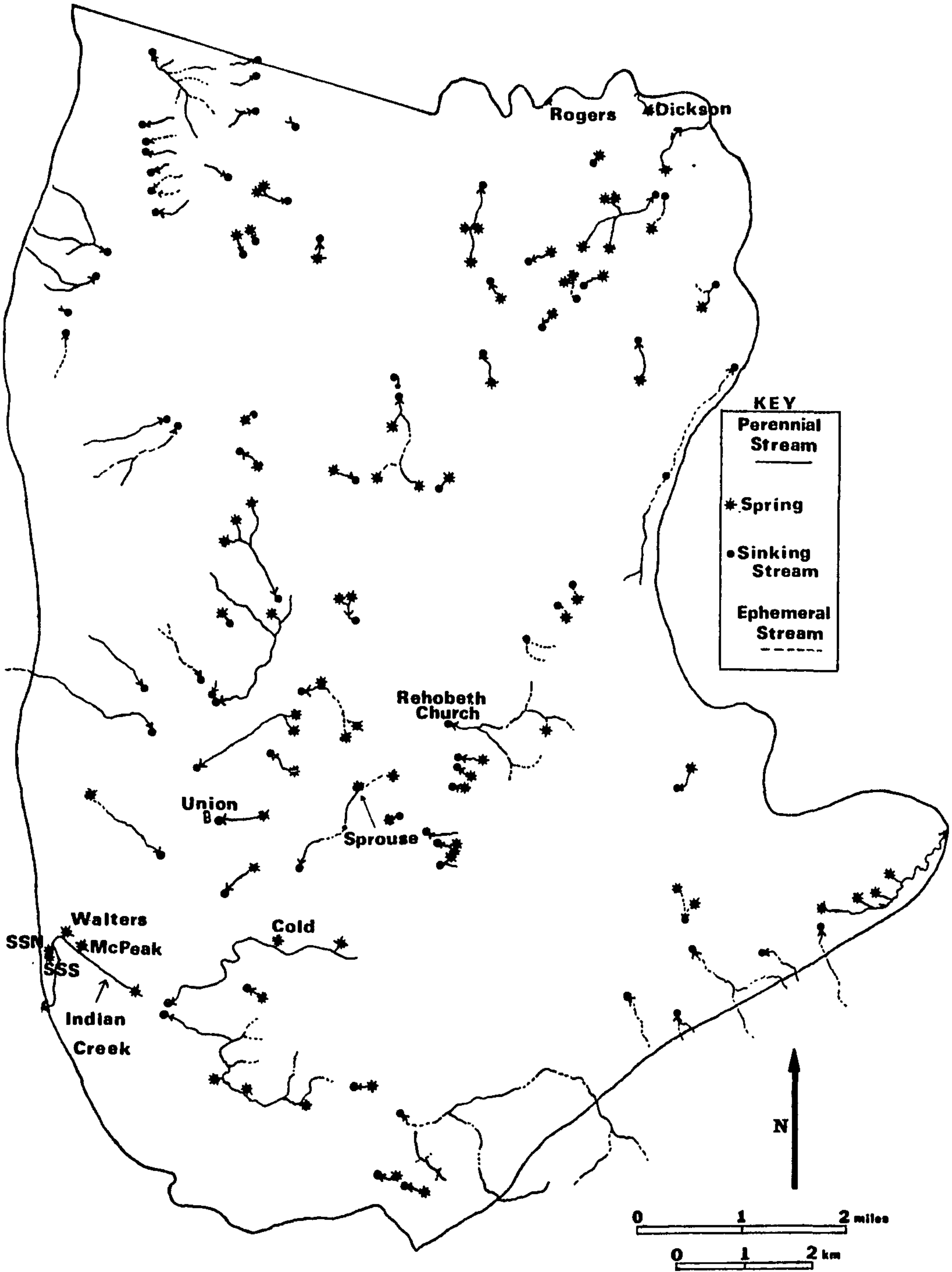

Figure 22. Sinking streams and springs of the study area. All proper names except Rehobeth Church refer to springs sampled during this study.

in the study area. Surface streams generally flow on the surface for only a few hundred feet before sinking occurs. Ephemeral streams on the east side of Swoopes Knobs feed most of the western sinking streams. Along the eastern and southern section of the area, both ephemeral and perennial streams flow over clastics and sink into the lower section of the Greenbrier Group, thereby recharging the aquifers. Ground water is commonly perched on the Greenville, Taggard, Patton, and Maccrady shales. Where these units crop out, there are commonly springs whose water moves on the surface for only short distances before sinking into the limestone. Water can therefore discharge from one aquifer and recharge another.

The most common form of discharge in the carbonate rocks of Monroe County is springs. Figure 22 shows the abundance of springs in the study area. The larger springs are located near local base level along the banks of Second and Indian creeks. Dickson Spring and Walters' Spring are two of the largest springs issuing into the Second and Indian creeks, respectively. Springs contribute much of the flow of Second and Indian creeks, with the heads of each of these being a spring.

Springs are of both the conduit and diffuse types. Water moving through caves form conduit springs which can be classified as either phreatic (water-filled) or vadose (air-filled). Many of the conduit springs in the study area have both vadose (open channel flow) and phreatic (closed channel flow) sections. During floods, vadose caves feeding conduit springs may fill to become completely phreatic for short periods of time. Conduit springs have fast flow-through times and have high variations in discharge and ground water chemistry compared to diffuse springs.

Diffuse springs are fed by waters that have moved through joints, fractures, and bedding planes. Ground water storage is higher for diffuse springs with discharge and water chemistry having little seasonal variation (Shuster and White, 1971). Conduit springs have concentrated recharge by sinking streams, but diffuse springs are fed by diffuse infiltration. Diffuse springs may represent insipient conduit springs that will enlarge with time. Diffuse springs appear to be rare in Monroe County except for small springs that may have had neither the time nor water flow rates necessary for conduit development. In some cases, diffuse springs may be a function of lithology where a particular rock unit does not lend itself to cavern development. Shuster and White (1971) have found this in central Pennsylvania where diffuse springs are usually in dolomite.

Ground water seeps are less detectable than springs but are assumed to occur most commonly along the intersection of local base (stream) level and aquifer outcrops. These seeps combined with some diffuse springs, are the primary source of discharge for the diffuse flow aquifers from which the well waters are derived.

Sinking streams feeding major springs drop rapidly down dip to a level not much higher than the resurgences themselves. Dickson Spring has several insurgences like this in its large catchment area. The water leaving the siphon in Rehobeth Church cave has a gradient of less than a half degree as it moves to Dickson Spring.

The rate of ground water movement in the carbonates of West Virginia is highly variable. The rate of movement in carbonate aquifers is a function of the size of the basin, the difference in elevation between insurgence and resurgence, the amount of water moving through the system, the size of the conduits, and the proportion of phreatic versus vadose flow. Generally, water will move fastest during high flow through a small basin with a great deal of relief. Large conduits which exhibit primarily vadose flow will also increase ground water flow velocities. The presence of siphons, clay fills, and underground lakes will all slow down ground water movement.

Ground water storage is low in Monroe County but recharge is high so that dry-weather flow in streams is mostly from springs and not from seepage along stream channels. In most other geologic terrains seepage is a more important source of ground water runoff. The greater lag time (difference in time between peak discharge of springs and peak discharge of surface streams) enables springs to be approaching the peak of their hydrographs as the streams they empty into are receding (Hess, 1974).

Climate and Precipitation

The climate of the study area is typical for West Virginia; a temperate climate exists with a rather wide range of temperature and precipitation. Precipitation in summer months is usually from storms moving north to northeast from the Gulf of Mexico. In winter months, high pressure systems from the west and north predominate in generating storms.

The average annual precipitation for the three year period of 1972, 1973, 1974 is 35.87 inches a year (Union Station, U.S. Weather Bureau). The annual precipitation for the twelve month study period (October 1974 to September 1975) was 36.14 inches. Therefore, the rainfall was not very different from the mean. A plot of monthly precipitation is shown in Figure 23. The lowest value is 0.90 inches for the month of December, 1974, while 5.37 inches for March, 1975, was the maximum value. Appendix D shows the daily precipitation from the Union Station for the period of water sampling.

Evapotranspiration is highest during the growing season which is generally from May to October. Recharge to the soil and aquifers is minimal during these months. This is reflected by the low summer and fall stream flow. Temperature extremes for the study period were a high of 87 degrees Fahrenheit (30.6°C) in July 1975, and a low of 5 degrees F (-15°C) in January 1975 (Figure 24). The mean annual temperature for 1975 was 51.5 degrees F (10.8°C). This average temperature is reflected by the temperature of the interior of caves and the diffuse springs, which remain near this temperature.

Drainage Systems

During the first field season in 1973, central Monroe County was explored to determine the "best" or most representative springs

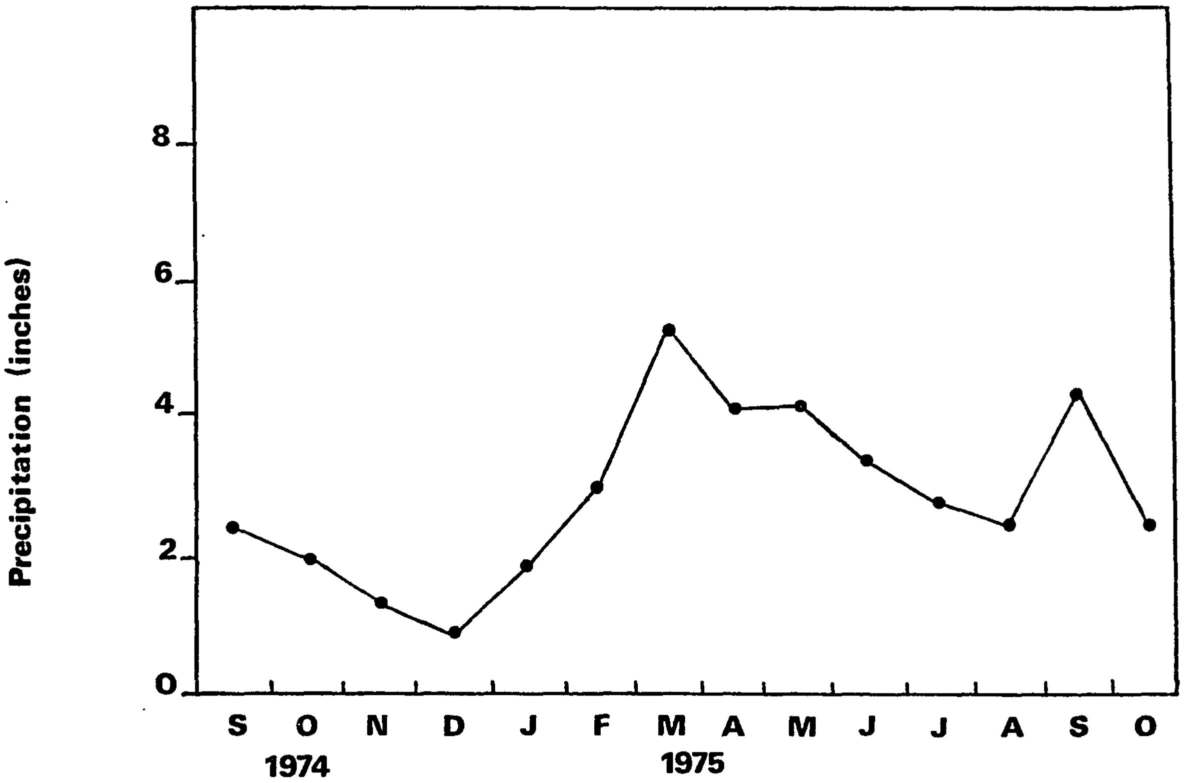

Figure 23. Monthly precipitation data for the spring study period (1974-75), from the Union Station, U.S. Weather Bureau.

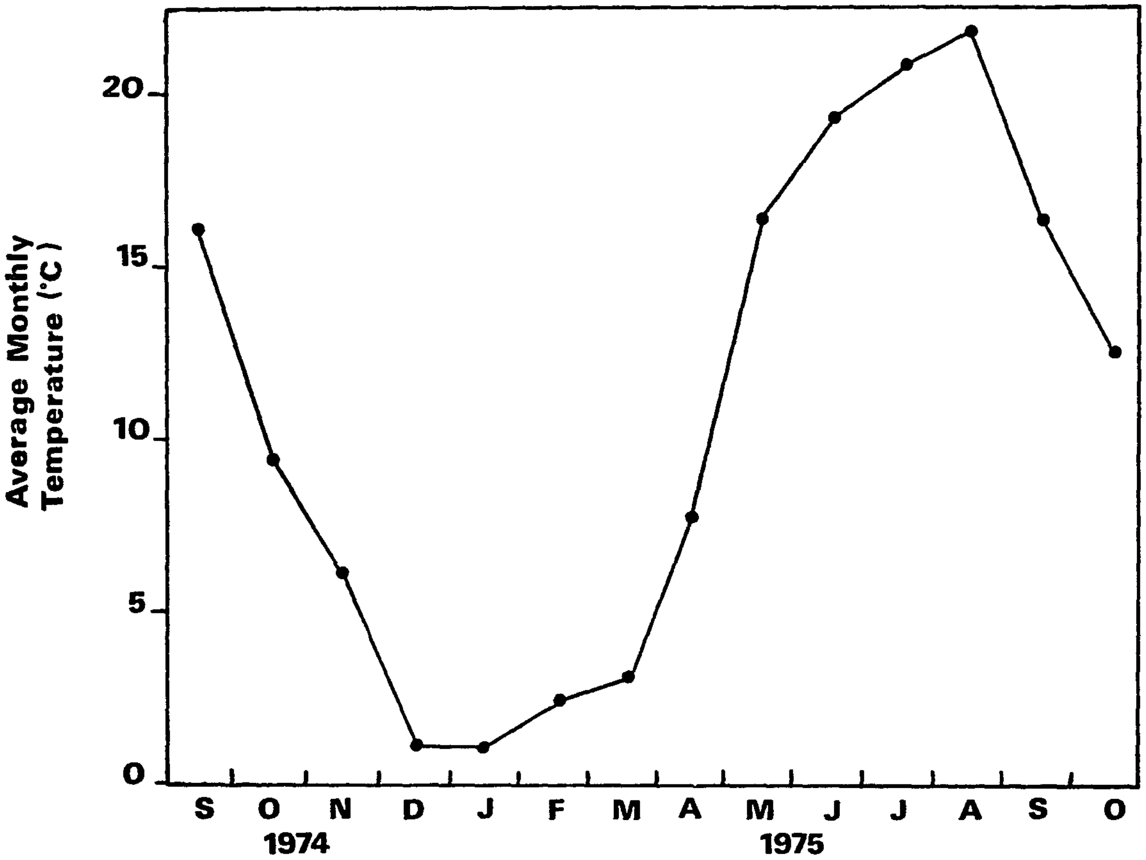

Figure 24. Monthly temperature data for the spring study period (1974-75), from the Union Station, U.S. Weather Bureau.

to study. Earlier work by William K. Jones (oral communication, 1973) helped greatly in this. He had previously performed a few spot-water analyses, which included testing for coliform bacteria. To get as much information as possible for a variety of springs, representative spring types of the following were chosen for detailed study: large, small, unpolluted, and polluted. Dickson Spring was chosen as a large, unpolluted spring, and Walters' Spring was chosen as a large, polluted spring. Rogers' Spring was selected to represent a small, unpolluted spring, while McPeak's Spring was chosen as a small polluted spring, since it was known to be the path for much of Union's sewage prior to the construction of the treatment plant. Cold Spring was chosen because it was known from cave exploration to represent a vadose cave system, and it too is small and polluted. These springs were sampled about once every two weeks for the study period.

The Rehobeth Church Insurgence was selected for sampling because it is a non-karst surface stream that sinks to later discharge at Dickson Spring. Sampling of this insurgence allowed a comparison of water chemistries of the insurgence and the spring. The above springs and Rehobeth Church Insurgence were sampled for flow rate and water chemistry once every two weeks for 13 months.

Three other sites were chosen but were sampled only once a month for the same time period. A spring known as Sprouse's Spring at the headwaters of the Cold Spring Basin was one of these.

This spring was chosen to determine any changes in water chemistry between the headwaters and spring resurgence of the limestone basin. Two mineral springs, for which Monroe County is famous, were sampled monthly for their unique chemical character and obvious hydrogeologic difference from the other karst springs. The two springs are Salt Sulphur North (SSN) and Salt Sulphur South (SSS), which are located near U.S. Route 219.

The basins for Dickson, Walters', Rogers', McPeak's, and Cold Springs were partly defined by fluorescein dye traces performed primarily by William K. Jones and to a lesser extent by the author, who used both Rodamine B and Fluorescein dyes. Basins were further delineated by tracing topographic divides where possible.

Discharge Measurements

One purpose of this study was to relate seasonal fluctuations of chemical parameters to discharge for springs and insurgent streams. To achieve this, it was first necessary to gage each of the five springs using methods of the U.S. Geological Survey (Corbett, et al., 1962). A six foot pole marked in tenths of feet was placed at each of the gaged sites in such a manner as to assure that some portion (but not all) of the pole would be under water at all times. Small pools, created either by nature or man, proved to be the best locations. Discharge measurements were then made about once every two weeks at each spring or stream during times of low, moderate, and high flow.

Discharge was measured with the aid of a U.S. Geological Survey standard current meter with an appropriate rating table for determining flow velocity. This method first entails stretching a measuring tape tightly across the spring channel and dividing it into a somewhat arbitrary number of sections. At each section, the water depth is recorded, and the current meter is set 0.6 of this distance below the stream surface to estimate average flow velocity, by recording the number of revolutions of the meter paddle wheel in a specified number of seconds (as determined by the rating table). This procedure is continued for each section so that the discharge for each stream section can be calculated from multiplying the values of width, depth, and velocity. The total discharge in cubic feet per second (cfs) is then the summation of the calculated discharges for all stream sections.

Rating curves were then produced for each of the springs or streams as shown by the example in Figure 25. In most cases, only four discharge measurements were reported for each spring to get a straight line relationship when plotted on log-log paper. Once the rating curves were made, it was possible to accurately determine discharge from the gage heights recorded at each sampling time.

Dickson Spring Basin

Dickson Spring, with a basin or catchment area of 24.68 square miles, is the largest of all the karst springs in central Monroe

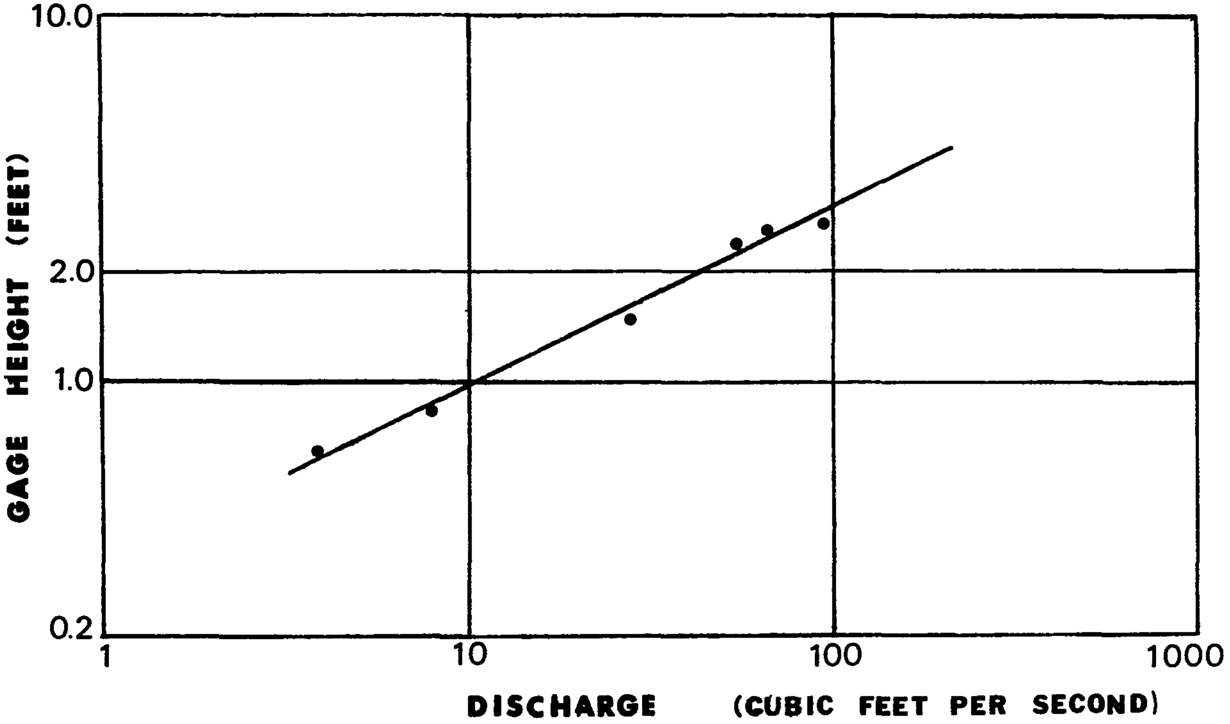

Figure 25. Rating Curve for Dickson Spring for determining spring discharge.

County. High flows of up to 107 cfs were observed during the sampling period but flows much higher than this probably occurred. The lowest flow observed was 6.6 cfs. Discharge values measured for this spring during the 28 sampling periods are plotted in Figure 26.

This spring is located along a cliff at the extreme northern boundary of Monroe County where it discharges into Second Creek (Plate 3, Figure 27). Dickson Spring emerges at the base of the Patton Limestone on the western limb of the Hurricane Ridge syncline where the rocks are dipping 13 degrees to the southeast. The spring emerges from a pile of rock debris, but during high flow also boils up from a pool in front of these rocks. There is no cave entrance that allows exploration of the spring system from its place of emergence.

At least five sizable insurgences have been traced to Dickson Spring. Many other smaller insurgences are assumed also to emerge at this spring. The insurgence at Rehobeth Church was traced by W. K. Jones (oral communication, 1973) during low flow (September 1972); it took 19 days to travel 7.3 miles, assuming a straight line distance.

Walters' Spring Basin

Walters' Spring (Figure 28) has the second largest spring catchment area of basins studied (Plate 3). It has an area of 10.49 square miles. This basin is partially overlain by the McPeak's Spring basin. The spring is located 3.4 miles south of Union on the north side of State Route 219 (Plate 3) along a

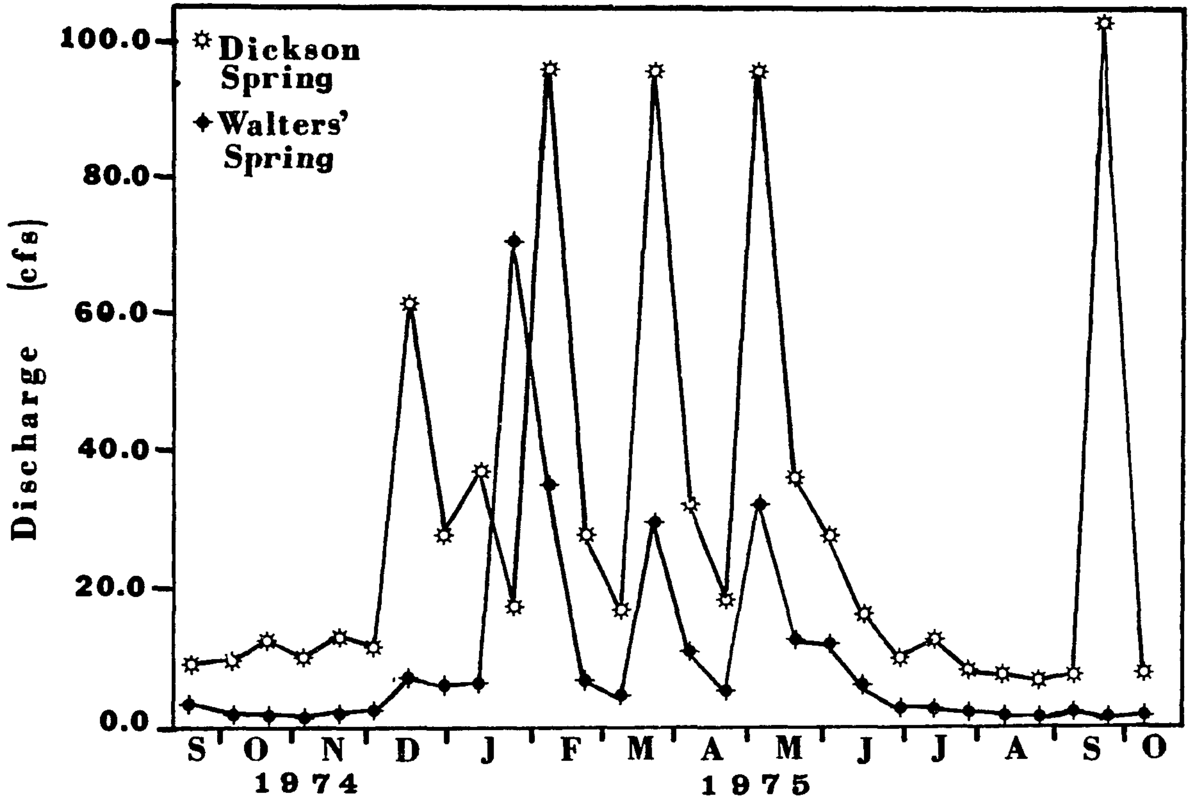

Figure 26. Bimonthly discharge measurements for Dickson and Walters' Springs.

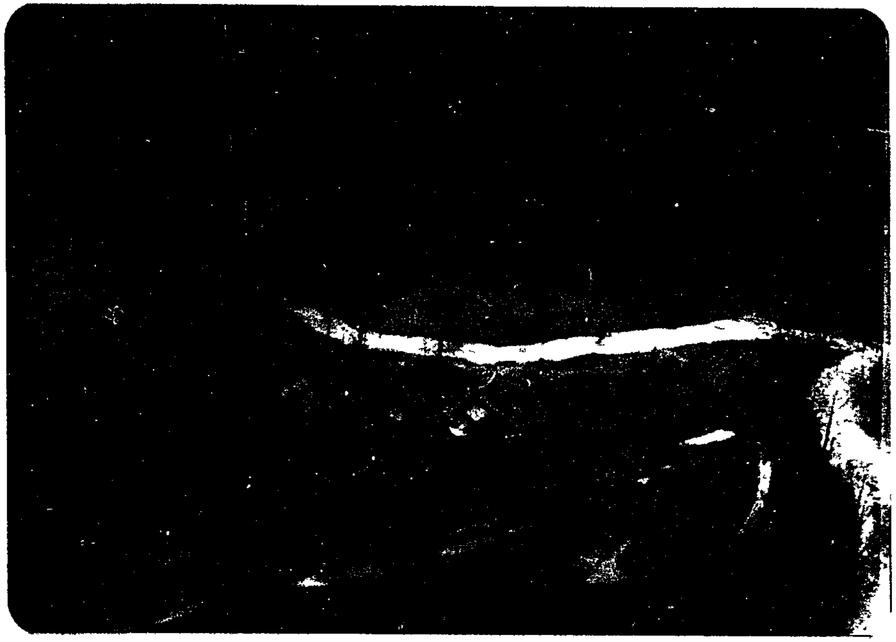

Figure 27. Photograph of Dickson Spring (located of left side of photograph).

Figure 28. Photograph of Walters' Spring during high flow.

thrust fault within the broken beds of the Greenville Shale. Four major insurgent streams sink in the Pickaway and Union limestones and travel up-strata until the Greenville Shale is encountered; this shale then acts to direct the cave waters to Walters' Spring. The thrust fault allows the water to pass through a small portion of the Greenville Shale.

The distance from the nearest known insurgence to Walters' Spring is 1.99 miles, while the farthest known insurgence is 3.79 miles away. Two of the insurgent streams enter caves that can be traversed for several hundred feet to siphons. These caves are generally small and are known to rapidly fill with water during storms. No known cave allows entry into the main drainage system near the spring, probably indicating that this cave system is primarily phreatic (or of closed channel flow) shortly down-gradient from the insurgence points. Walters' Spring had measured discharges ranging 1.0-125.0 cfs during the study year, but averaged around 5.0-10.0 cfs (Figure 26).

McPeak's Spring Basin

This small basin of 2.28 square miles has its resurgence at McPeak's Spring, located 3.2 miles south of the town of Union on the north side of State Route 219 (Plate 3). Low flow for McPeak's Spring was 0.03 cfs during the study period, while the average flow was 0.2 cfs (Figure 29). Figure 30 shows the spring at relatively high flow. High flow values are difficult to determine for the spring alone because during heavy rains, surface water runoff

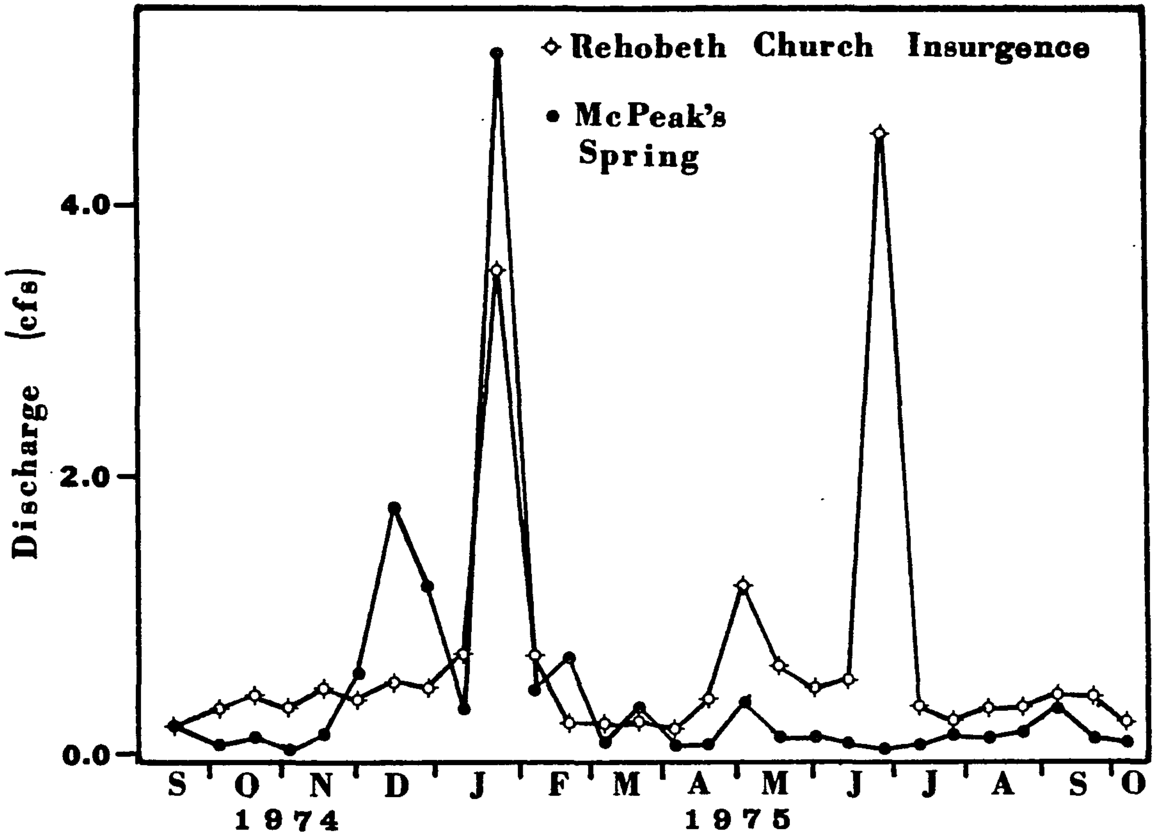

Figure 29. Bimonthly discharge measurements for Rehobeth Church Insurgence and McPeak's Spring.

Figure 30. Photograph of McPeak's Spring at high flow.

from the nearby stream channel mixes with the spring. Spring flow rates as high as 2.3 cfs without any surface contribution have been measured, while combined low rates of 11.7 cfs have been recorded.

This spring is located at the Greenville Shale-Union Limestone contact. Two small streams sink near the Union-Pickaway contact and flow stratigraphically upward to finally discharge at McPeak's Spring where the Greenville Shale acts as a ground water barrier along Indian Creek. The distance between the nearest insurgence and McPeak's Spring is 1.14 miles, while the farthest known insurgence is 1.89 miles from the spring. During extremely high flow, some underground water is taken by an upper flow route through Broyles Cave, where it discharges at the head of Indian Creek.

Rehobeth Church Insurgence

Rehobeth Church Insurgence is a small stream that enters Rehobeth Church Cave immediately behind the historic landmark of Rehobeth Church in Monroe County (Figure 31). The insurgence is located on the northwest flank of the Hillsdale anticline, 2.7 miles east of Union on State Route 3 (Plate 3). The dip of the rocks at the cave entrance is 30 degree northwest. About 500 ft into the cave, the dip increases to almost vertical, where a westward-dipping thrust fault is encountered. Past the fault the dip decreases to about 30 degrees.

The surface stream bed is on the Maccrady Shale throughout most of its length and was studied to determine the character of

Figure 31. Photograph of Rehobeth Church Insurgence, near Rehobeth Church.

noncarbonate surface waters entering the karst aquifers. The stream sinks into the Sinks Grove Limestone and travels underground, crossing the Hurricane Ridge syncline to emerge at Dickson Spring. The stream drops over 100 vertical ft in the cave down dip before arriving at a siphon. This is characteristic of several of the known insurgences of Dickson Spring.

The average flow rate for the stream during the 13 month study period was 0.4 cfs and the range was 0.15 to 0.7 cfs (Figure 29). During very large floods the cave is knwon to fill with water, causing the surface stream to pond. This was not observed during the study.

Cold Spring Basin

This small basin has its ground water resurgence at the entrance of Cold Spring Cave (or Walker Farm Cave), which is located approximately 0.5 miles east of the Willow Bend Road along the Burnside Branch Valley (Plate 3). The size of the basin is only 0.94 square miles. High flow is seldom more than 2.0 cfs, with an average flow for the 13 month study period of 3.8 cfs (Figure 32). The cave where the spring emerges (Figure 33) can be traversed for nearly 1,500 ft along strike-oriented passage to a siphon. The cave is in the nearly horizontal arenaceous Taggard Limestone Member which rests on the thin Lower Taggard Shale Member. The cave averages 10-15 ft high and 20 ft wide, and contains a vadose canyon passage cut through sediment fill on the cavern floor. Two other

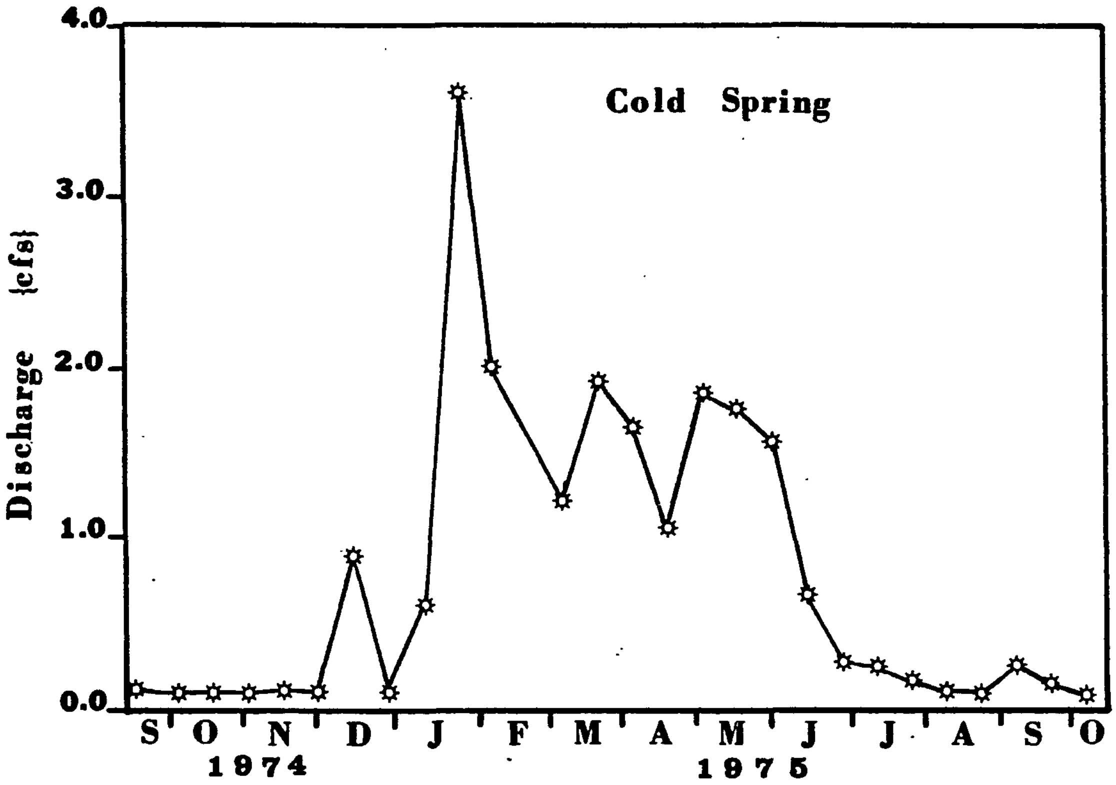

Figure 32. Bimonthly discharge measurements for Cold Spring.

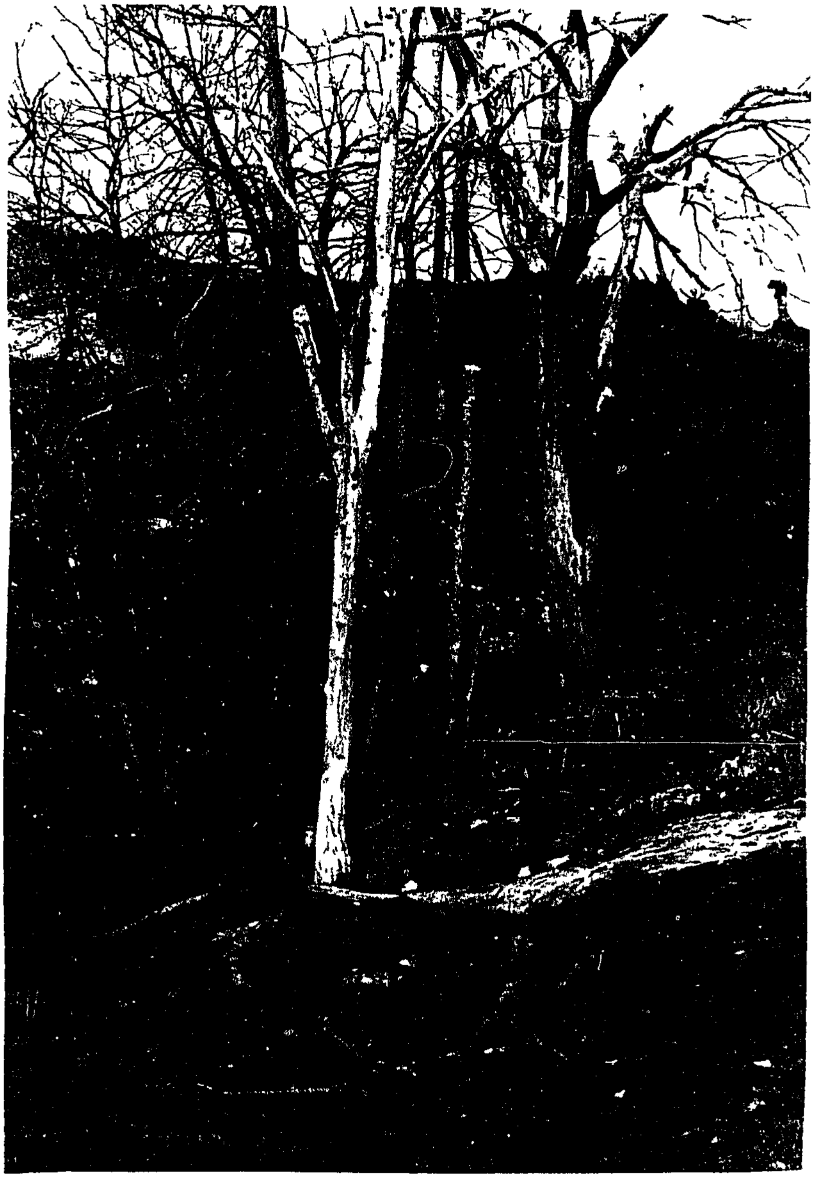

Figure 33. Photograph of Cold Spring at the entrance of Cold Spring Cave.

small caves are known in the upper portion of the basin between the only known insurgence and the resurgence. These two caves have 500 ft of explorable passage. The distance between the insurgence and resurgence is only 3,600 ft. Polluted waters from a dairy farm above the cave enter the cave by diffuse infiltration near the insurgence point.

Sprouse's Spring

This sampling site actually represents the combination of several small springs that are located in the upper portion of the Cold Spring basin (Figure 34). This site was sampled to check for changes in water quality before and after water traveled through the Cold Spring-Walker Well cave system. The water travels over the surface for several hundred feet before reaching the sampling site, and then continues into a pond. It is the water leaving this pond that actually enters the northern extension of the cave system. At the sampling station the rocks are dipping about 10°NW with the stream flowing on the cherty limestone beds of the upper Patton Limestone. The water travels over the Lower Taggard Shale Member and sinks into the Taggard Limestone Member. Water flows underground from there in the Taggard Limestone Member to the Cold Spring resurgence along the axis of an unnamed gently folded syncline. Discharge was not measured at this sampling station.

Rogers' Spring Basin

Rogers' Spring with an area of 1.99 square miles (Jones, written communication, 1976), is the only known resurgence for catchment

Figure 34. Photograph of Sprouses' Spring entering farm ponds, near the center of photograph.

waters of this basin. The spring is located in the lower Sinks Grove Limestone, about 0.5 miles west of Dickson Spring at Rogers' Mill (Plate 3). It discharges into Second Creek. Here the limestone is very cherty with a 10 degree dip to the southeast: the spring is located on the west flank of the Hurricane Ridge syncline. During high flow the spring issues from several upper level conduits on the side of a high cliff, but only one flows throughout the year (Figure 35). Average flow for the spring is only about 0.35 cfs, but an estimated high discharge of 82.0 cfs has been observed by the writer (Figure 36). The discharge was recorded at this spring bimonthly.

Two small springs, one of which contains a short cave, join and flow for less than 2000 ft before sinking into the only insurgence that has been traced to Rogers' Spring. This sinking stream drops over 150 ft in less than 6000 horizontal feet.

Portions of this basin are believed to overlie the Dickson Spring basin. So far it has been impossible to explore either end of this system. Scuba divers have penetrated a few feet into an upper overflow conduit, but were blocked by breakdown in the siphon. This information combined with the chemistry data, indicates that the spring may be phreatic (closed channel flow) in its downstream segment.

Salt Sulphur Springs

The Salt Sulphur Springs of Monroe County are located 2.2 miles south of Union on the east side of State Route 319 (Plate 3).

Figure 35. Photograph of Rogers' Spring during high flow.

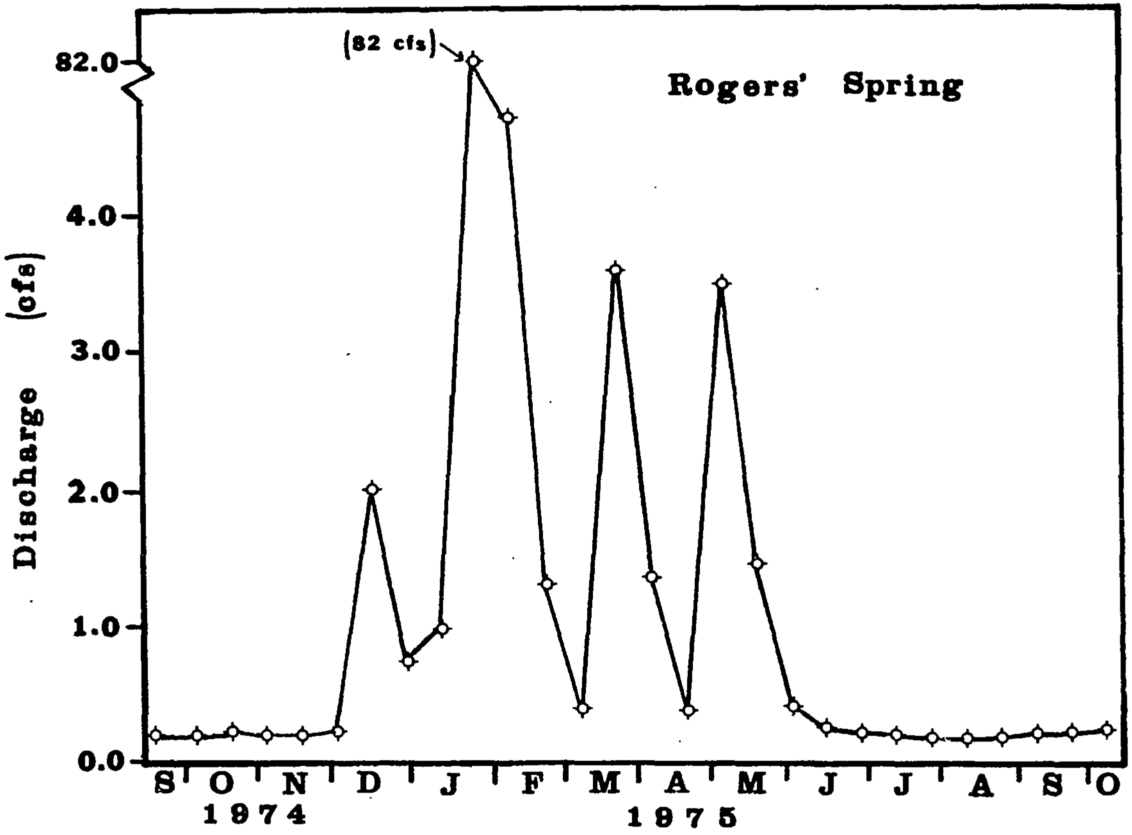

Figure 36. Bimonthly discharge measurements for Rogers' Spring.

Geologically, the springs are located within the lower section of the Greenville Shale near the Union Limestone contact. The rocks are nearly flat-lying on both sides of the small valley containing the springs and Indian Creek. The thrust fault situated at the emergence of Walters' Spring is in line with these springs, and forms a nearly one mile long photo-lineament.

The Salt Sulphur Springs of Monroe County (Figure 37) were an early attraction and were once believed to be a panacea for the old, weak, and ill. The springs became a resort center in 1820 and flourished until the Civil War (Morton, 1916). Originally, there were three springs: the Iodine, Salt Sulphur, and Sweet springs. Only the Iodine and Salt Sulphur springs were studied because a preliminary water analysis showed the Sweet Spring to have a chemistry similar to Indian Creek only a few feet away. The Iodine and Salt Sulphur springs are respectively referred to in this report as Salt Sulphur North (SSN) and Salt Sulphur South (SSS). Water samples were taken on a monthly basis from these springs.

The earliest discussion of these springs was in a small pamphlet by J. J. Moorman, M.D. (1859). In this report, the Iodine spring was described as being ten degrees warmer than the other two springs, varying in temperature from 62 to 68 degrees Fahrenheit. The Sweet Spring (referred to as the Upper or Old Spring) contained no iodine, but the Salt or New Spring did. The 1859 analysis of these waters were reported in grains per wine gallon (Moorman, 1859).

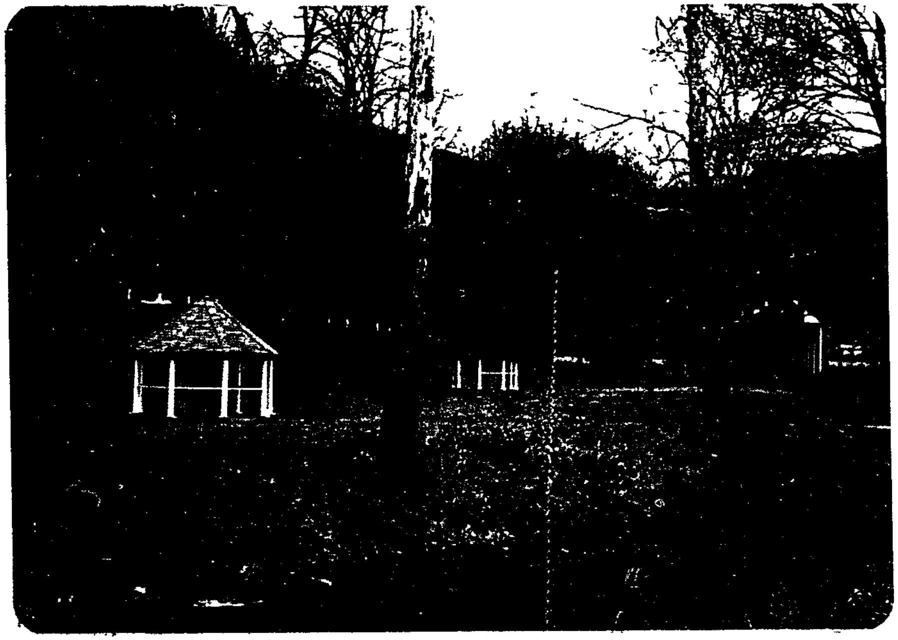

Figure 37. Photograph of the two Salt Sulphur Springs in Salt Sulphur Springs, West Virginia. Salt Sulphur Spring South is in the foreground and Salt Sulphur Spring North is in the background.

A second early reference to these springs is found in the "Springs of West Virginia" by Price, et al. (1936). All three were found to be similar in chemistry and have a 50 gallon-per-minute flow rate as noted in the 1859 report. A major change has occurred since 1936. The Sweet Spring was found to have normal carbonate geochemistry, containing negligible concentrations of sulfate. All three springs now have no flow except after heavy rains. Water levels of the springs were measured and appear to fluctuate with the shallow water table of the location. These facts strongly indicate that the Sweet Spring has greatly decreased in dissolved solids, and that the Iodine and Salt Sulphur springs are now merely small seeps. It is rumored by local residents that the earthquake of 1970 in Monroe County had some effect on the flow of these springs.

The origin of sulfur springs has long been debated, and two theories predominate: (1) they originated from an upward movement of deeply circulating ground water that was affected by the intrusive magmatic body that caused the ancient volcanism near Monterey, Virginia; (2) they were created by the release of connate waters from deep sedimentary rocks (Price, et al., 1936). The results of this study do not help in distinguishing between these two theories of sulphur spring origin. A possible third theory for the Salt Sulphur springs is one of diffuse flow of ground water through sections of the Greenville Shale in which the high sulfate concentrations and lower pH could be due to pyrite weathering.

Cavern Geology

Stratigraphic Distribution of Caves

As in most of the karst terrains of West Virginia, there is a large variety of cavern types in central Monroe County. The Monroe Study Group of the West Virginia Speleological Survey compiled the most recent description of Monroe County caves (Hempel, 1975).

Along the western section of the area, there are pits developed near the contact of the Greenville Shale and Union Limestone (Hempel, 1974). The terrain in this area is rugged, being near the top of the Swoopes Knobs. Water from storms forms ephemeral streams that flow over the impure Alderson Limestone and sink into the Union Limestone. The Greenville Shale (which is sometimes sandstone) is believed to act as a caprock in a similar fashion to that described by White (1969). Mott Hole, Burdette Shoe Pit, and Moores' Cave are examples of this with 150 ft, 85 ft, and 30 ft drops, respectively.

Pits also developed at the top of the Patton Limestone with the Patton Shale acting in a similar manner as the Greenville Shale. There are at least twenty unnamed pits at the top of the Patton Limestone that have little or no cave passage developed at the bottom. Two pits like those that have been described are Black Snake Pit and Dead Turtle Pit.

The high impurity of the Alderson Limestone has caused it to have the least amount of cave development in it. When present, Alderson caves are short and narrow, or consist of one small room.

The lower Hillsdale Limestone is also very shaly and impure and contains no caves in Monroe County similar to the "contact" caves described in Greenbrier County (Jones, 1973a). This may be a function of the greater elevation of the Hillsdale Limestone above local base level found in central Monroe County. The clay rich Pickaway Limestone with its tightly cemented "Pickaway joints" (Figure 9) likewise has poor cave development. Caves are often linear, narrow passages with streams on the floor. Walker Pond Cave is an example of this.

In the Sinks Grove and upper Hillsdale limestones, caves are common and often extensive. Caves in these zones are often canyon-like with entrance passages situated down dip, opening into larger diameter passages that end in siphons. These passages are usually lined with chert,making traverses in them both difficult and painful. Ellison's and Rehobeth Church caves are two examples.

Union and Patton Limestone caves generally are of large diameter and volume. These caves often have upper dry levels with lower levels containing streams. Medville (1975) suggests that Union Limestone caves with active streams "tend to be less broken down and somewhat smaller in cross-section" than caves in other Greenbrier Limestone formations. Caves of the Union and Patton Formations often show bedding plane passages with large width to height ratios. Crowder Cave is an example of this type of cave development. The purity of these two formations lends itself to greater lengths of cavern development, but the great cross-sectional size of the cave passage is due to the thick unjointed beds in the ceiling. White and White (1969) describe this latter effect on the formation of cave ceiling breakdown related to bed thickness and cave passage diameter.

Caves and springs are often found associated with the shales of the Taggard Formation. It is common to find a spring or cave immediately above the upper red Taggard Shale Member that quickly sinks into a swallet insurgence within a few stratigraphic feet. A few caves also are formed within the Taggard Limestone Member; often such caves are extensive, such as Ogden's Cave (1200 ft long) and Cold Spring (Walker Farm) Cave (1500 ft long).

Cave locations placed over the geology map, combined with personal cave exploration by the author, were necessary to accurately determine the principal formations in which each cave was developed. Since most of the larger caves are nearly horizontal with passages developed primarily along strike, they are generally developed within one formation. Accumulated cavern length versus limestone formation of the Greenbrier Group was plotted on a histogram as shown in Figure 18. This distribution shows that there is a strong relationship of cavern development to stratigraphy.

In summary, caves are found primarily in the Union, Patton, and Sinks Grove limestones. From field inspection, these formations can be generalized as the most pure and thickest-bedded of the Greenbrier Group. Such lithologic associations with cave development have also been observed by Rauch (1972) and Rauch and White (1971) for central Pennsylvania. Perhaps more importantly, these formations are found next to shale units that may act as barriers to ground water flow. Caves are smaller and less abundant in the Alderson, Pickaway, Taggard, and lower Hillsdale limestones, primarily because of their impure nature, in all probability. This evidence suggests a combination of stratigraphic and lithologic factors controlling cavern development that deserve future study.

Cave Orientation

Several studies have been conducted throughout the eastern United States testing the geologic parameters controlling cavern orientation. White (1960) found that in the folded limestones near State College, Pennsylvania, the commonly high stratigraphic dip controls cavern orientation largely along the stratigraphic strike. Davies (1960) found from his research that most cave passages in the folded Appalachians are joint-controlled. Anderson (1961) and Palmer (1962) have shown that the caves of eastern New York are mostly joint-controlled. Deike (1968) noted that the mean amount of fracture-controlled cave passage for most karst regions is about 75 percent. He also found that for the low-dipping rocks of central Kentucky, this control is only about 40 percent. Deike (1969) found that near State College, Pennsylvania, most cave length is developed along the vertical strike joints of the limestone beds. Anderson (1961) and Deike (1969) concluded that the spacing of joints controls the arrangement of cave passages. Palmer (1974) has shown more recently that high-angle faults and joints have a great influence on passage trends in a large West Virginia cave (Ludington's Cave) in Greenbrier County.

Fracture control of solutioning was emphasized by Lattman and Parizek (1964) and by Siddiqui and Parizek (1971) in the State College area of Pennsylvania. They found that water-well yields were higher along fractures zones, as inferred by surface lineaments from aerial photographs. Also, a larger number of cavities were intersected during drilling along fracture zones. Rauch (1972) found that there are a greater number of caves near fracture zones associated with water and wind gaps in central Pennsylvania. Therefore, if lineaments are indeed fracture zones and avenues of rapid water movement, then one would expect to find a significant number of cave passages oriented along them.

For the purposes of trying to discover the relationship of subsurface conduit drainage to geologic structure, statistical tests were performed for interrelationships among joint, lineament, strike, and cavern orientation data. Rosette orientation diagrams were prepared for stratigraphic strike measurements (Figure 10), straight cave segments (Figure 38), joints (Figure 12), and lineaments (Figures 13 and 14). Joint orientations were measured from surface outcrops by using a brunton compass. Lineament orientations were measured from aerial photographs. Straight cave segments defined as any straight 50 ft length of passage were measured from existing cave maps (Hempel, 1975). The chi-square test against rectangular distributions showed preferred orientation at the 0.001 alpha probability level (0.001>P) for both the cave and strike data. Cave passages are oriented primarily between due North and

N70°E (Figure 38). A comparison of strike and cave segment orientation distributions suggests at first that most cave passages parallel or nearly parallel the stratigraphic strike. However, a modified and strengthened version of the Kolmorgorov-Smirnov test (K-S test), after Werner (1956b), was used to compare these two distributions; this test gave a significant result, indicating different distributions (or populations) at the 0.01 alpha probability level (Ogden, 1974). This indicates that cave orientation is not significantly dominated by stratigraphic strike alone.

Lineament and joint orientation distributions were also compared by the modified K-S test to the cave segment orientation rosette; both were found to be significantly different from the cave orientation distribution at the 0.01 alpha probability level. A comparison of joint and lineament orientation distributions was then made to see if lineament azimuths in the study area are strongly related to the orientation of joints observed in outcrops. The same version of the K-S test showed a significant difference at the 0.01 alpha probability level. This suggests that either lineaments cannot be inferred to have a genetic origin associated with joint swarms, or else the joint swarms are significantly different in orientation than other measured joints. It may also be possible that the joints are en echelon to the lineaments.

The lack of statistical associations between cave passage orientation and the orientation of lineaments, stratigraphic

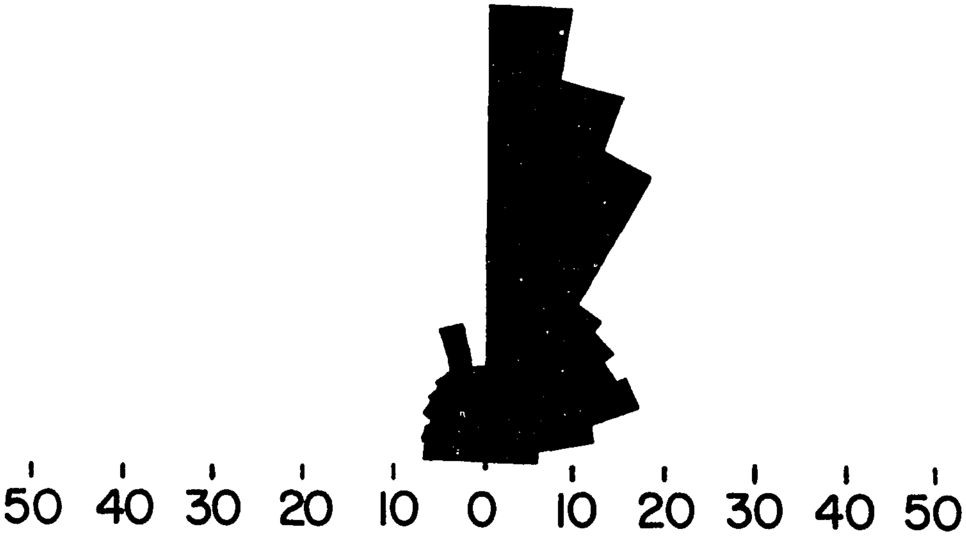

Figure 38. Orientation rosette for straight cave segments of 50 ft length from existing Monroe County cave maps. Scale is in number of cave segments, and 10 degree class intervals are used.

strike, and joints in central Monroe County, emphasizes that no single structural factor (of those tested) is predominantly and uniformly controlling the orientation of cave passages. Partly because the rocks in this area are neither flat-lying nor strongly folded, a combination of structural geologic parameters control the orientation of cave passages.

Visual comparisons of the orientation rosettes indicate that the stratigraphic strike is apparently the most important structural factor affecting cave passage orientations. Joints oriented N58°W and N27°W are likely to be an additional cave-controlling factor. Evidence from cave exploration and dye-tracing of ground water indicates that strike-oriented passages cross folds via shorter joint-oriented passages.

Aquifer Hydrology

Introduction

Monroe, and neighboring counties in which the Greenbrier Limestone crops out, have experienced recent growth and the beginning of light industrial development. Although the population is still not dense, the pressure on the environment and the ground water reservoirs has already been felt. Water in the Greenbrier Limestone of Monroe County has been known by locals to be at a generally great depth, and extensive drilling is usually required the ground water zone. Until recent years this has limited ground water use due to the overall low income level of people in the area.

With the migration of people from the cities and towns back to the country, drilling (and subsequent ground water use) has rapidly increased. Therefore a detailed study of the Greenbrier Limestone aquifers was deemed necessary; the results of this study are important for the evaluation of present aquifer conditions and for aiding in future land and ground water uses.

Well Data

The first step in this aquifer evaluation study was to locate the wells in the study area and obtain information on their physical characteristics. Drilling has been carried out in a random fashion with only a few drillers keeping records of the wells. Unfortunately, the State of West Virginia does not require drillers to file information on new wells with the State, and most drillers are hesitant about releasing their information. A. Anderson of Lewisburg was the only well driller willing to release information, and this was minimal. Approximately forty wells had been drilled in central Monroe County by this driller. It was necessary for the author to collect additional well information from the well owners themselves. All wells known to the author were inventoried.

The first set of well water samples collected for chemical analysis were taken in the fall of 1974, with fall being the driest season in the study area. A total of 76 water samples were collected in a ten week period. Wells were chosen for sampling in such a manner as to get a large aerial spread for each aquifer. Time limitations prohibited sampling every well. A second set of samples were collected during the next spring (1975) season.

Eleven wells were not resampled then, due to lack of owner permission or disuse of the wells. Nine new wells were sampled in that spring. A total of 118 wells were inventoried for basic physical characteristics during the two sampling periods. These parameters are well depth, depth to water, driller, yield, and elevation of the well. The purpose of the two sampling periods was to look for overall seasonal variation in water levels and ground water geochemistry. The physical well data can be found in Appendix B, while the chemical data (to be discussed in Chapter IV) is in Appendix C. Chisholm and Friel (1975) inventoried 16 wells in the study area for physical characteristics as part of a U.S. Geological Survey report on the New River Basin. Seven of the wells were sampled for chemical analysis of their water. Fourteen of their wells were resampled by this author. Water levels of three of these wells are included in this report (Appendix B); other water levels were remeasured by the author.

Aquifer Distribution of Wells

The results from the well data collection show that there are three major aquifers within the Greenbrier Limestone. These all occur startigraphically just above or just below a shale unit. If an aquifer occurs below a shale, the ground water is confined and rises in the well above the top of the aquifer. Most of the inventoried wells indicate confined aquifers. Going up the stratigraphic column, the three major aquifers are the Hillsdale-Maccrady aquifer, the Patton-Taggard aquifer, and the Union-Greenville aquifer. There is also a minor aquifer in the Sinks Grove Limestone that is confined but is of only local importance.

The stratigraphic distribution of surveyed wells shows that 47 wells are in the Hillsdale-Maccrady aquifer; 43 wells are in the Patton-Taggard aquifer; 14 wells are in the Union-Greenville aquifer; 11 wells are in the Sinks Grove aquifer. One well was found to receive water from the stream alluvium of Second Creek. Two wells were located in caves.

Pumping Tests

An estimate of aquifer productivity was made in the study area by five pumping tests. Only five well owners would allow their wells to be used for the test. Two parameters were used to evaluate the aquifers: (1) specific capacity and (2) transmissivity. All tests used a single pumping well with no observation wells nearby to determine these test parameters.

Specific capacity, or gallons per minute pumped per foot of drawdown, is determined by the formula:

$$C = Q/s \tag{1}$$

in which C is the specific capacity, Q is the average pumping rate in gallons per minute, and s is the drawdown during pumping (Wenzel, 1942). In the pumping tests performed in Monroe County, each well was pumped for 10 minutes, with the drawdown measured at the end of each minute of pumping. The drawdown or water depth was then periodically measured for the next forty minutes, to determine the rate of well recovery after the pump was shut off. The specific capacity gives a better estimate of well productivity than well yield in gallons per minute alone.

Transmissivity is an indication of the permeability of an aquifer. It was determined by the following formula (Wenzel, 1942):

$$T = \frac{264\ Q}{s} \log_{10} t/t' \qquad (2)$$

where T is the coefficient of the transmissivity in gallons per day per foot of aquifer width, Q is the pumping rate in gallons per minute, s is the drawdown in feet, t is the time in minutes since pumping began and t' is the time in minutes since pumping stopped. This formula assumes that the coefficient of storage (S) remains constant during and after well pumping. In reality this does not occur. Jacob (1963) discusses this problem and offers correction methods by the equation

$$T = 264\ Q\ (\log_{10} t/t') - \log_{10} (S/S') \qquad (3)$$

where S is the coefficient of storage before pumping and S' is the coefficient of storage after pumping. The graphic plotting of s versus the common log ratio of t/t' can be expressed by the equation Jacob (1963)

$$\text{Slope} = \Delta s/\Delta \log_{10} (t/t') \qquad (4)$$

After determining the slope of the line, the coefficient of transmissibility can be calculated by (Wenzel, 1942)

$$T = 264\ Q/\text{slope} \qquad (5)$$

Since the coefficient of storage does not remain constant, the plotted slope line does not pass through the origin. Therefore, the calculated T is only a rough measure of the actual T (Jacob, 1963).

This method assumes that the residual drawdown at a certain time after pumping has stopped, "will be the same as if the discharge of the well had continued but a recharge well with the same flow had been introduced at the same point at the instant the discharge actually stopped" (Sole, 1975). Table 4 shows the resulting data for the pumped wells.

Piezometric Maps

Piezometric maps were prepared for aquifers where enough well data were available. The sparcity of wells enabled the preparation of maps for only two aquifers in two localized areas. Plate 3 gives the location of wells used, while Appendix B gives the elevation and depth to water for the wells; these data were

Table 4

PUMPING TEST RESULTS

Well No.	Aquifer	Static Water Level (ft below surface)	s (ft)	Q	C	T
M103	Hillsdale-Maccrady	141.0	4.3	6.05	1.41	1542.6
T100	Patton-Taggard	19.2	10.4	3.62	0.35	380.2
T104	Patton-Taggard	148.8	16.7	6.12	0.37	1923.4
T121	Patton-Taggard	53.2	11.2	3.00	0.27	284.2
G100	Union-Greenville	12.6	24.0	6.00	0.25	265.9

Q: Pumping rate in gallons per minute.

C: Specific capacity in gallons per minute per foot drawdown.

T: Transmissivity in gallons per day per foot of aquifer.

s: Drawdown after 10 minutes of pumping.

utilized in preparation of the piezometric maps (Plate 4 and Plate 5) for this study.

Depth to water data were gathered from one of four methods or sources in order of reliability: (1) measurement by this author; (2) U.S. Geological Survey records; (3) well drillers; and (4) home owners. Drillers depth estimates were usually within ten feet of the depths that this author measured.

The Piezometric maps for this study are not significantly affected by seasonal fluctuation in water level. Table 5, showing the changes in water depth for three unpumped wells in the study area, indicates that measured fluctuations in ground water level are minor. Well T121, in the Patton-Taggard aquifer, fluctuated only 1.3 ft in 14 months. One deep Hillsdale-Maccrady aquifer well (M147) varied by 4.5 ft in water depth, from four depth measurements. Likewise, a Union-Greenville well that was spot checked three times showed a total fluctuation of only 2.8 ft.

Hillsdale-Maccrady Aquifer

Probably the most productive zone of the Greenbrier Limestone comprises the upper Maccrady Shale and lower Hillsdale Limestone. The average yield for this aquifer is 35 gallons per minute (gpm) with a range from 6 to 100 gpm. One pumping test (see Table 4) gave a specific capacity of 1.41 gpm/ft for well M103. The average well depth is 386 feet.

Table 5

WATER LEVELS FOR THREE MONITORED WELLS

Well T121
(Also a U.S. Geological Survey Monitored Well)

Date; 1974	Water Level*	Date; 1975	Water Level*
July 3	51.70	January 1	52.10
August 7	52.00	February 5	51.90
September 4	52.00	March 5	51.30
October 2	52.20	April 2	51.20
November 6	52.00	May 7	51.50
December 4	52.30	June 4	51.30
		July 2	51.80
		August 6	52.00
		September 3	51.90

Well M147

Date	Water Level*
October 3, 1974	281.2
February 9, 1975	277.2
April 15, 1975	276.7
June 4, 1975	280.2

Well G100

Date	Water Level*
September 22, 1974	8.0
October 13, 1974	6.0
June 5, 1975	5.2

* in feet below land surface.

A detailed description and photograph of this zone can be seen in Chapter II. This aquifer is confined above by shale units within the lower Hillsdale, and below by the thick shale zone of the middle to lower Maccrady Formation. A study by Martens and Hoskins (1948) found that the base of the Greenbrier Group is porous, consisting of sandy dolomite, dolomitic sandy limestone, and dolomitic sandstone that have been a source of oil and gas elsewhere. This porous nature for the lower Hillsdale Limestone also causes it to be a ground water aquifer in Monroe County.

The piezometric surface of the Hillsdale-Maccrady aquifer (Plate 4) shows that recharge occurs in the southeast section of the study area along the base of Little Mountain. Ground water is believed to discharge to the north either along Second Creek or the Greenbrier River at Caldwell. Outcrops of the Hillsdale-Maccrady contact along the Second Creek are at a higher elevation than the water level of two nearby wells; one of these wells is two miles south of Second Creek. This suggests that water movement is along the Hurricane Ridge syncline (Caldwell syncline of Greenbrier County) under Second Creek, discharging at Caldwell where there are lower elevation outcrops along the river. More wells are needed along Second Creek to show if the piezometric surface is indeed under Second Creek for this aquifer.

Sinks Grove Aquifer

The Sinks Grove Limestone of the Greenbrier Group is locally productive in the west and northwest sections of the study area.

Of the ten wells located in this section of the strata, no reported yields are available. This aquifer is highly friable and shaly and contains many bedding plane partings. Generally, the Sinks Grove aquifer is less shaly than the Hillsdale-Maccrady aquifer. The Sinks Grove aquifer is confined by the overlying Patton Shale. A few wells apparently indicate that the unnamed shale separating the Hillsdale and Sinks Grove acts as a lower confining unit.

Patton-Taggard Aquifer

The Patton-Taggard aquifer is probably the second most productive aquifer in the study area. This aquifer is confined under the shales of the Taggard Formation; however, some wells penetrating this unit also obtain some perched ground water from above the Upper Taggard Shale. Usually, only one or two gpm is obtained from this upper perched zone. The average yield for the Patton-Taggard aquifer wells is 23 gpm with a range of from one to one hundred gpm. The average specific capacity from three pumping tests is 0.33 gpm/ft (Table 4).

Figures 7 and 8 in Chapter II show detailed stratigraphic sections of this aquifer. The upper Patton Limestone is a very sandy and porous unit near the top. There are also several thin shaly units with many bedding plane partings. Although probably not as productive as the Hillsdale-Maccrady aquifer, this zone has an average well depth of only 227 ft. Shallower wells make this aquifer more economically advantageous for a water supply but more susceptible to contamination than the Hillsdale-Maccrady aquifer. The piezometric surface (Plate 5) shows that this aquifer is recharged along the limbs of the Hurricane Ridge syncline in the northern section of the field area. This syncline plunges southwest, controlling water movement and discharge in that direction.

Union-Greenville Aquifer

The Union-Greenville aquifer has been important only around the community of Salt Sulphur Springs. This area has a shallow water table due to its close proximity to Indian Creek, which acts as the local base level and ground water discharge zone. Wells drilled into this aquifer in other parts of the county are seldom productive. Around Salt Sulphur Springs, ground water is confined below the Greenville Shale. Two wells in this area are flowing wells. The average well depth for this area is only about 125 ft; many wells have become contaminated, in part because of the shallow ground water. A few wells that were drilled into the exposed Union Limestone to the north of Salt Sulphur Springs had to go deeper for water to the lower Union or Pickaway Limestone. Two wells show yields of 12 and 15 gpm for this aquifer. One pumping test for well G100 gave a specific capacity value of 0.25 gpm/ft (Table 4). Too few wells exist to enable the preparation of a piezometric map for this aquifer.

Relationship of Caves to Aquifers

Although caves act as important avenues of ground water movement, the well inventory has shown that there are non-cavernous aquifers within the Greenbrier Limestone that are independent of the solution conduits. Figure 39 shows a schematic representation of the relative positions of the Patton-Taggard aquifer, the Hillsdale-Maccrady aquifer, the piezometric surface of each aquifer, and the Dickson Spring conduit drainage system. The piezometric surfaces to not correspond to levels of cave streams, in most cases.

The elevation difference between the siphon in Rehobeth Church Cave and the water level in two nearby wells is over 100 ft. In the northern part of the study area the piezometric surface of the Hillsdale-Maccrady aquifer may be below the level of the Dickson Spring drainage system. Wells are sparce near Second Creek making it difficult to estimate the level of the piezometric surface.

Leakage from the caves to the aquifers or vice versa is believed to be negligible due to the intervening shale units. Therefore, the two types of karst aquifers (diffuse and cavernous) must be treated as independent systems with differences in flow regimes and ground water quality.

Relationship of Well Yields to Photo-Lineaments

Whether or not photo-lineaments have a strong effect on the yields of nearby water wells has been a subject of debate and controversy. Lattman and Parizek (1964) and Siddiqui and Parizek

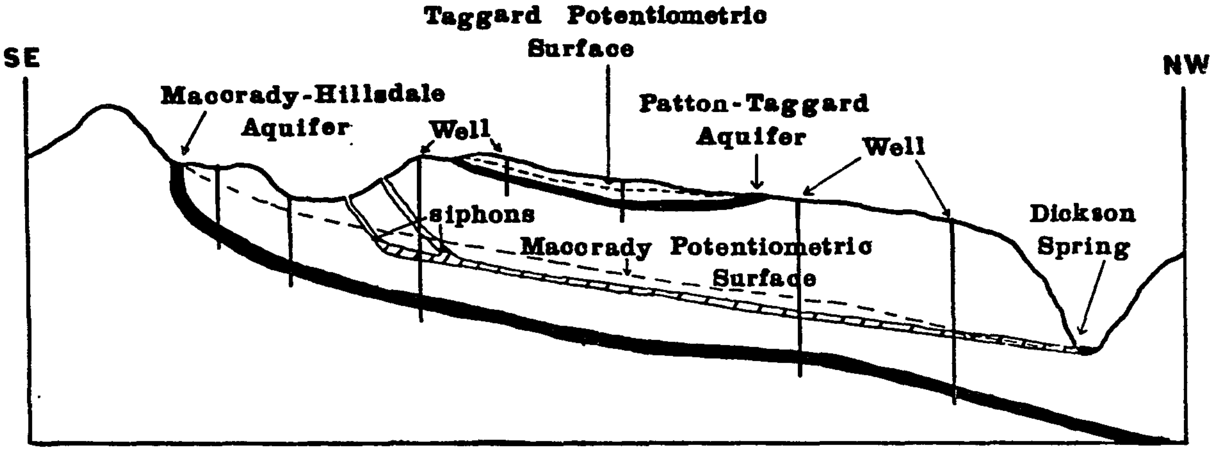

Figure 39. A schematic diagram showing the relationship of aquifers and spring drainage conduit systems.

(1971) have shown that wells near fracture traces have significantly higher yields than other wells in the carbonates of Nittany Valley, central Pennsylvania. Parizek (1976) states that a relationship can be found between well yields and large photo-lineaments for the Gatesburg Dolomite in central Pennsylvania but does not find a good relationship for wells in Limestone. He defines photo-lineaments from Landsat and/or Skylab photographs and assumes a one km wide belt of influence. In no case does Parizek statistically test the two parameters for a significant relationship. LaRiccia and Rauch (1976) have shown a good relationship in the Frederick Valley of Maryland. LaRiccia (oral communication, 1976) has found a similar positive relationship in the Lebanon Valley of Pennsylvania.

Meisler (1963) found that well yields were not related to lineaments in the Lebanon Valley of Pennsylvania. Meiser (oral communication, 1976) states that in the Altoona area of Pennsylvania, he has found little evidence for a relationship. He also describes several instances where Parizek has been unable to locate good producing wells along photo-lineaments. Whiteside (oral communication, 1976) has found little relationship between the two in the flat-lying Mississippian carbonates of Kentucky and Tennessee. Finally, LaRiccia (oral communication, 1976) has tenatatively shown that well yields are not statistically related to fracture traces in the Hagerstown Valley of Maryland.

A relationship between well yields and lineaments was tested by the author for central Monroe County. Due to the lack of state laws requiring water well reports from well drillers in West Virginia, there is little good yield information available from reports or files. Well yield (gpm) data were collected from drillers' personal records and memory. Only 19 Hillsdale-Maccrady wells and 21 Patton-Taggard wells have yield information available. The Patton-Taggard and Hillsdale-Maccrady aquifers were both tested for lineament-well yield relationships by the Fisher exact probability test (Siegel, 1956). This nonparametric test determines the probability of a significant relationship or trend being present for the contingency table shown in Figure 40. Wells are classified as being high or low producers (based on median yield) and near or far from the nearest photo-lineament. Two types of tests were performed: (1) wells less than 100 ft versus wells greater than 100 ft photo-lineament; and (2) wells less than 200 ft versus wells greater than 200 ft from the nearest photo-lineament. Once the contingency tables are constructed, the following formula is used to calculate the Fisher exact probability (Siegel, 1956):

$$P = \frac{(A + B)!(C + D)!(A + C)!(B + D)!}{N!A!B!C!D!} \qquad (6)$$

where P is the alpha probability of a significant relationship, and A, B, C, and D are the number of wells in the respective table categories (Figure 40). N is the sum total of A, B, C, and D.

		WELL YIELD	
		LESS THAN 20 GPM	GREATER THAN 20 GPM
LINEAMENT PROXIMITY TO WELL	LESS THAN 100′	[A] 3	[B] 4
	GREATER THAN 100′	[C] 6	[D] 6

Figure 40. An example of a contingency table for the Fisher exact probability test. This cell tests well yields versus well proximity to photo-lineaments for the Patton-Taggard aquifer, with number of wells indicated in each table or cell category.

The results of the tests are shown in Table 6. In all cases, there are few high producing wells on photo-lineaments. The calculated P values are all much higher than the alpha 0.05 value chosen to indicate statistical significance. The highest alpha probability of 0.43 indicates that there is a high probability of getting the observed pattern of well occurrence, by chance, and the null hypothesis of there not being a relationship can therefore not be rejected.

The explanation for the lack of associations between photo-lineaments and well yields in this study could possibly be due to one or more reasons. First, there were only gallons per minute well yield data available, whereas other researchers have usually tested more reliable specific capacity (gpm/ft) or specific capacity index (gpm/ft/ft) data for well productivity. Secondly, the study area is not as intensely deformed as the Valley and Ridge province to the east and northeast, where fracture zones may show up better as photo-lineaments or may represent wider zones of influence on ground water movement and well yields. Another reason may be one of lithologic differences; the Ordovician and Cambrian carbonates of the Valley and Ridge province have a higher percentage of dolomite and hence wells in dolomite, whereas there is little dolomite in the Mississippian carbonates of the study area. Most studies showing significantly higher yields for near-lineament wells have been done in the Valley and Ridge province. Finally, there is the problem of an individual defining

Table 6

Results of the Fisher Exact Probability Test Comparing Well Yield and Proximity of Nearest Photo-Lineament

Data Tested for well nearest to Photo-Lineaments	Number of Wells in Each Cell				Alpha Probability
	A	B	C	D	
	Patton-Taggard Aquifer				
Wells less than 100' vs Wells farther than 100'	1	2	6	6	0.43
Wells less than 200' vs Wells farther than 200'	4	5	6	6	0.20
	Maccrady-Hillsdale Aquifer				
Wells less than 100' vs Wells farther than 100'	3	1	6	5	0.37
Wells less than 200' vs Wells farther than 200'	4	3	6	5	0.37

lineaments from photographs. A liberal mapper of photo-lineaments will find more photo-lineaments in a given area and thus will have more wells located near them. A higher number of lineaments increases the chances of a single lineament not representing a fracture zone, which could dilute any actual relationship between well yields and lineament proximity. Finally, Kulander and Dean (oral communication, 1976) have found many of the photo-lineaments in the area not to be joint swarns. More research is needed to resolve the fact that photo-lineaments are demonstrated to influence well yields in some carbonate terrains but not in others.

AQUEOUS GEOCHEMISTRY

Selected Literature Review

In recent years that have been many studies pertaining to the geochemistry of carbonate waters. Back (1963) and Back and Hanshaw (1970) have worked with the spatial variations of carbonate waters in Florida. Jacobson and Langmuir (1971 and 1974) investigated the controls on the quality variations of some carbonate spring waters in central Pennsylvania. They found discharge to be more important in controlling spring chemistry than season. White and Stellmack (1965) and Shuster and White (1971 and 1972) have studied the seasonal effects on springs in central Pennsylvania. They have found that diffuse and conduit springs can be distinguished by the variation of chemical parameters due to seasonal effects. Thrailkill (1972) and Hess (1974) have studied karst springs in central Kentucky and have found both seasonal and discharge effects on spring water chemistry.

Carbonate well water geochemistry has been investigated in central Pennsylvania by Jacobson and Langmuir (1971) and Langmuir (1971). They have demonstrated the controls of carbonate rock solution and water saturation through the theoretical treatment of relationships between Pco_2, pH, and HCO_3^- content. Jacobson, et al. (1971) have used R-mode factor analysis of carbonate well waters to show relationships among chemical variables. Drake and Harmon (1973) have been able to discriminate between six carbonate water environments on the basis of the calcite saturation index and equilibrium carbon dioxide partial pressure. Nutter (1973) has compiled a great deal of information on the well waters in carbonates of western Maryland. He found aquifers to be primarily diffuse with a wide range in well yield and ground water quality.

In West Virginia, Hobba, et al. (1973) have studied carbonate well and spring waters in the Potomac River basin. Werner (1976) has worked with seasonal geochemical differences in springs of Pocahantas County, West Virginia, and has distinguished between diffuse and conduit springs from ground water geochemistry. Rauch and Jones (oral communication, 1976) have studied geochemical seasonal and discharge differences of springs in Greenbrier County, West Virginia. Finally, sixteen wells and three springs have been sampled in central Monroe County by Chisholm and Friel (1975) as part of a New River basin study. This was a basic data collection report with few geologic or geochemical interpretations.

Methods of Chemical Analysis and Data Reduction

Chemical variables were measured both in the field and in the laboratory. Temperature, specific conductance, and pH were measured in the field at each collection station. Temperature was measured by a pocket mercury thermometer in degrees Celcius to the nearest 0.1 degree, with an estimated precision of ±0.2

percent in precision at lower conductances. Error increased with higher specific conductance values due to problems of interpolation. Two correction curves were prepared for the meter during the 13 months of sampling, by plotting the known conductance of standard NaCl solutions with meter readings. The pH was measured with a Beckman model N-2 field pH meter using a Thomas Company combination electrode. The meter was calibrated with standard pH 4 and 7 buffers before each measurement and was corrected for water temperature. The pH was read to the nearest 0.01, and measurements are precise within ±0.05.

During each sampling period water samples were usually collected within ten hours of each other. Quart samples were taken using plastic containers. Each container was filled so as to eliminate all of the trapped air.

Bicarbonate titrations were performed within 24 hours of sampling on 50 ml pipeted samples using the methods of Langmuir (1971). Before titration, lab pH was measured and compared to field pH. The lab and field pH usually differed by less than 0.1. Weak hydrochloric acid (.01-.05 N) was added to each sample until the pH dropped to about 4; pH and ml of acid added were then recorded to produce titration curves for detection of the inflection point. The mls of acid corresponding to the inflection point were then used to determine the bicarbonate concentration. The inflection points of the curves usually occurred around pH 4.5.

The remaining portions of water samples were then acidified by adding one drop of concentrated sulfuric acid, after each bicarbonate titration. Two water samples were taken in the field when sulfate was to be tested, with only one being acidified. The water samples were then tested in the laboratory for concentrations of nitrate, chloride, sulfate, calcium hardness (as mg/l $CaCO_3$) and total hardness (as mg/l $CaCO_3$).

Nitrate and sulfate concentrations were measured using 25 ml pipeted samples by the colorimetric and turbitity techniques, respectively; these tests were performed on a Hach Company DR-EL unit. The Hach Company nitrate and sulfate tests were modified and improved over the test manual instructions. First the instrument readings for individual colorimeter bottles were corrected for light transmittal differences associated with imperfections in the glass bottles. Then the Hach Company test scales were corrected by analyzing standard solutions with known nitrate and sulfate concentrations. A "reagent blank" correction was also made for each test. The precision of the nitrate analysis was within about ±10 percent, while precision for the sulfate test is somewhat better, being within ±3 percent.

Calcium and total hardness concentrations were determined by using modified Hach Company EDTA titration methods. The precision for each test using 25 ml samples, was within ±4 percent. The magnesium concentration as mg/l of dissolved $CaCO_3$ was then found by subtracting the calcium hardness from the total hardness.

The chloride concentration was determined by modified Hach Kit methods involving the titration of 100 ml samples with standard mercuric nitrate solution. The precision for chloride was ±10 percent.

Appendix A and C contain the chemical analysis data for this project for the spring and well samples respectively. Sulfate was analyzed only for the Salt Sulphur springs, for the last two months of sampling for other springs, and for the spring, 1975, well samples.

The measured chemical parameters were then punched on cards and run through a modified computer program written by Jacobson (1969) at the Pennsylvania State University. This program is listed and described by Jacobson (1973). A copy of this program can also be obtained from Rauch (West Virginia University). From this program several other useful variables were obtained. The saturation indices for calcite (SIc) and dolomite (SId) were derived along with the theoretical aqueous carbon dioxide pressure (Pco_2). Garrels and Christ (1965) and Langmuir (1971) discuss in detail the calculations involved in determining these three derived variables from the measured ones. Saturation indices of the water are calculated in the program by the following formulas:

$$SIc = \log (IAPc/Kc) \qquad (7)$$

$$SId = \log (IAPd/kd)^{1/2} \qquad (8)$$

where

$$IAPc = [Ca^{+2}]\,[CO_3^{-2}] \qquad (9)$$

$$IAPd = [Ca^{+2}]\,[Mg^{+2}]\,[CO_3^{-2}]^2 \qquad (10)$$

Kc is the dissociation equilibrium constant of calcite ($CaCO_3$) with a low degree of ion complexing (Jacobson and Langmuir, 1974). Kd is the dissociation constant of dolomite ($CaMg(CO_3)_2$) (Langmuir, 1971). This program also gave a value of percent error that gives an estimate of operator accuracy and completeness of chemical analyses. The values of percent error are calculated by:

$$\left| \frac{(\text{Epm cations - Epm aniona})}{(\text{Epm cations + Epm aniona})/2} \right| \times 100 \qquad (11)$$

Ionic strength is calculated based on the concentration of all ions by the Debye-Hückel method. These calculations are not considered valid for the Salt Sulphur Springs and a few Hillsdale-Maccrady wells where the ionic strength is greater than 0.01.

Various parametric and non-parametric statistical tests were then performed on the data to help determine the spatial and temporal trends in carbonate ground water geochemistry, as well as to determine associations among the water quality variables.

Occurrence, Properties, and Sources of Chemical Parameters

Specific Conductance

Specific conductance may be the most important single variable representing overall water quality. It is a measure of the capability of water to conduct an electric current, which is in turn a measure of the concentration of dissolved solids and the degree of ionization of various dissolved chemical species. An approximate relationship exists between specific conductance and total dissolved solids (Hem, 1970). The range in specific conductance in the study area was 117 to 3105 μmhos/cm^2. The higher values were recorded for the Salt Sulphur Springs. Most values fall in the range of 250 to 450 μmhos/cm^2. A specific conductance greater than 600 μmhos/cm^2 usually indicated pollution.

Calcium and Magnesium

Calcium and magnesium (Ca^{+2} and Mg^{+2}) are the two most common cations found in the carbonate ground water of Monroe County. They are primarily derived from the dissolution of calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). In some carbonate terrains, gypsum ($CaSO_4 \cdot 2H_2O$) dissolution also contributes calcium to water. These cations are responsible for the high hardness of the carbonate water in the study area. Calcium tends to precipitate, forming $CaCO_3$ deposits in plumbing systems and scales on cooking implements (Nutter, 1973).

Dissolved calcium and magnesium are the main causes of water hardness. Hardness is noticed when an excessive amount of soap is needed to produce a lather. The following is a commonly used hardness classification (Nutter, 1973):

Hardness in mg/l as $CaCO_3$	Classification of water
0-60	soft
61-120	moderately hard
121-200	hard
more than 200	very hard

Nearly all wells in central Monroe County are very hard.

Bicarbonate and Carbonate

Bicarbonate (HCO_3^-) is the most abundant anion in unpolluted carbonate waters of the study area. This anion is primarily the direct product of the dissolution of limestone and dolomite by the action of dissolved carbon dioxide in water. Bicarbonate is generated by the following limestone dissolution equations (Hem, 1970):

$$CO_2 + H_2O \rightleftarrows H_2CO_3 \qquad (12)$$

$$CaCO_3 + H_2CO_3 \rightleftarrows Ca^{+2} + 2HCO_3^- \qquad (13)$$

$$CaCO_3 + H_2O \rightleftarrows Ca^{+2} + HCO_3^- + OH^- \qquad (14)$$

Bicarbonate and carbonate (CO_3^{-2}) together represent alkalinity in carbonate waters; however, bicarbonate is more concentrated than carbonate by several orders of magnitude for the pH range in waters of the study area (Hem, 1970).

pH

The pH of water "represents the negative base-10 log of the hydrogen ion activity in moles per liter" (Hem, 1970). The pH is affected by carbonate dissolution (equations 13 and 14) and the equilibrium state among HCO_3^-, CO_2^{-2}, and H_2CO_3. Waters with pH values below 7 may indicate the presence of sulfuric acid from pyrite weathering or dissolved H_2S gas. The range in pH for the study area was 6.80 to 8.30. Most measurements were between 7.40 and 7.80.

Nitrate

Nitrate (NO_3^-) is normally present in minor amounts in ground water because little is found in rocks and soils. Nitrate is the end product of oxidation in the nitrogen cycle of living organisms. High concentrations of nitrate may indicate pollution from sewage, barnyard wastes, or nitrate fertilizers (Nutter, 1973). The U.S. Public Health Service (1962) places a recommended limit of 45 mg/l on the nitrate concentration. Higher concentrations than this may cause methemoglobinemia (a blue babies disease) in infants. Six wells and one spring sample exceeded this limit, but several more were close to it. Most of these wells are close to stockyards.

Chloride and Sodium

Chloride (Cl^-) is a common constituent of carbonate water, but is generally found in small concentrations in central Monroe County in unpolluted wells and springs. Nutter (1973) suggests that high chloride concentrations may be related to contamination by domestic sewage. In the study area, some wells have been contaminated by the improper storage of road salts. A few wells exceed the U.S. Public Health Service (1962) recommended limit of 250 mg/l, but no springs do; water over 250 mg/l in chloride generally has a salty taste. Springs often have higher concentrations of chloride after the melting of snow and ice because of road salt spreading. Chloride in water may also be contributed by salt licks placed in meadows for cattle, but this is believed to be of minor importance.

Sodium (Na^+) was not analyzed for, but is believed by this author to be nearly equivalent to the chloride concentration in most of the samples. This is probably not the case for the Salt Sulphur springs and polluted wells. Sodium is usually in the form of the Na^+ ion when the total solids concentrations are below 1000 mg/l as are most of the samples (Hem, 1970). Sodium is commonly derived by cation exchange (Ca^{+2} and Mg^{+2} for Na^+) on clay minerals within shales and shaly limestones. The primary pollution source of sodium in the study area is from the use and storage of road salt.

Iron

Iron occurs in the Fe^{+2}, Fe^{+3}, and complexed hydroxide states when dissolved in water, although it readily precipitates to form $Fe(OH)_3$ (Hem, 1970). It can be derived from pipes, pumps, and casings of wells. Iron can also be derived from pyrite and siderite that occurs in shales and limestone. Only minor amounts of these two minerals were observed in the study area, so they are not believed to be important contributors of iron to water.

A few spot analyses were performed to test for total dissolved iron, but only a trace was present in water tested. Iron is objectionable when found in concentrations over the Public Health Service (1962) limit of 0.3 mg/l. Excessive iron in water causes staining and an unpleasant taste and color (Hem, 1970). Only one well was found to have over the health limit in Monroe County, but this well had not been pumped for several months. The higher pH of carbonate waters will cause iron precipitation, explaining the low concentrations in the study area (Krauskopf, 1967).

Sulfate

Sulfate (SO_4^{-2}) is generally in low concentration in carbonate waters, but is found in greater amounts when gypsum or pyrite are present. The U.S. Public Health Service (1962) recommended limit for sulfate is 250 mg/l. This value was exceeded by the Salt Sulphur springs' samples and some of the well samples of the Hillsdale-Maccrady aquifer. High sulfate water will often taste bitter and have a bad "rotten egg" smell from the H_2S present; it may also cause a laxative effect (Nutter, 1973).

Spring Water Chemistry

Analysis of Water Quality Trends

Each of the five springs (Dickson, Walters', Rogers', McPeaks's, and Cold Springs) and the Rehobeth Church Insurgence were sampled biweekly for 13 months (28 samples). Sprouse's Spring and the two Salt Sulphur springs were sampled monthly (14 samples). The geochemical data and discharge measurements can be found in Appendix A. The objectives of this part of the study are to: (1) explain differences in variable means, (2) explain variations among the sampling sites, and (3) interpret the nature of the ground water flow systems. The means of the variables and the coefficients of variation are found in Table 7a, 7b, and 7c. The coefficient of variation is defined as:

$$\text{Coefficient of Variation (CV)} = \sigma/u\ (100) \qquad (15)$$

where σ is the standard deviation of a measured variable, and u is the arithmetic mean. Shuster and White (1971) have shown this to be a useful parameter for numerically expressing seasonal variations of variables.

Figures 41-55 show the seasonal trends for SIc (saturation index for calcite) Pco_2, temperature, and total hardness. Some or

Table 7a

Means and Coefficients of Variation (CV) for Measured Variables at Surface Sampling Sites

	pH		Temperature (°C)		Spc. Cond. (micro mhos/cm^2		Discharge* (cfs)		Ca^{+2} (mg/l)		Mg^{+2} (mg/l)	
Spring	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Dickson	7.43	1.6	11.2	9.8	320	40.0	39.7	105	59.9	13.8	5.4	39.2
Walters'	7.85	2.0	12.0	17.5	382	9.0	9.3	163	72.0	14.5	8.2	43.2
Rogers'	7.84	2.3	11.6	8.9	328	8.0	3.8	405	64.2	9.9	5.8	52.9
McPeak's	7.58	2.9	11.8	16.9	483	17.0	0.2	114	87.5	19.2	2.3	53.2
Cold	7.84	2.8	12.6	29.4	399	11.0	0.8	112	64.7	15.9	4.7	32.8
Rehobeth+	7.84	3.8	12.1	49.8	352	49.0	0.6	166	56.6	51.2	13.8	62.3
Sprouse's	7.81	3.8	12.1	37.2	399	16.1			72.7	19.7	3.6	40.2
Salt Sulphur South	7.03	2.0	14.2	46.6	899	32.3			153.8	38.4	10.5	23.2
Salt Sulphur North	7.12	1.9	12.4	46.6	2120	41.9			300.0	40.0	58.9	25.0

*Discharge was not measured at Sprouse's, Salt Sulphur South, or Salt Sulphur North.

+The Rehobeth Insurgence is the only non-spring of the surface sampling site.

Table 7b

Means and Coefficients of Variation (CV) for Measured Variables at Surface Sampling Sites

	HCO_3^- (mg/l)		Tot. Hard. (mg/l as $CaCO_3$)		Cl^- (mg/l)		NO_3^- (mg/l)		SO_4^{-2} (mg/l)		SIC¢	
Spring	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Dickson	175	16.2	172	8.1	4.7	10.6	9.3	29.0	18.4	20.9	-0.17	64.7
Walters'	215	28.2	200	10.2	7.2	23.6	7.9	29.1	12.1	25.0	0.43	34.9
Rogers'	193	34.0	181	8.3	0.9	20.5	9.2	26.1	7.4	12.0	0.32	62.5
McPeak's	246	14.3	237	18.6	12.4	58.3	14.0	37.4	35.3	10.5	0.39	85.7
Cold	171	20.1	181	13.1	29.3	27.3	13.4	32.1	15.1	11.4	0.29	93.1
Rehobeth+	212	50.5	198	46.5	3.2	43.8	2.4	87.5	41.8	72.7	0.26	280.8
Sprouse's	204	21.3	196	19.4	10.9	11.9	16.5	26.1	20.5	10.5	0.35	120.0
Salt Sulphur South	324	75.4	415	23.3	35.0	25.2	2.3	90.7	230.1	42.4	0.04	101.2
Salt Sulphur North	275	86.9	991	45.8	41.7	26.4	2.9	95.3	1021.1	49.6	0.30	90.0

+The Rehobeth Insurgence is the only non-spring of the surface sampling sites.

¢Saturation index for calcite.

Table 7c

Means and Coefficients of Variation (CV) for Measured Variables at Surface Sampling Sites

Spring	SID*		Pco_2¢		Ca/Mg		Mean
	Mean	CV	Mean	CV	Mean	CV	Vc/VC
Dickson	-0.65	64.7	-2.27	7.9	7.95	54.7	10.6
Walters'	-0.28	54.1	-2.60	6.9	11.0	55.6	8.2
Rogers'	-0.20	12.5	-2.63	8.3	12.6	55.2	10.5
McPeak's	-0.54	19.8	-2.47	10.5	16.4	59.5	38.8
Cold	-0.24	10.3	-2.68	7.8	9.5	51.1	13.4
Rehobeth+	0.01	30.8	-2.70	7.8	3.0	55.4	3.2
Sprouse's	-0.26	16.9	-2.58	10.1	10.0	53.1	20.2
Salt Sulphur South	-0.66	20.1	-1.61	9.9	17.3	143.2	14.4
Salt Sulphur North	-0.10	21.0	-1.79	11.7	11.6	166.1	4.3

+The Rehobeth Insurgence is the only non-spring of the surface sampling sites.

*Saturation index for dolomite.

¢Log CO_2 pressure.

all of these variables have been used by Thrailkill (1968), Shuster and White (1971 and 1972), and Hess (1974) in their analyses of seasonal trends of chemical variables of springs.

Temperature (Figures 41-43) shows the most marked seasonal variation with the lowest temperatures usually occurring about the end of January. Maximum spring and stream temperatures are usually during July and August. Surface waters such as the Rehobeth Church Insurgence and Sprouse's Spring show high temperature fluctuations, as evidenced by their coefficients of variation (C.V.'s, Table 7a). The Salt Sulphur springs have the highest C.V.'s because of their extremely low flow rate, which allows the stagnant water to equilibrate with air temperature. Dickson and Rogers' springs have the deepest ground water drainage systems, and therefore show the most stable temperature with the lowest C.V.'s (Table 7a); these springs also probably exhibit the longest lag times between recharge and discharge events, giving the ground water more time to equilibrate in temperature. Cold, McPeak's, and Walters' springs are known to have shallow drainage systems, and therefore have temperature C.V.'s between those for Dickson and Sprouse's springs.

Figures 44-47 show the seasonal trends in Pco_2 for the sampling sites. The Salt Sulphur springs have the highest Pco_2 mean values (Table 7c), probably in part because of their low pH values from the sulfuric acid generated by pyrite oxidation in the Greenville Shale, and also partly because of organic material (primarily leaves) that are blown into the spring pools.

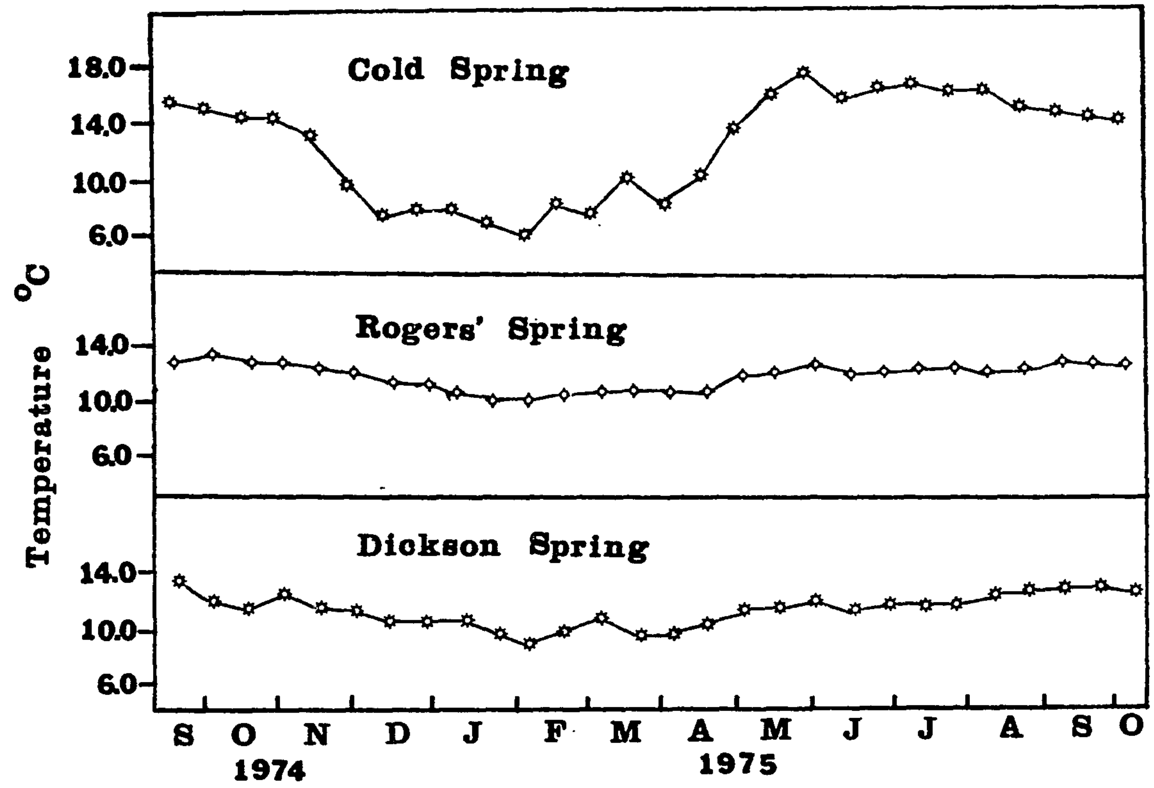

Figure 41. Time series temperature data for Dickson, Rogers' and Cold springs.

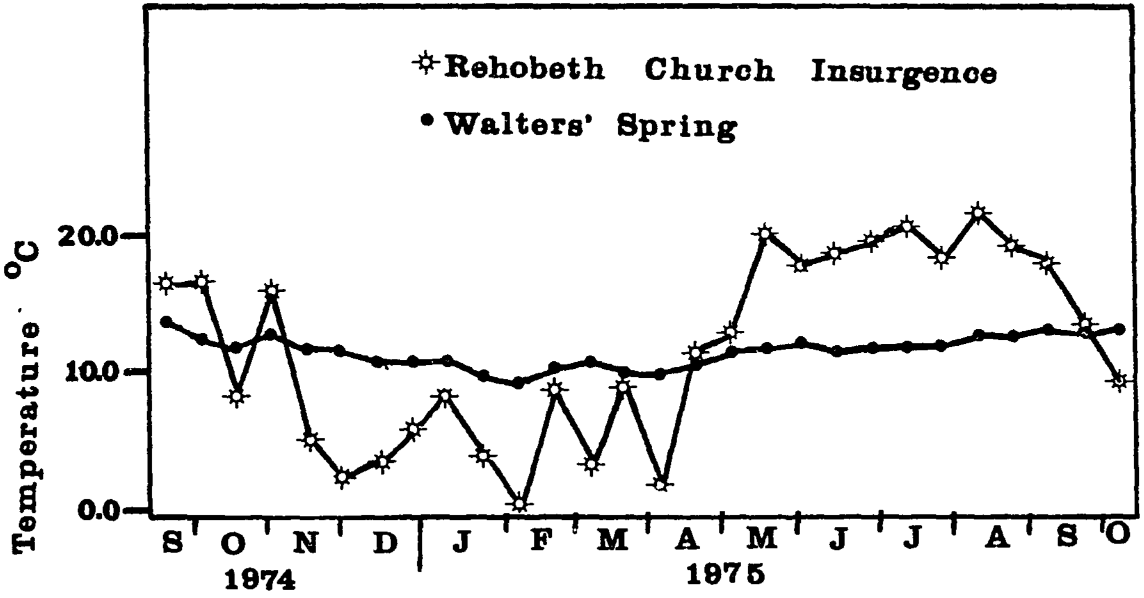

Figure 42. Time series temperature data for Walters' Spring and the Rehobeth Church Insurgence.

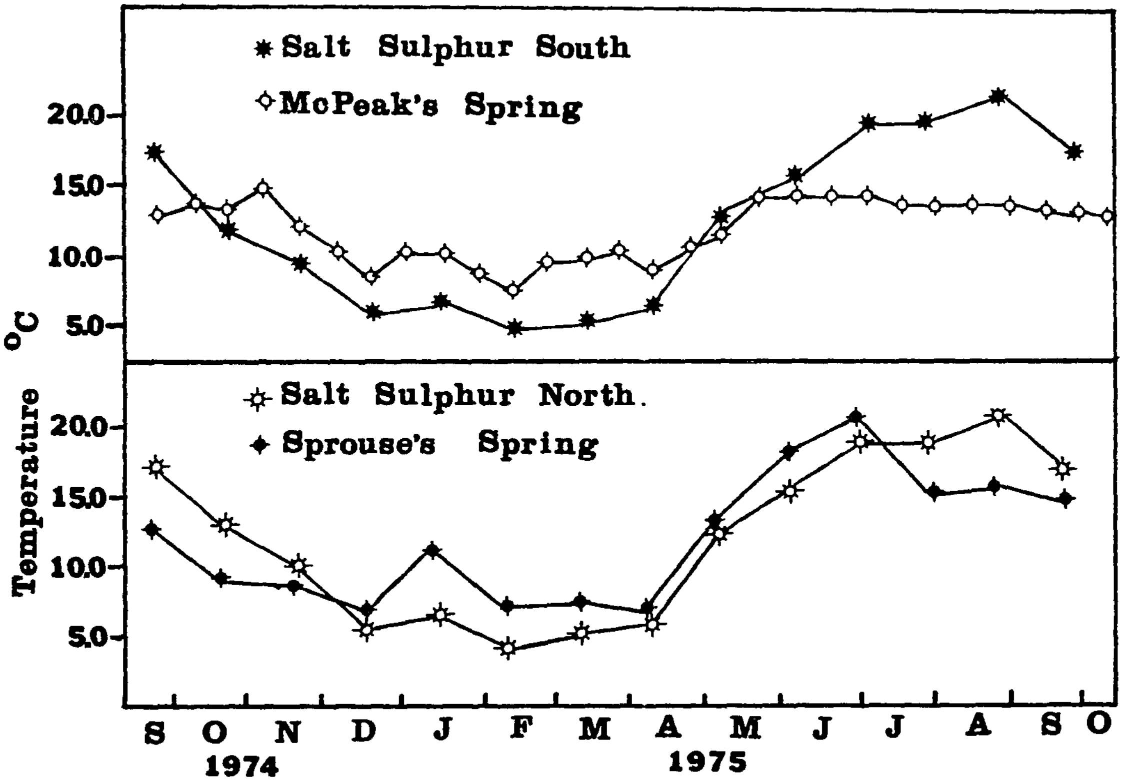

Figure 43. Time series temperature data for McPeak's, Sprouse's, and the Salt Sulphur springs.

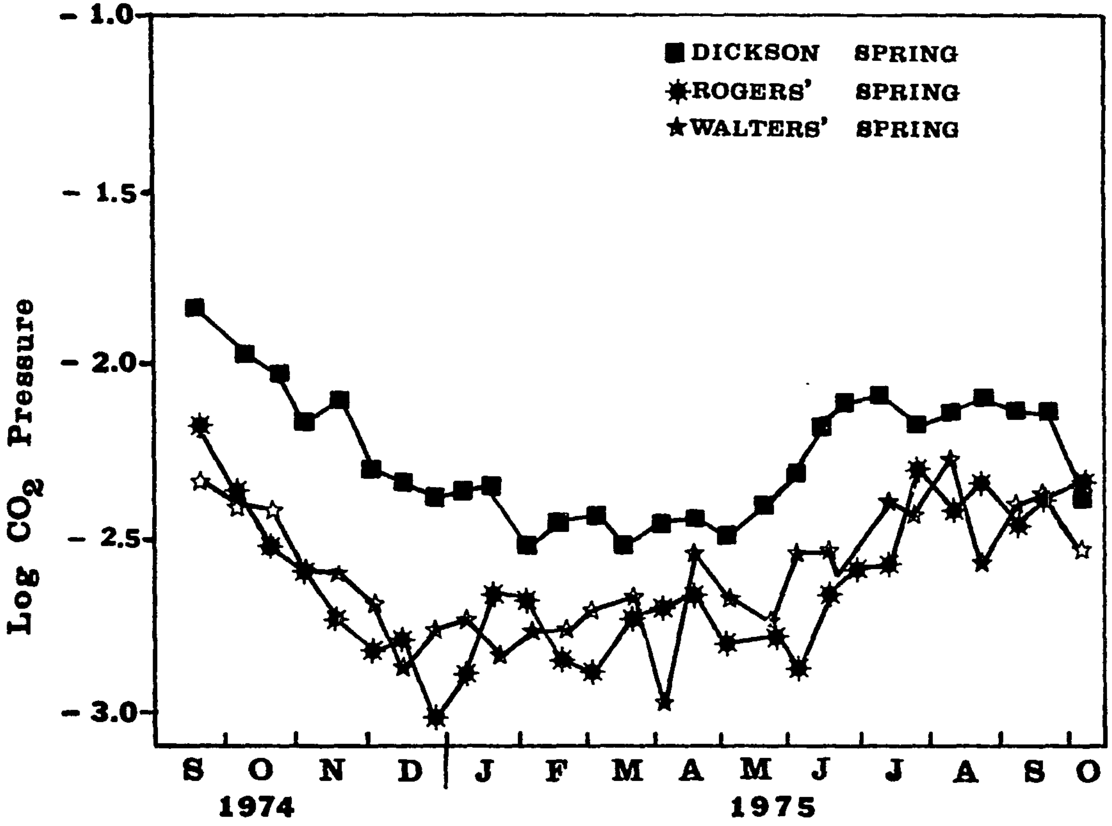

Figure 44. Time series log CO_2 pressure data for Dickson, Rogers' and Walters' springs.

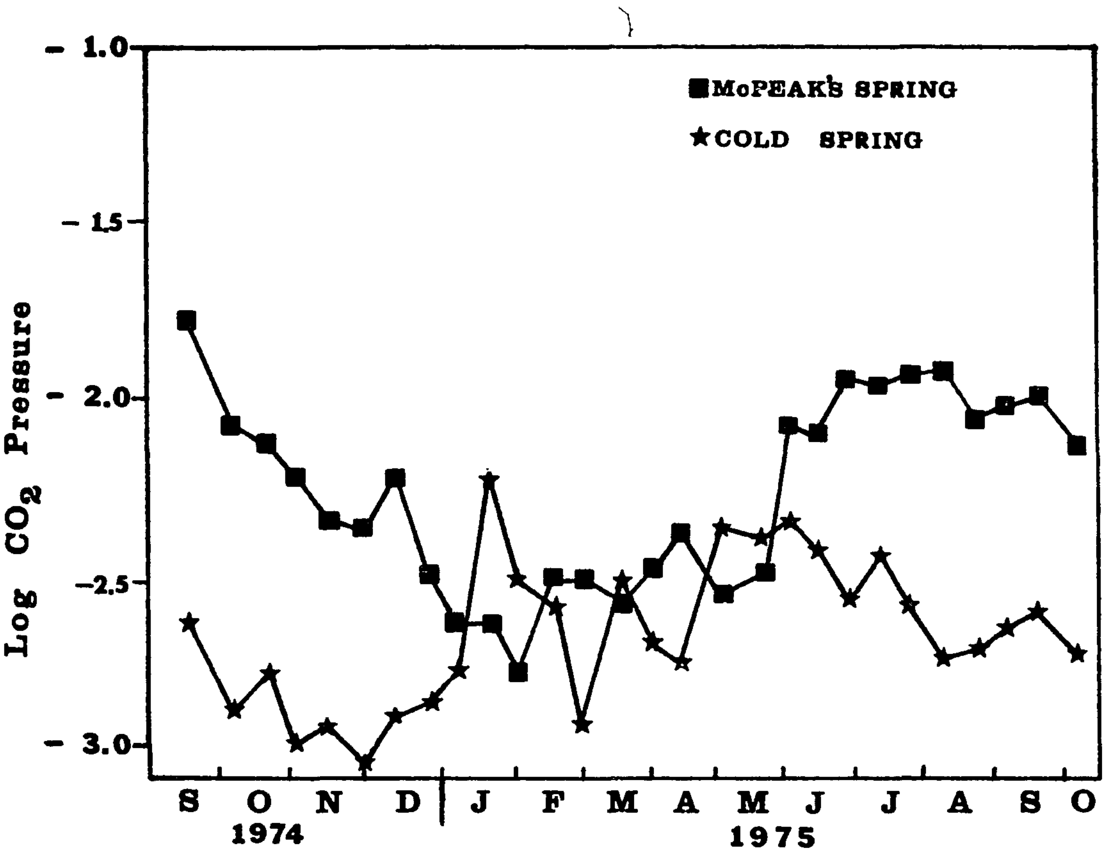

Figure 45. Time series log CO_2 pressure data for McPeak's and Cold springs.

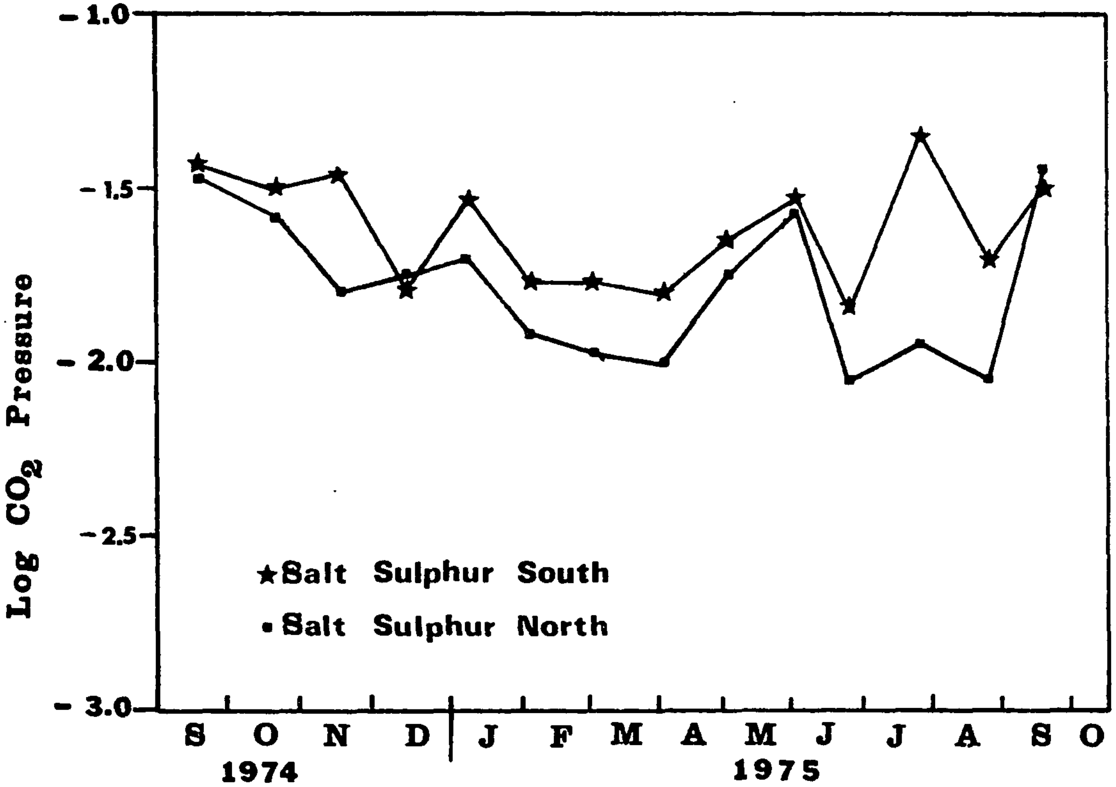

Figure 46. Time series log CO_2 pressure data for the Salt Sulphur springs.

Figure 47. Time series log CO_2 pressure data for Sprouse's Spring and the Rehobeth Church Insurgence.

Dickson Spring has the second highest Pco_2 (compared to the sulfur springs), probably because ground water has lost less CO_2 gas on its way to the spring, due to the predominant phreatic (closed channel flow) character of this drainage system. Evidence for this is that the Dickson drainage system is the deepest of those studied. The other springs and stream have lower Pco_2 values (Table 7c), probably because of partial degasing of CO_2 fo the air before resurgence.

Dickson, Walters', Rogers', and McPeak's springs all show seasonal trends (Figures 45-48), with maximum Pco_2 during the summer and minimum Pco_2 during the winter and early spring. This reflects the growing seasons and recharge through CO_2 rich soils to the ground water drainage systems. The other sites show poor (if any) seasonal Pco_2 trends. The Salt Sulphur and Sprouse's springs may have shown better trends if they would have been sampled more often. The Rehobeth Church Insurgence as well as the Salt Sulphur springs, Sprouse's Spring and Cold Spring are all flowing on or near the surface which may decrease seasonal effects. Shuster and White (1971) have found little seasonal variation of Pco_2 in central Pennsylvania springs, but Hess (1974) has found a strong relationship for central Kentucky springs.

Plots of total hardness are shown in Figures 48-51. The total hardness means are shown in Tables 7a and 7b. The Salt Sulphur springs have the highest mean total hardness values, probably due to H_2SO_4 dissolution of limestone as evidenced by

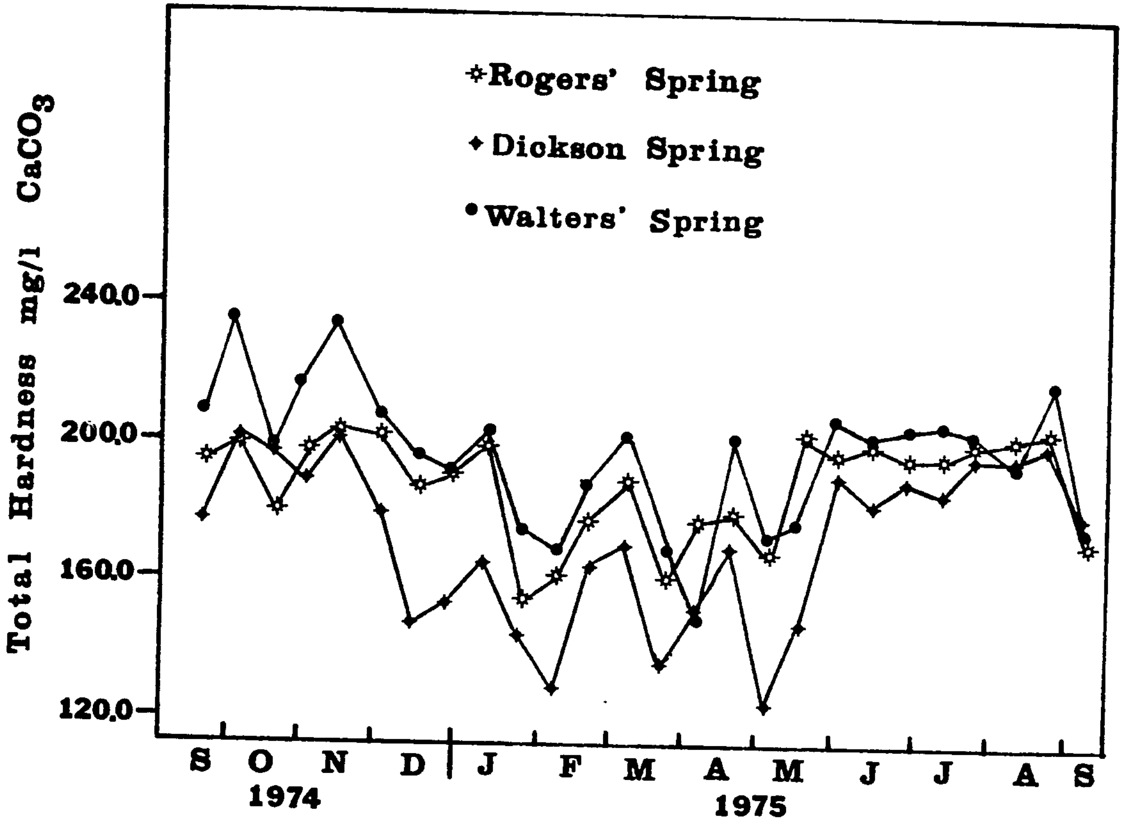

Figure 48. Time series total hardness data for Dickson, Walters', and Rogers' springs.

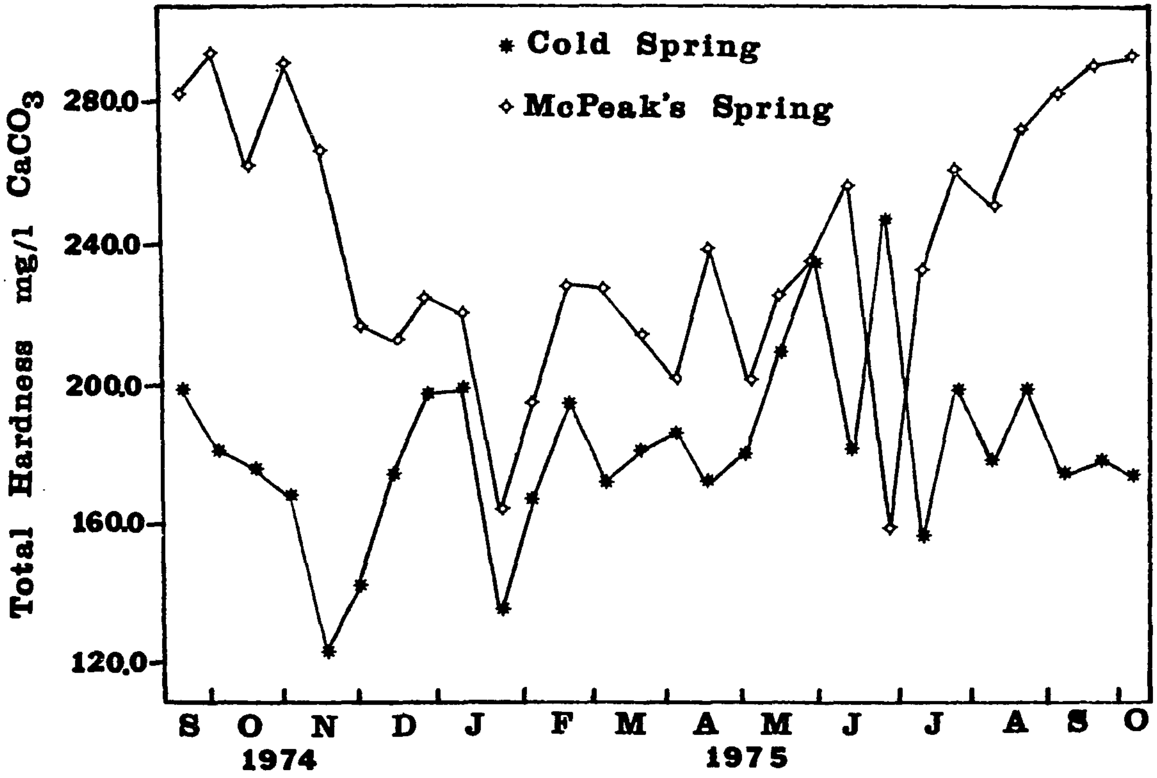

Figure 49. Time series total hardness data for McPeak's and Cold springs.

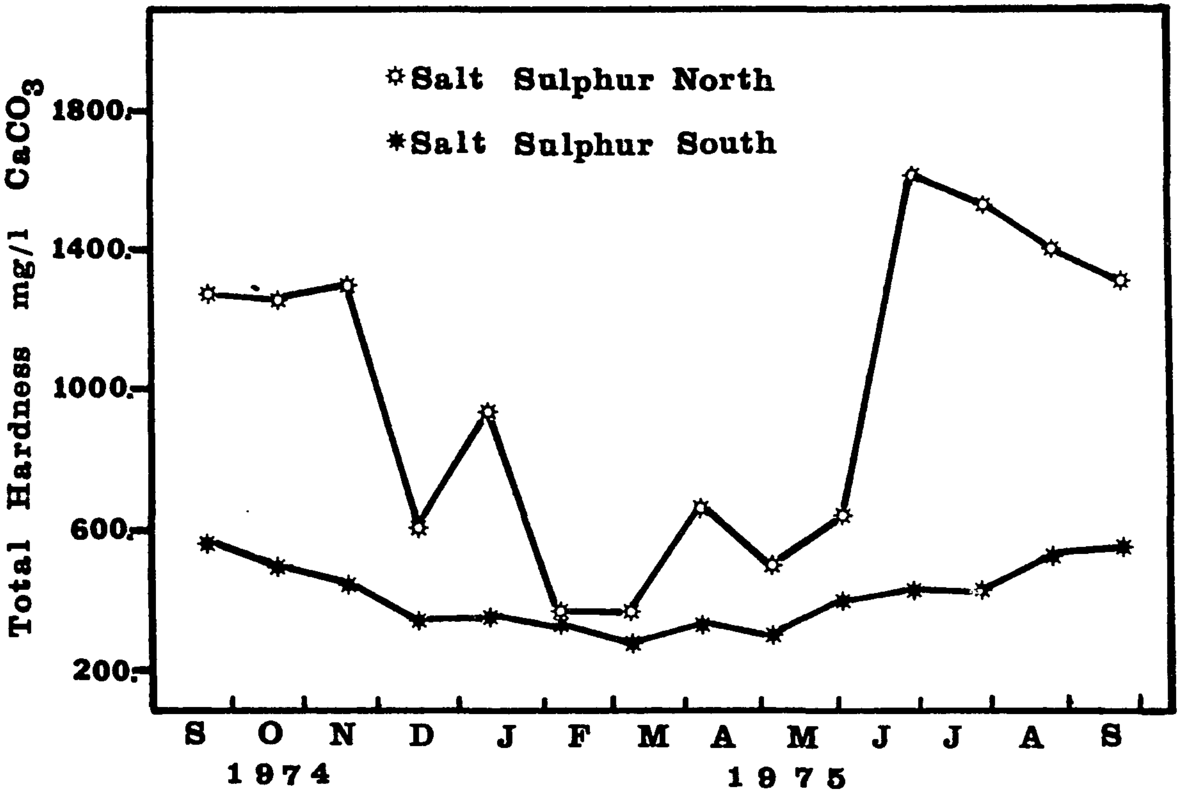

Figure 50. Time series total hardness data for the Salt Sulphur springs.

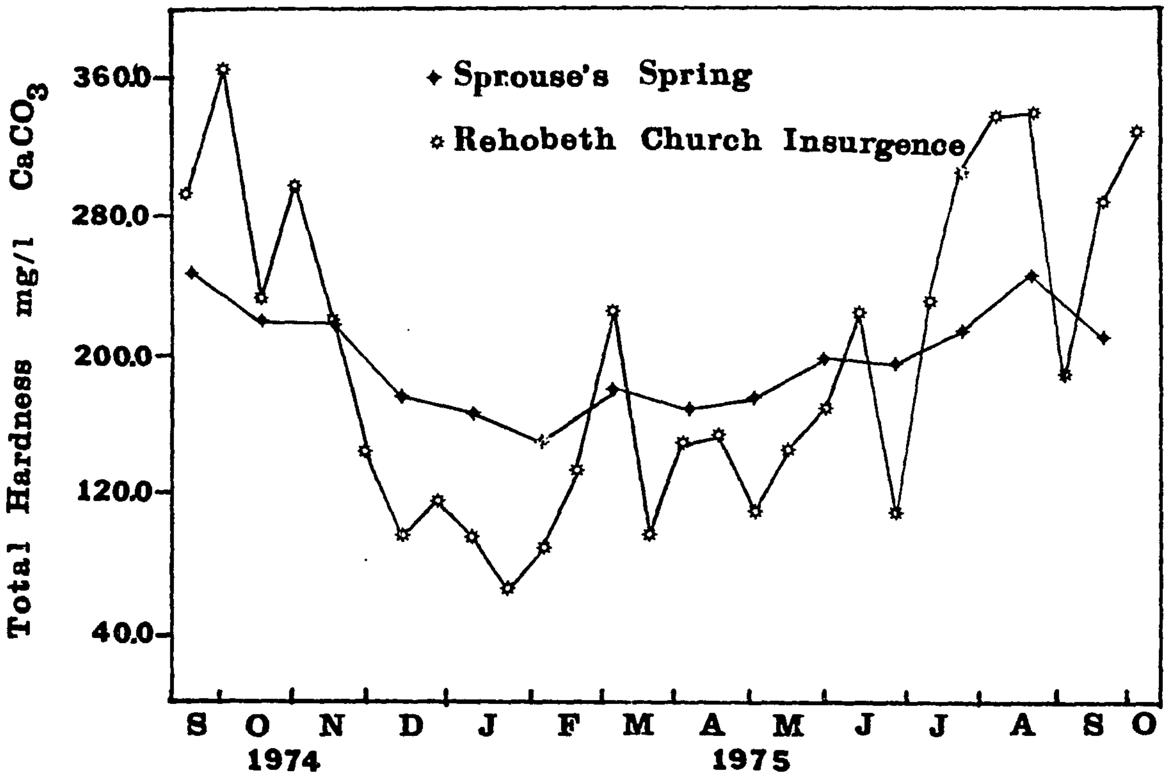

Figure 51. Time series total hardness data for Sprouse's Spring and the Rehobeth Church Insurgence.

the high SO_4^{-2} and low pH. McPeak's Spring has the next highest mean total hardness which may be due to pollution which is known to enter the drainage system. The rest of the sampling sites have similar values with differences probably due to basin size and the residence time of the water underground.

All of the sampled springs and streams except Cold Spring show definite seasonal trends. Total hardness is low in the winter and high in the summer. Such trends are explained by the seasonal temperature and Pco_2 trends. The carbonate dissolution rate is highest for higher Pco_2 values (and hence H_2CO_3 concentrations), and for higher temperatures which also affect dissolution kinetics. Cold Spring may be affected more by discharge effects that mask seasonal trends. Another explanation may be that the water entering the Cold Spring system comes from a pond where the water may have more time to equilibrate with the limestone.

The highest coefficients of variation for hardness are found for the Salt Sulphur springs. This may be due largely to the input of softer rain water into the springs after storms (which has been observed). The lower coefficient of variation for Salt Sulphur South Spring (as compared to Salt Sulphur North Spring) is probably due to the original lower hardness of the spring before dilution by rain water.

Rehobeth Church Insurgence and Sprouse's Spring have the next lowest mean hardness C.V.'s as is expected for surface waters that are more easily diluted by rainfalls. McPeak's and Cold springs have lower values than Sprouse's Spring due to the residence time underground. Dickson, Rogers', and Walters' springs have the lowest C.V.'s due to their larger basin size (longer residence times) and postulated phreatic nature as compared to the vadose nature of Cold and McPeak's springs.

Plots of SIc versus season are shown in Figures 52-55. The means and coefficients of variation for each sampling site are found in Tables 7a and 7b. All of the springs except Dickson Spring have positive mean SIc values, indicating supersaturation with respect to calcite. The computation procedure involved in determining SIc and the original data were all checked for errors in trying to explain the high SIc values. No errors were found despite careful checking. Comparison of the raw data to published data (Langmuir, 1971; Hess, 1974) also indicates that the Monroe County waters are indeed supersaturated. Possible explanations for the supersaturation may be longer residence times and/or an abundance of diffuse recharge to the drainage system, coupled with a significant loss of dissolved CO_2 gas from karst waters. Gypsum dissolution from the upper Maccrady Shale may also increase calcite saturation. Salt pollution from $CaCl_2$ applied to roads in winter may also partly explain some spring and stream supersaturation.

Walters', Rogers', and Sprouse's springs have the highest mean SIc values. Walters' and Rogers' both have longer residence times that may cause higher supersaturation. Since Dickson Spring

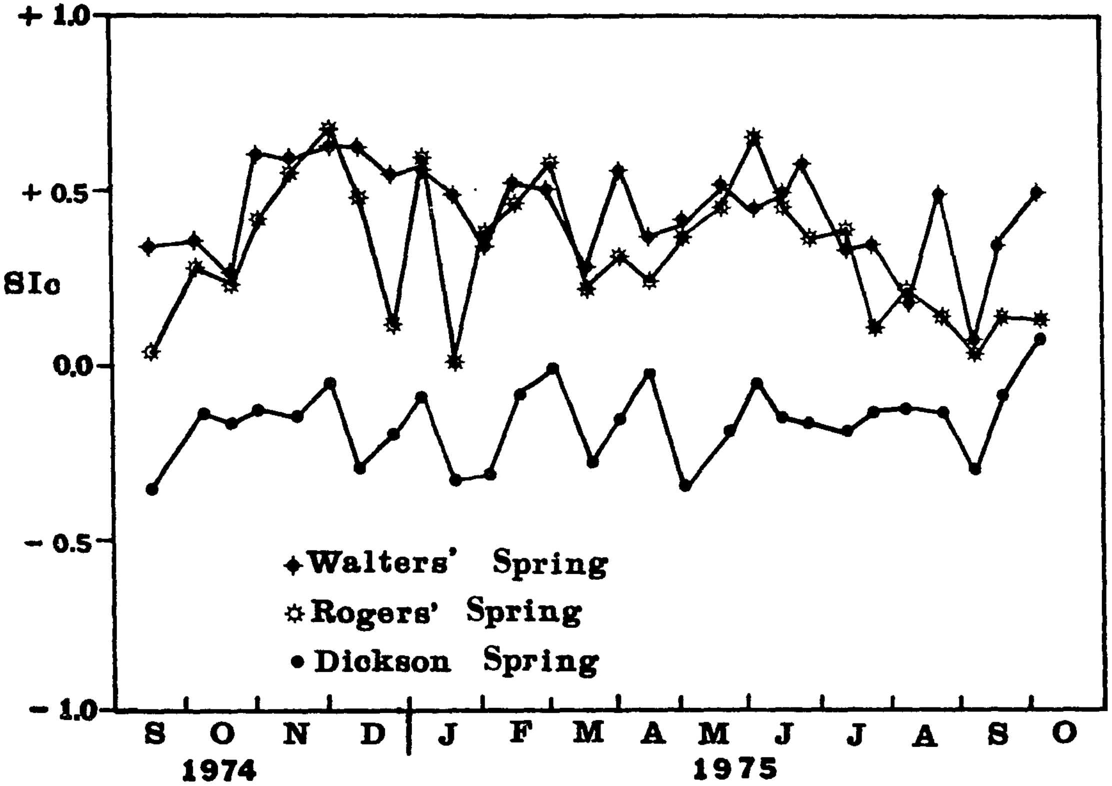

Figure 52. Time series SIc data for Dickson, Rogers', and Walters' springs.

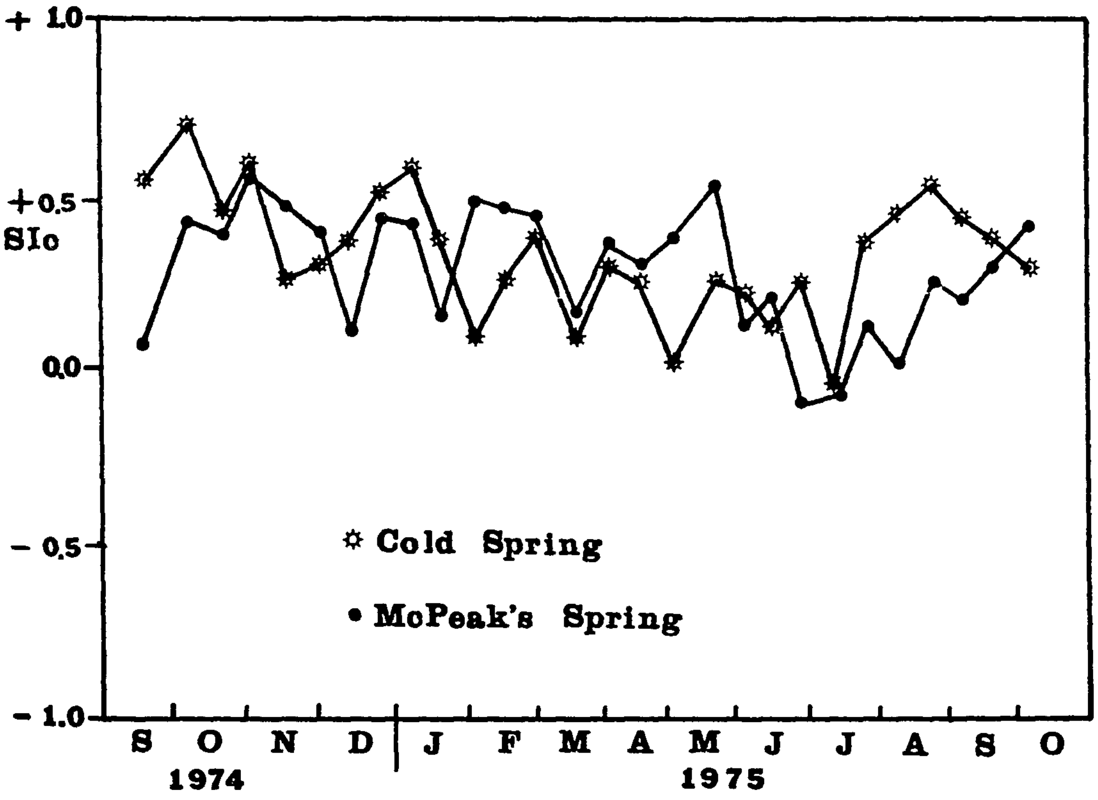

Figure 53. Time series SIc data for McPeak's and Cold springs.

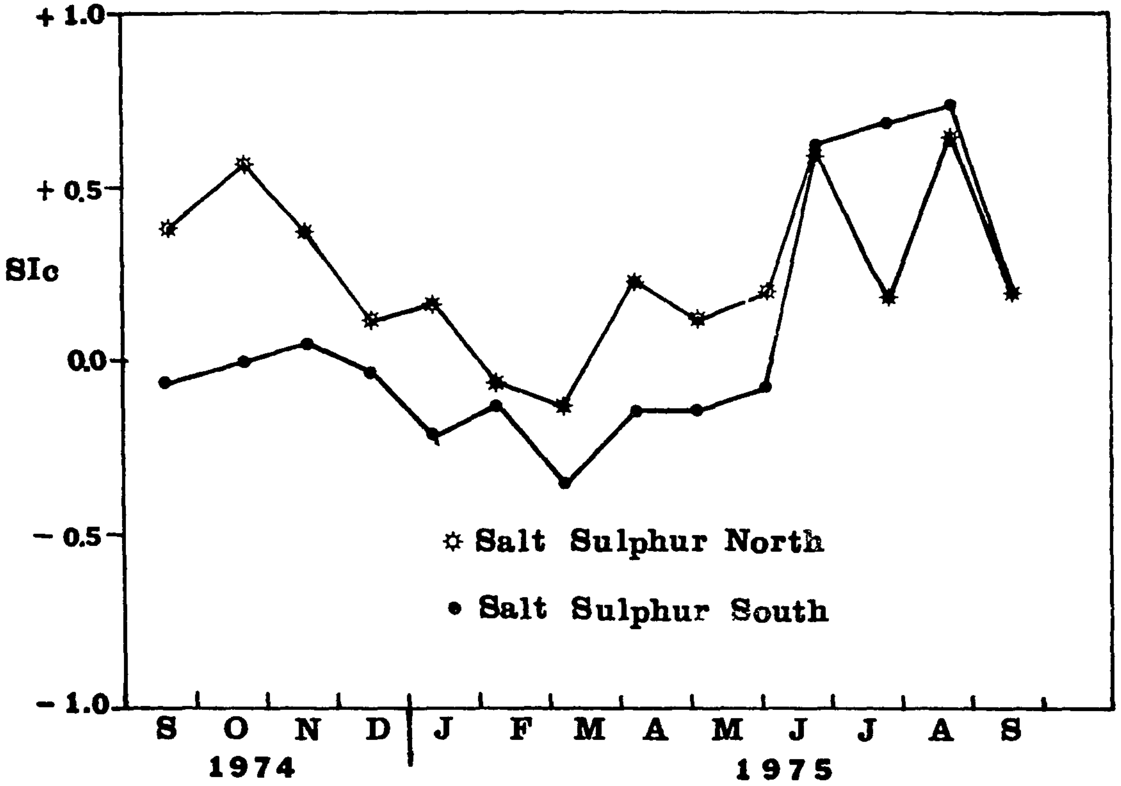

Figure 54. Time series SIc data for the Salt Sulphur springs.

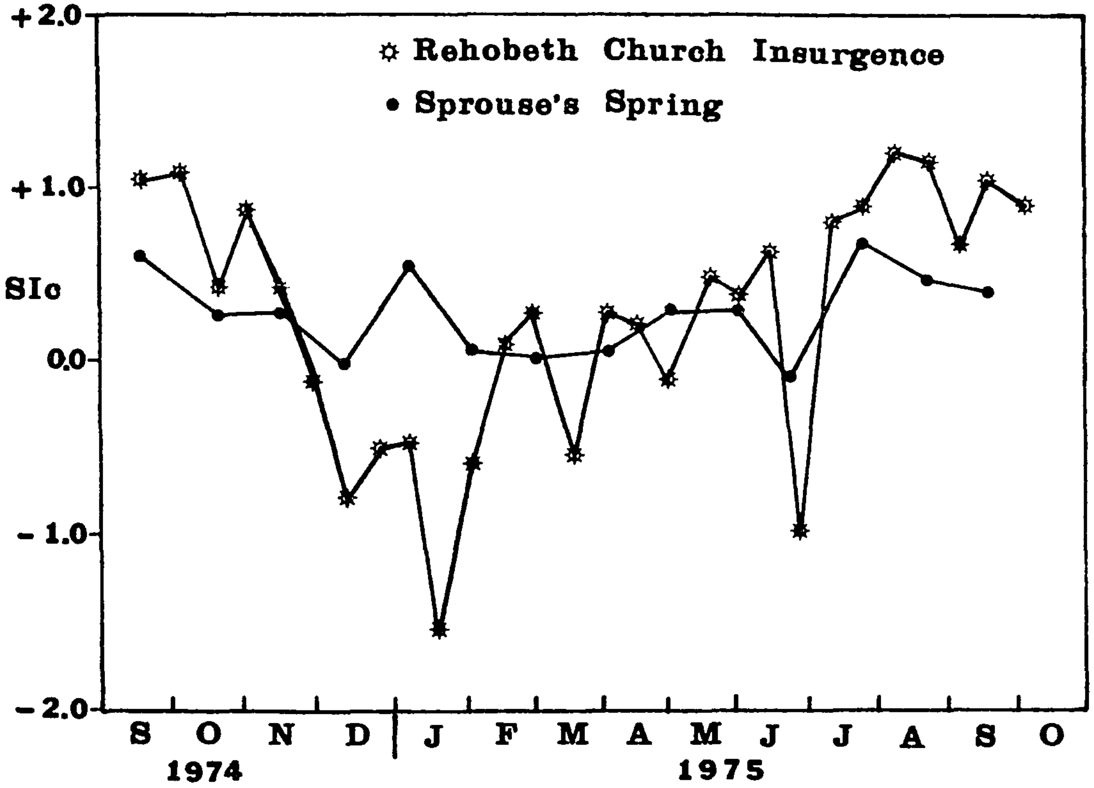

Figure 55. Time series SIc data for Sprouse's Spring and the Rehobeth Church Insurgence.

is usually undersaturated this explanation does not appear to hold. The other springs have nearly the same mean SIc values except for Salt Sulphur South Spring which has the next to lowest (Table 7b). These differences may be due to small differences in residence times and the amount of diffuse recharge.

The studied Monroe County springs have SIc values that are more similar to those of the diffuse springs studied by some researchers. Werner (oral communication, 1976) attributes his lower SIc values to the faster flow through times due to the higher karst relief. Shuster and White (1971) noted that as undersaturated spring water moves downstream and loses carbon dioxide, it approaches saturation with respect to calcite and becomes supersaturated (up to an SIc of 0.30) without depositing travertine. A similar situation may exist for Rehobeth Church Insurgence and Sprouse's Spring. Walters' Spring was usually sampled 100 to 200 ft below the spring's emergence which may have had a similar effect in increasing calcite saturation as found by Shuster and White (1971).

Little or no seasonal SIc trends appear to exist. These trends may be masked in part by discharge effects. Dickson and Walters' springs and the Rehobeth Church Insurgence have SIc values that are strongly correlated to discharge. Shuster and White (1971 and 1972) and Hess (1974) found the degree of calcite saturation of spring waters to be related to discharge.

The C.V.'s for SIc show the springs and streams most easily affected by rains to have the highest variation. These are the Rehobeth Church Insurgence, and Sprouse's, Cold, McPeak's, and the Salt Sulphur springs. Springs that have larger or deeper basins tend to be less variable. These are Dickson, Walters' and Rogers' springs.

Calcium-magnesium ratios were not plotted but show no evidence of seasonal trends. The means of this ratio help to indicate the type of rock through which the water traveled. A ratio of unity indicates that the water traveled solely through dolomite whereas a Ca/Mg ratio of 10:1 probably indicates movement through limestone alone. Rehobeth Church Insurgence and Dickson Spring are the only sites having a ratio significantly below 10 (Table 7b). The Rehobeth Church Insurgence is lowest due to the dolomite found in the lower Hillsdale and upper Maccrady Shale upon which this stream flows. There are several insurgences like this which flow to Dickson Spring, giving it a somewhat lower ratio than for other springs.

The ratio of the volume of the dissolved calcite to that of dolomite for each site can be calculated from the following formula:

$$\frac{Vc}{Vd} = \frac{\text{Vol. dis. calcite}}{\text{Vol. dis. dolomite}} =$$

$$\frac{((Ca^{+2}) - (Mg^{+2}))/(\text{density of calcite})}{(Mg^{+2})/(\text{density of dolomite})} \qquad (16)$$

This ratio shows the Rehobeth Church Insurgence and the Salt Sulphur North Spring to have a high volume of dissolved dolomite compared to the other sites (Table 7a). The difference between the Salt Sulphur springs is not easily explained. Springs that have flowed through very pure limestones such as the Union and Patton (McPeak's Spring and Sprouse's Spring respectively) have a high Vc/Vc ratio as well as a high Ca/Mg ratio. Lower ratios simply indicate increasing amounts of dolomite in the rocks. The high Vc/Vc value for McPeak's Spring may be due to the pollution known to enter this drainage basin at times from Union.

Summary

The chemistry of the springs and streams have helped to discern the nature of their flow systems. Dickson Spring is a deep system with a large basin that has the most constant seasonal chemistry. It is usually undersaturated with respect to calcite and has relatively higher amounts of dissolved dolomite from insurgent streams. It is also probably primarily phreatic.

Rogers' Spring also has a relatively constant water chemistry and is inferred to be phreatic. Dye traces have shown it to drain a deep basin of high gradient despite its small basin size. These characteristics cause it to have the highest coefficient of variation for discharge of any of the sites at which discharge was measured (Table 7a).

Cold and McPeak's springs are known to have explorable cave systems and are therefore vadose. The spring water chemistry is highly variable for both, due to their small basin sizes (and hence fast flow through times) and vadose nature.

Walters' Spring has the second largest basin of those studied and is known to have a vadose section at the head of the basin. The lower basin is believed to be phreatic which would explain the intermediate coefficients of variations for many of the chemical variables.

Sprouse's Spring and the Rehobeth Church Insurgence are surface streams and therefore are readily affected by storms. Their high coefficients of variation for most variables show this. The Salt Sulphur Springs are obviously diffuse from the unusual chemical character of the water. The influx of storm runoff masks the diffuse nature causing these springs to have the highest coefficients of variation for most variables.

Pollution of Springs

Introduction

Contamination of springs is a sad problem that occurs too often. Karst springs are the most susceptible to contamination due to rapid infiltration rates and the nature of underground flow. In Monroe County a common form of spring pollution results from the filling of dolines with trash and dead animals. Such dolines are commonly connected to springs via joint systems or solution cavities. Other common sources of karst spring pollution are stockyards, fertilizers, pesticides, sewage, and road salts. Little industry exists in Monroe County, and therefore this is not a source of spring pollution.

Chloride and nitrate concentrations were chosen as two indicators of pollution (Nutter, 1973) that could readily be measured. Time series diagrams for these two variables for the nine spring and stream sampling sites are shown in Figures 56 to 63.

Chloride Contaminated Springs

All of the sampling sites usually show higher concentrations of chemical constituents during the summer and early fall months when there are the highest temperatures and the lowest discharge values. Chloride is no exception to this for all the sites except for Cold Spring. Anomalously high peaks are found throughout the winter months which may possibly be attributed to road salt spreading during ice and snow storms. Precipitation data from Appendix D help in this interpretation.

A large snow storm occurred between the fifth and sixth sampling periods. All sites except for Sprouse's and the Salt Sulphur springs show chloride peaks soon after the storm. Another snow storm occurred between the eighth and ninth sampling periods. Again, most of the sites showed peaks except for the Rehobeth Church Insurgence. Yet another snow and ice storm occurred before the twelfth sampling period followed by minor peaks found for all sites except the Salt Sulphur springs and Cold Spring.

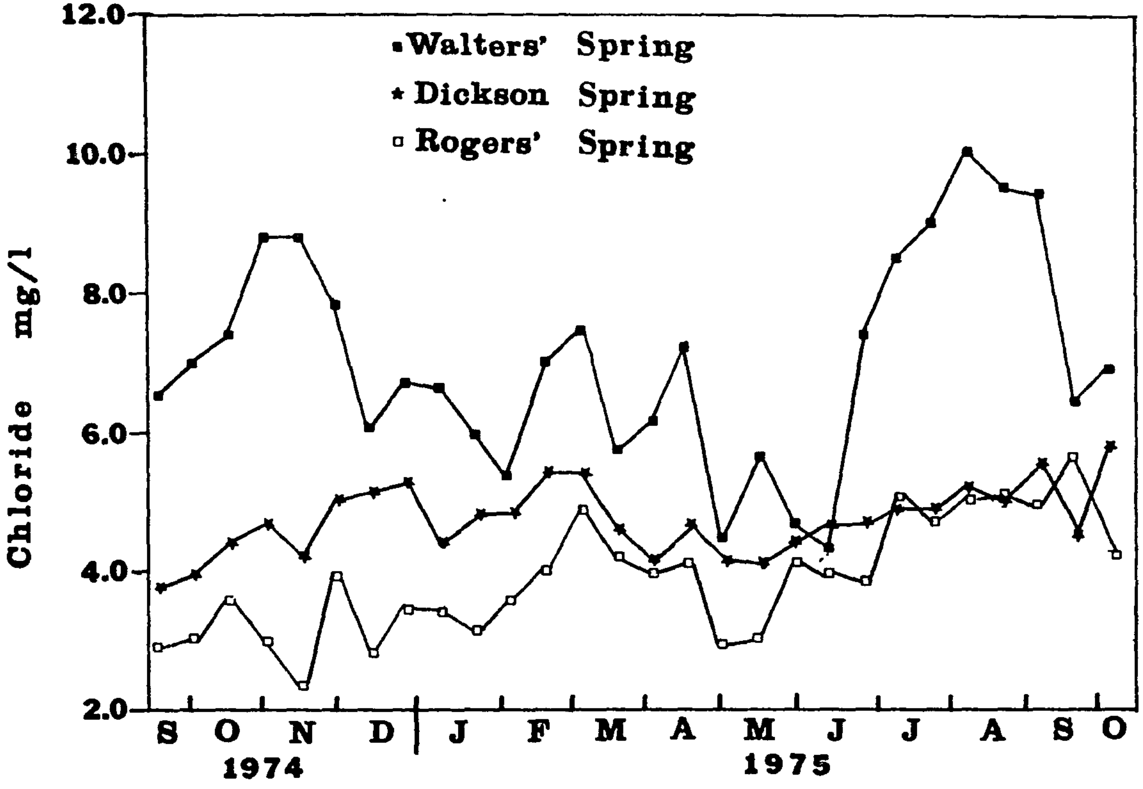

Figure 56. Time series chloride data for Dickson, Walters', and Rogers' springs.

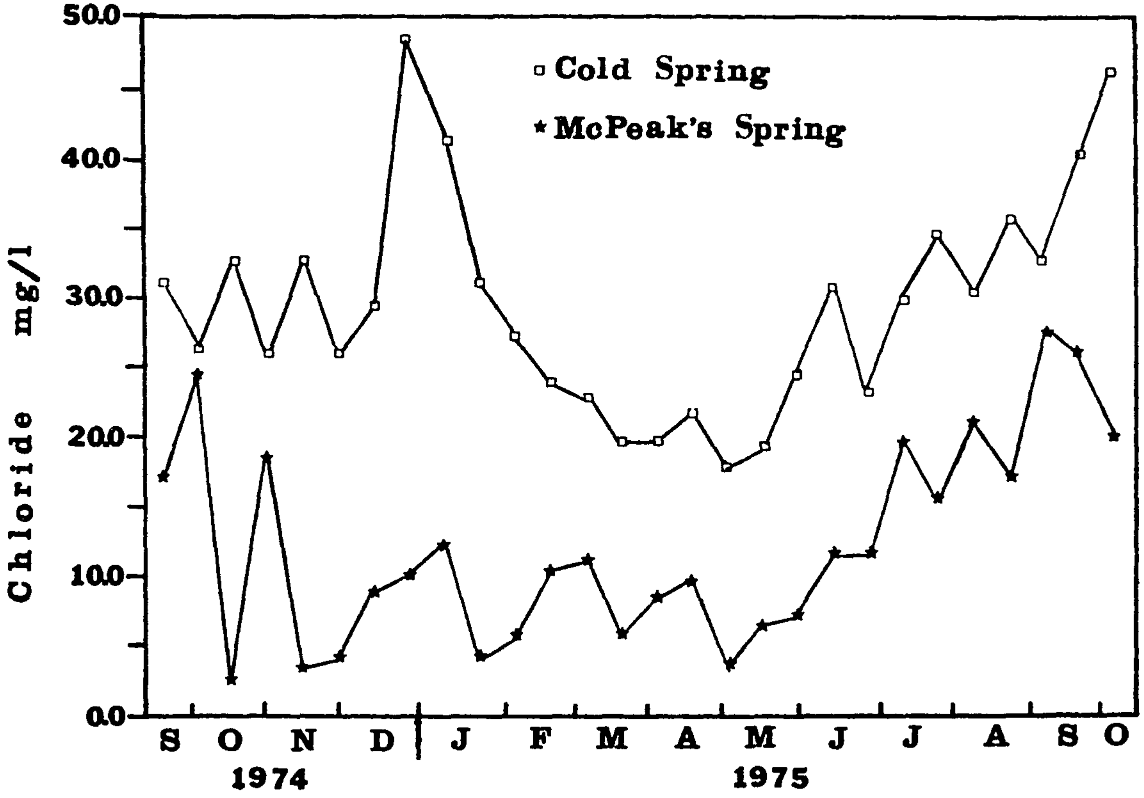

Figure 57. Time series chloride data for McPeak's and Cold springs.

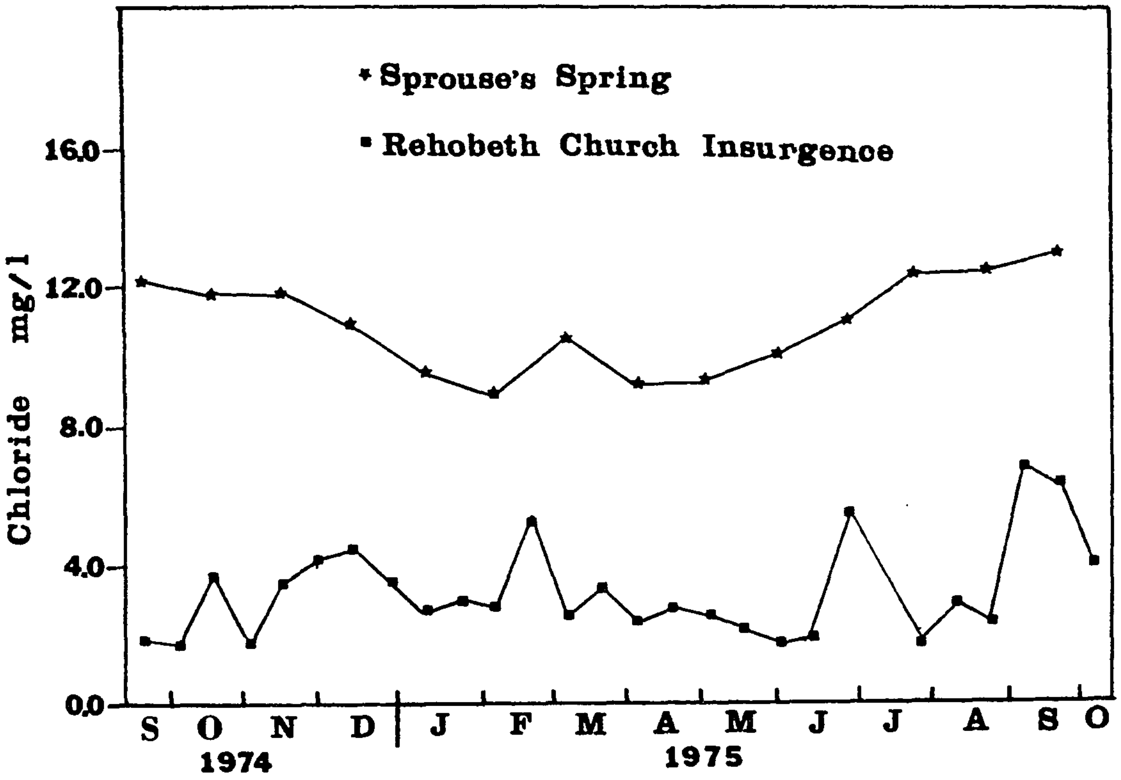

Figure 58. Time series chloride data for Sprouse's Spring and the Rehobeth Church Insurgence.

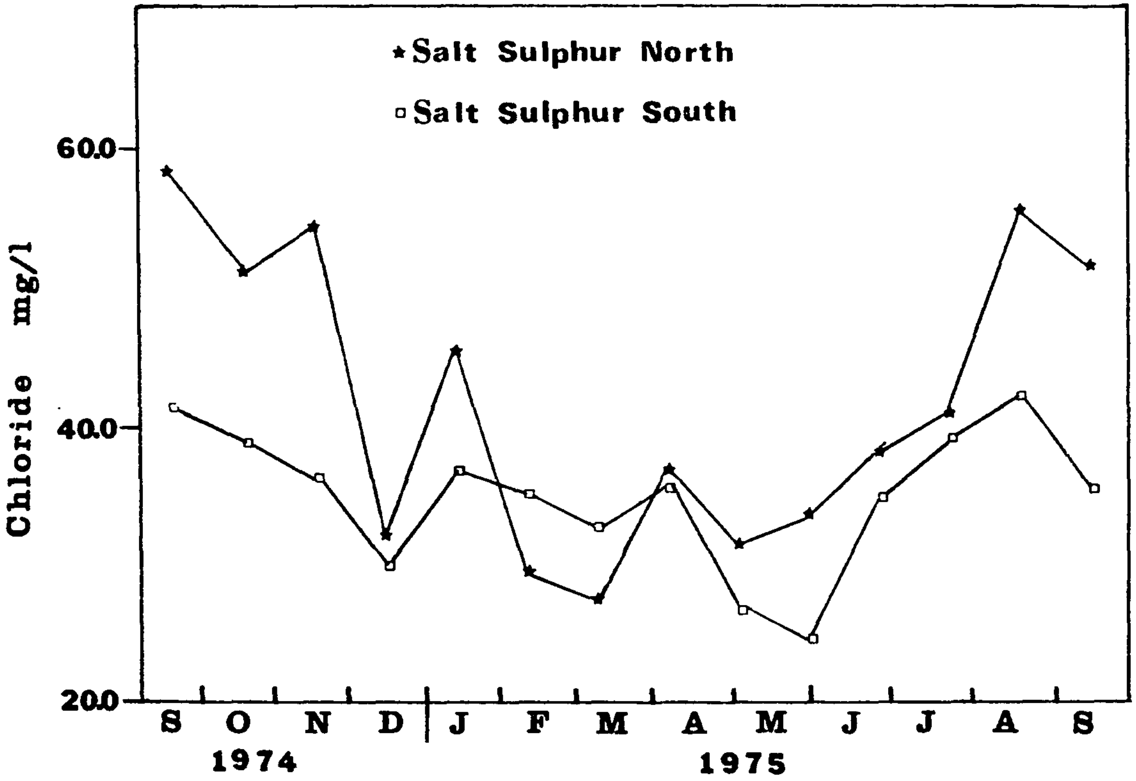

Figure 59. Time series chlroide data for the Salt Sulphur springs.

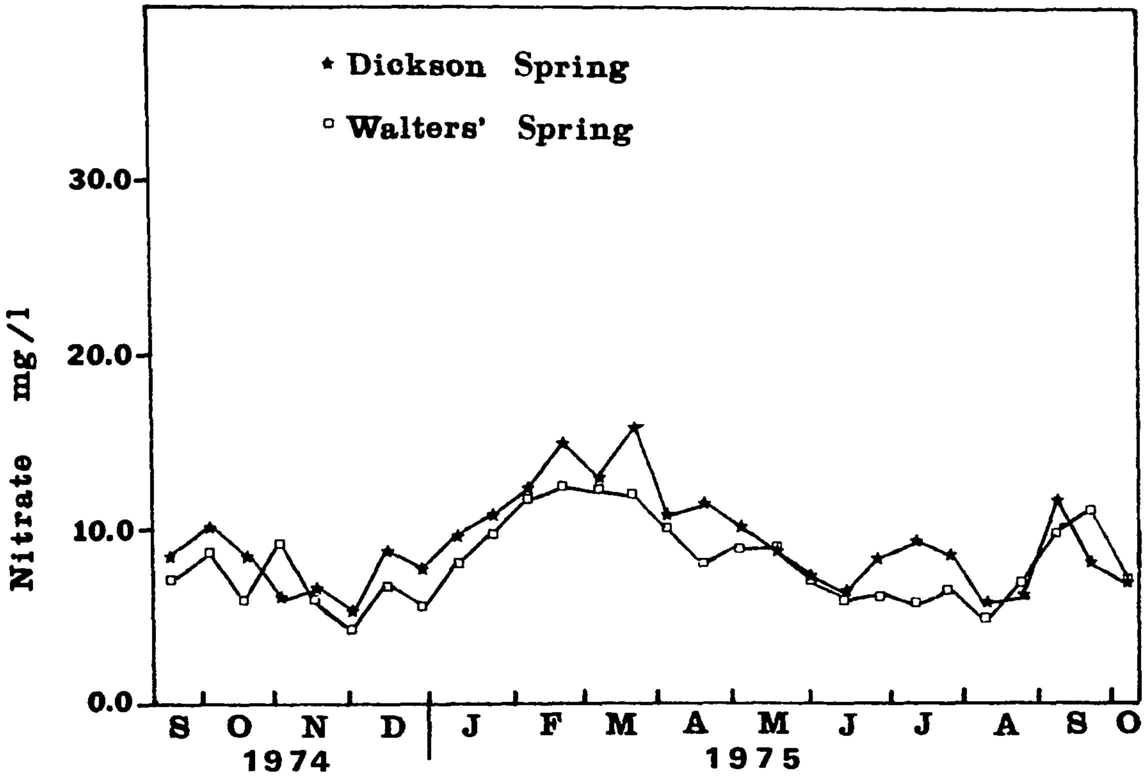

Figure 60. Time series nitrate data for Dickson and Walters' springs.

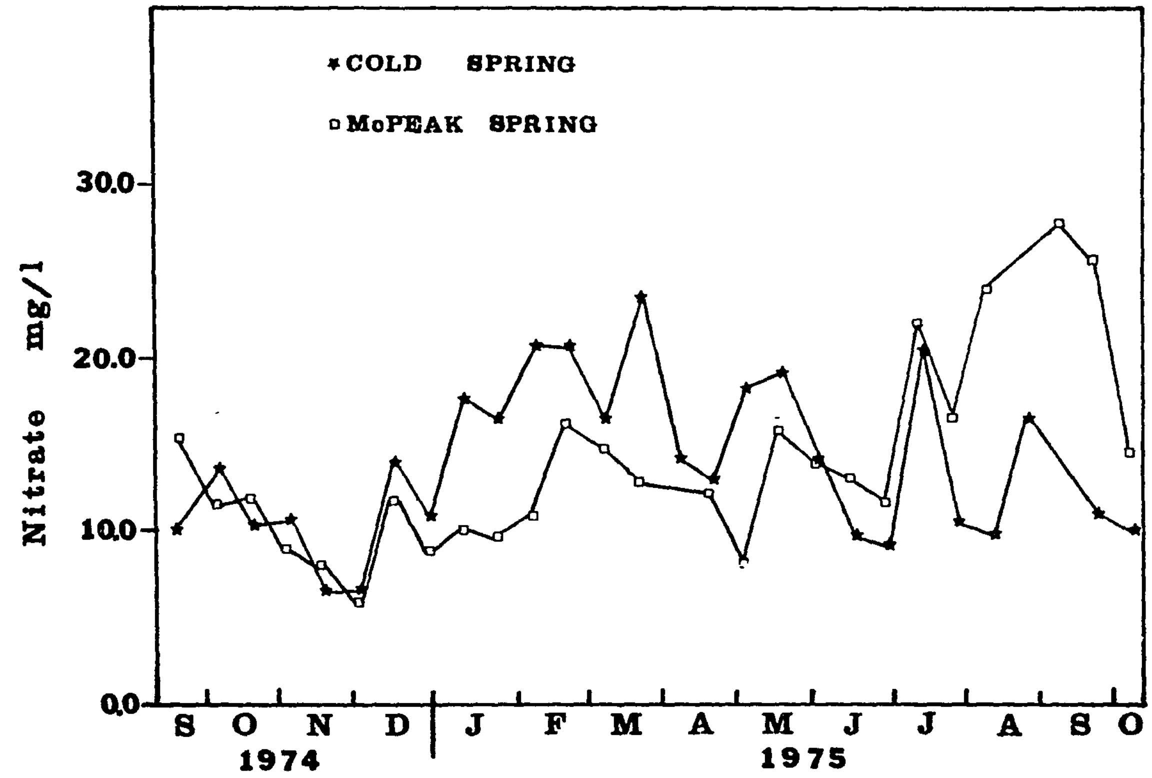

Figure 61. Time series nitrate data for McPeaks's and Cold springs.

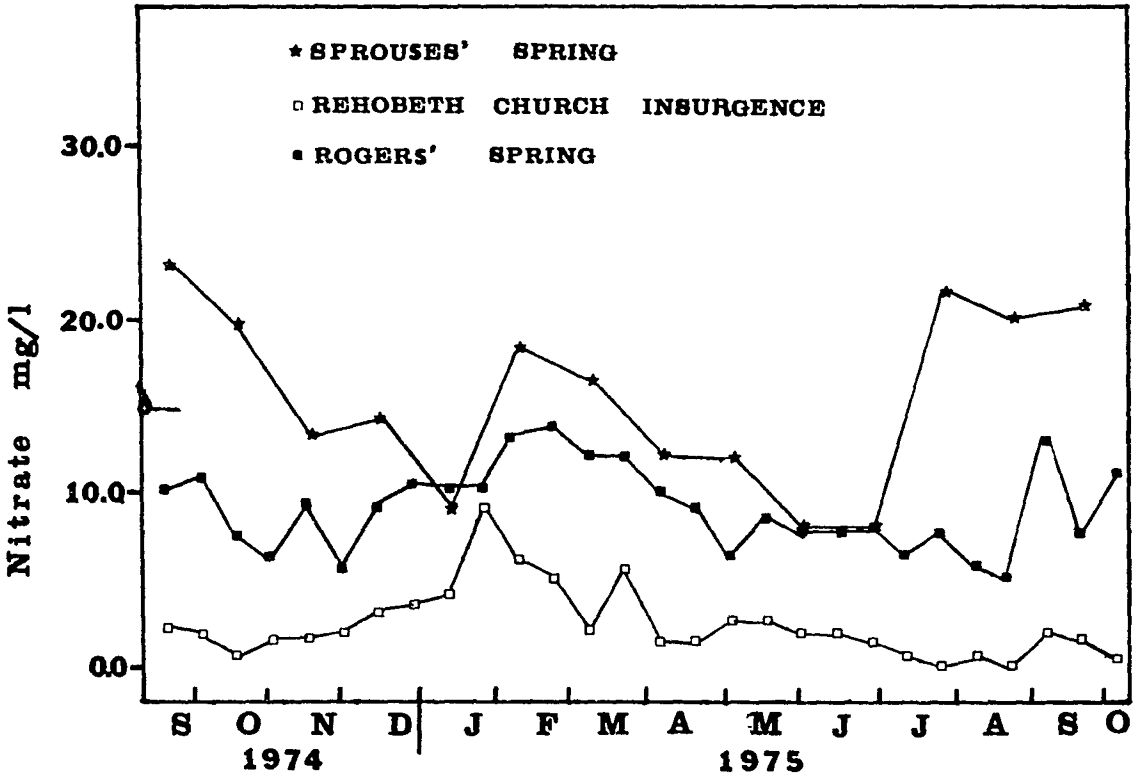

Figure 62. Time series nitrate data for Sprouse's and Rogers' springs and the Rehobeth Church Insurgence.

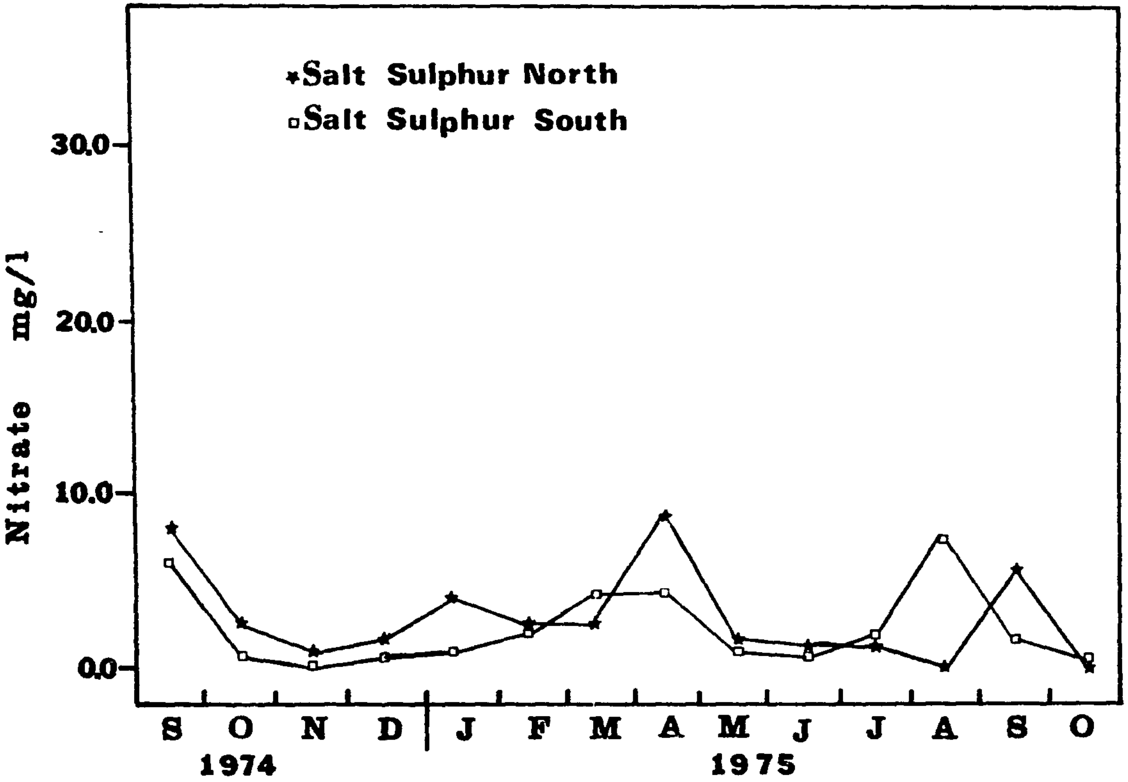

Figure 63. Time series nitrate data for the Salt Sulphur springs.

Cold and McPeak's springs show the highest chloride concentrations for the conduit springs and have high coefficients of variation (Table 7b). Both of these springs are close to major highways and receive road runoff. Sprouse's Spring receives little highway drainage and shows a regular trend toward lower chloride concentrations in the winter. This spring sinks soon after resurging and enters the Cold Spring system where there is nearly three times the chloride concentration.

The two Salt Sulphur springs have the highest chloride concentrations; these springs were noted to receive winter and spring melt-waters from the direction of State Route 219, which is only about 100 ft away. Although sampled only monthly, the Salt Sulphur springs show winter peaks that approximately correspond to those of McPeak's and Cold springs.

Rogers' and Dickson springs have the lowest chloride concentrations, which may be due to their long distance from highways or to dilution effects. An observation of possible concern is that both of these springs increased by one to two mg/l of chloride between the beginning and end of the study period. These springs also show no definite seasonal trends in chloride concentration.

Rehobeth Church Insurgence had two winter peaks corresponding to snow and ice storms and has one of the highest coefficients of variation (Table 7b). This basin containing this insurgence has few roads and perhaps the smallest population density of studied sites. Therefore, there is little contamination by man.

The evidence for chloride pollution by road salt spreading is not conclusive, due to the long time period between sampling periods and storm events. Storms that occur a few days after sampling will probably have little effect on the next set of samples. Differences in the time and intensity of chloride peaks are a function of basin size, type of flow (vadose, phreatic, or diffuse), duration of the storm, and the miles of salted highways in each basin. Despite these differences, a relationship between chloride peaks and road salt spreading is suspected, similar to the findings of Saleem (1976) in Chicago area springs and of Werner (1976) in Pocahontas County, West Virginia. Chloride peaks in other months are more likely a function of agricultural wastes and fertilizers, but their role for each sampling site is difficult to determine.

Nitrate Contaminated Springs

Time series plots for nitrate indicate that there are strong seasonal trends. Most of the springs reach maximum nitrate concentrations during the months of February and March. This is most likely related to the release of nitrate by plants and the soil after the growing season has ended and increased ground water recharge has occurred. Minor peaks of nitrate concentrations during August and September are more likely due to concentration effects during lower discharges. Another effect may be from the spreading of fertilizers, but this is less definite.

The Salt Sulphur springs and the Rehobeth Church Insurgence have the lowest nitrate concentrations. This is probably due to these sites being far away from household sewage systems. The insurgence runs through a large heavily grazed pasture but has low nitrate levels. This suggests that wastes from grazing animals is not a significant source of this contaminant here. Cold, Sprouse's, and McPeak's springs have the highest observed nitrate contents; these are probably caused by the observed pollution inputs from household sewage and barnyard wastes.

Spring Water Chemistry Facor Analysis

Introduction

Factor analysis was used to aid in interpreting the interrelationships among the measured and derived variables of several springs and one insurgence. Siddiqui and Parizek (1972) and Jacobson, et al. (1971) have described the use of factor analysis with carbonate waters of central Pennsylvania. They used R-mode factor analysis as does this author.

Factor analysis takes a data matrix of "p" variables on "n" samples and derives factors or components relating the variables. Variables are found to have different loadings under each factor with loadings representing the coefficients of the linear equation that the eigenvectors define (Krumbein and Graybill, 1965). These loadings also represent correlation coefficients between the variables and the factors themselves. "The eigenvalues represent the total variance accounted for by each component" (Drabish, 1975).

A rotated factor matrix is generated from the unrotated factor matrix "into a position which best fits the data, such that the high factor loadings are increased and the low factor loadings are further reduced" (Drabish, 1975). The loadings on each factor are then tested for significance (assuming normally distributed data) by using a significance table for correlation coefficients of two variables (Mendenhall, 1971). An alpha level of 0.01 was chosen for N-1 degrees of freedom in the study, where N is the number of observations or samples. From the factor analyses performed in this study, groups of related and independent variables were determined; then attempts were made to identify each factor according to the underlying principle which all highly loaded variables had in common for that factor.

In this study, five factors were needed to explain approximately 90 percent of the total data variation in the original data matrix. The remaining 10 percent was assumed to incorporate the errors of measurement and random variation in the data (Rauch, oral communication, 1976).

Factor analysis was performed in this study using the R-mode factor analysis program from the SAS procedures (Service, 1972). Thirteen chemical variables (pH, temperature, specific conductance, calcium, magnesium, bicarbonate, chloride, nitrate, total hardness, saturation index for calcite, saturation index for dolomite, carbon dioxide partial pressure, and calcium-magnesium ratio) and the physical variable of discharge were included in the analyses.

Factor analyses were performed on the data for three representative spring types that appeared to be physically and chemically different. These are Dickson, Cold, and the Salt Sulphur South springs. The Rehobeth Church Insurgence was also analyzed in a similar manner. Table 8 gives a factor analysis summary. This table lists the significant loaded variables under each factor for the four sites tested.

Dickson Spring

The original data analyzed for Dickson Spring are in Appendix A, and the rotated factor matrix, communalities, and percent variation explained by each factor are in Appendix F. Five factors were chosen to explain 92.5 percent of the total variance of the data. These factors have been named but these names are tentative. Twenty-eight samples were analyzed, with factor loadings being significant, if over $\geq$0.470 at the 0.01 alpha probability level.

The first factor, explaining the greatest percentage of information in the data matrix, represents limestone dissolution. From Table 8, temperature and Pco_2 are directly associated. This indicates that during the warmer periods, greater microbiotic activity in the soil zone results in greater decay rates and higher soil CO_2 partial pressures. Diffuse recharge would then result in higher Pco_2 values for Dickson Spring. This in turn results in greater carbonic acid concentrations, and hence lower pH during the warmer summer months. The higher H_2CO_3 content in turn results in greater carbonate dissolution rates, and hence in higher

Table 8

Factor Analysis Summary, Showing Significantly Loaded Variables for Each Factor.

Water Data Analyzed	Limestone Dissolution Factor	Dolomite Dissolution Factor	Carbonate Aggressivity Factor	Nitrate Pollution Factor	Carbonic Acid Factor	Salt Pollution Factor	Other Factors
Dickson Spring	+(pH) -(Temp) -(Spc)+ -(Ca) $-(CHO_3)$ -(Tot Hard) +(D)¢ $-(Pco_2)$	-(Mg) -(SId) -(Ca/Mg)	+(pH) +(SIc) +(SId)	+(Temp) $-(NO_3)$		+(Cl)	
Cold Spring	+(Spc) +(Ca) $+(HCO_3)$ +(Tot Hard)	+(Mg) -(Ca/Mg)	+(pH) -(D) +(SIc) +(SId) $-(Pco_2)$	+(Temp) $-(NO_3)$ -(D)		+(Spc) +(Cl)	
Salt Sulphur Spring South	+(Spc) +(Ca) $+(SO_4)$ +(Tot Hard)	+(Mg) +(SId) -(Ca/Mg)	+(Temp) $+(HCO_3)$ +(SIc)	$+(NO_3)$	+(pH) $-(Pco_2)$		
Rehobeth Church	+(pH), +(Spc), +(Ca), +(Mg), $+(HCO_3)$, +(Tot Hard), $-(NO_3)$, +(SIc), +(SId)				-(pH) +(D) $+(Pco_2)$	+(Cl)	+(Ca/Mg)* +(Temp)*

*These variables loaded highly on two separate factors, and are independent of each other.
+Specific conductance.
¢Discharge.

total hardness, calcium and bicarbonate concentrations, and specific conductance. Warmer periods are usually associated with lower spring discharge, probably because of higher evapotranspiration rates at that time. In turn, lower discharge in itself could act to increase the concentrations of carbonate dissolution products in spring waters.

The second factor having high positive loadings of pH, SIc, and SId represents carbonate aggressivity. This factor indicates that the degree of spring saturation with respect to calcite and dolomite is especially dependent on pH, and less so on the calcium concentration (which is not quite significant at the 0.01 alpha level). Higher pH indicates lower acid concentrations and hence less aggressive carbonate waters. SIc and SId are in turn inversely related to aggressivity.

The third factor indicates dolomite dissolution. As dolomite dissolution becomes increasingly important, the magnesium concentration increases, the ratio of dissolved calcium to magnesium decreases, and the aggressivity with respect to dolomite (or SId) increases.

The fourth factor indicates salt pollution from the single high chloride concentration loading. Such pollution in general most likely stems from salt licks in farmers' fields and road salts used during winter months. This pollution is largely independent of aqueous carbonate geochemistry, seasons, and spring discharge.

The fifth and final factor represents nitrate pollution. Such pollution probably originates from fertilizers and animal wastes from nearby farms. This factor, with its high nitrate concentration loading, indicates that such pollution is largely independent of aqueous carbonate geochemistry, spring discharge, and chloride pollution. However, nitrate pollution of this spring is higher during the colder winter months. This could result from less biotic activity in the upper soil zone during colder months; biologic interception and assimilation of nitrate in the soil zone could reduce nitrate recharge to ground and spring waters during the summer.

Cold Spring

The original data for Cold Spring are in Appendix A and the rotated factor matrix, communalities, and percent variation explained by each factor is in Appendix F. Five factors explained 91.3 percent of the total variance of the data for this spring. Twenty-eight samples were taken with the minimum level of significance of loadings being the same as for Dickson Spring.

For Cold Spring, the same basic factors exist as for Dickson Spring, but there is some rearrangement of important factor loadings with two factors being reversed. Factor one represents carbonate aggressivity. As the Pco_2 and hence carbonic acid concentration increases, there is a reduction in pH and an increase in carbonate aggressivity (as indicated by decreasing SIc and SId).

These changes occur as the spring discharge increases, probably indicating that storms wash more organic material and high Pco_2 soil water into the cave feeding this spring.

The discharge relationship for Cold Spring is opposite to that for Dickson Spring; this difference probably results from the Cold Spring drainage system being closer to the surface and rapidly responding to storm events. The Dickson Spring system is at greater depth and responds more slowly to storms.

The second factor represents limestone dissolution, as total hardness, calcium concentration, bicarbonate concentration, and specific conductance are all highly associated. A major difference between Cold and Dickson springs is that the just-mentioned carbonate dissolution variables are independent of temperature, discharge, and acid content for Cold Spring. This may in part reflect the fact that the short residence time for ground water in the Cold Spring system does not allow the carbonate dissolution rate to respond significantly to changes in at least discharge and acid content.

The third factor indicates dolomite dissolution. This is similar to the equivalent factor for Dickson Spring, except that SId is not significantly associated with magnesium concentration and the calcium to magnesium ratio.

The fourth factor shows the effect of nitrate pollution. Like Dickson Spring, nitrate concentration is independent of aqueous carbonate geochemistry and chloride content. Unlike

Dickson Spring, the nitrate pollution level is significantly associated with discharge as well. Storms apparently recharge more nitrate from overlying farms into the shallow Cold Spring system.

The fifth factor represents salt pollution. Because the chloride (probably from dissolved halite) content is relatively high for Cold Spring, it composes a significant part of the total dissolved solids, and hence is associated with specific conductance. Road salts are again suspected as the major source of this pollution.

Salt Sulphur South Spring

The original data for this spring are in Appendix A, and the rotated factor matrix, communalities, and percent variation explained of each factor is in Appendix F. Table 8 shows the variables that loaded significantly on each factor. Five factors explained 90.5 percent of the total variance of the data for this spring. Fourteen samples were taken with a significant loading being ≥ 0.641 (Mendenhall, 1971).

The limestone dissolution factor is the first factor. It is similar to that for Cold Spring except that bicarbonate is not highly loaded on this factor, while sulfate is. Several interpretations may be placed on the significance of sulfate. Given the fact that sulfate is much more concentrated than chloride, it is unlikely to originate from upward-moving connate brines. The sulfate may originate from pyrite weathering in the Greenville

Shale which would generate sulfuric acid. This acid would then dissolve limestone in the upper Union Formation as ground water moves diffusely to the Salt Sulphur springs. Sulfuric acid probably is a major factor in limestone dissolution for these springs no matter what interpretation is given to their origin.

The second factor indicates carbonic acid effects. As the Pco_2 increases, the carbonic acid increases in concentration, and the pH drops. Carbonate dissolution by carbonic acid may be minor here, as no other variables load highly on this factor.

The third factor represents dolomite dissolution and is similar to that factor for Dickson Spring previously discussed. The fourth factor illustrates nitrate pollution, while the fifth factor represents carbonate aggressivity. The spring waters become less aggressive during warmer periods.

The conclusions from factor analysis for Salt Sulphur South Spring are somewhat tentative since a small number of samples (14) commonly leads to less reliable factor loadings.

Rehobeth Church Insurgence

The data used in the factor analysis for this insurgence can be found in Appendix A while the rotated factor matrix, communalities, and percent variation explained of each factor is in Appendix F. Twenty-eight samples were analyzed, giving the same critical alpha level of significance for factor loadings as for Dickson Spring. Rehobeth Church Insurgence had 88.7 percent of the total variance of the data explained by five factors. The significant loadings of variables for each factor are shown in Table 8.

The first factor for this insurgence has most of the factor loadings for both the limestone dissolution and carbonate aggressivity factors for the analyzed springs. This factor is therefore termed the carbonate dissolution and aggressivity factor. Perhaps the relatively simple nature of this insurgent stream compared to the tested springs is responsible for the great number of loadings on the first factor.

The second factor is similar to the carbonic acid factor of Salt Sulphur South Spring, except that in addition, the carbonic acid concentration is higher during high stream flows. The third factor represents salt pollution, while the fourth and fifth factors represent the calcium to magnesium ratio and temperature, respectively. These latter two variables are independent of each other and the other measured variables.

Conclusions

The various types of water in Monroe County show similar relationships among measured variables. Similar variables commonly load significantly under the same factors with minor variations. The various types of water in Monroe County show similar relationships among measured variables. Similar variables commonly load significantly under the same factors with minor variations. The findings from these factor analyses are somewhat similar to those of Werner (oral communication, 1976). He has investigated carbonate spring waters of Pocahontas County, West Virginia, and found four factors in common with those of this author; these are carbonate dissolution, salt pollution, dolomite dissolution, and nitrate pollution factors. His loadings are, for the most part, similar to this author's, with exceptions due probably to differences in the spring flow systems. Finally Jacobson (1973) has likewise found similar variable associations for central Pennsylvania, with carbonate dissolution, salt pollution, and nitrate pollution factors being similar to those of this author.

Storm Response of Springs

Introduction

As described earlier, both seasonal and short-term fluctuations in spring water chemistry and discharge have been used to distinguish the type of aquifer system draining to a spring. In addition, the storm response of springs can indicate the nature of such karst aquifers. Walters', McPeak's and Cold springs were therefore studied for their discharge and chemical responses to a storm (Ogden and Rauch, in press).

The effects of rainstorm on October 15, 1974, were measured at each of the three springs. The storm began in the early morning of October 16th and ended at about 1:00 p.m. on the same day. Rain measurements for the time period are shown in Table 9.

Table 9

Precipitation Data from Union Station, West Virginia from U.S. Weather Bureau (1974)

Date	Precipitation (inches)
October 14, 1974	0.00
October 15, 1974	0.00
October 16, 1974	1.30
October 17, 1974	0.12
October 18, 1974	0.00
October 19, 1974	0.00
October 20, 1974	0.03

Both discharge and water quality measurements were made starting two days prior to the storm, when base flow was in effect (since it had not rained for several days preceding the storm). Measurements were taken every two to three hours during the storm and less frequently thereafter until October 20. No significatn rain fell again for several days after the storm. All previously described water chemistry parameters were also measured for the storm study.

Cold Spring

Plots of time versus pH, total hardness (as mg/l $CaCO_3$), chloride concentration (mg/l), and discharge (cms or cubic meters per second) are given for Cold Spring in Figure 64. The dashed line indicating base flow conditions was determined two days prior to the storm. The estimated measurement error or precision was ±0.05, ±3.9 mg/l, and ±1.4 mg/l, respectively, for pH, total hardness, and the chloride concentration; these values are useful in interpreting differences between plotted points of Figure 64 and succeeding figures. For Cold Spring, minimum values for pH and total hardness come between four and seven hours after the peak in discharge. There was no significant precipitation after the October 16th storm to affect the fall of the hydrograph. Four days after the storm, all variables had nearly returned to the base flow conditions which preceded the storm. The range in pH (maximum minus minimum values) was 0.47 pH units, while total hardness ranged 78.0 mg/l, and chloride ranged 32.2 mg/l.

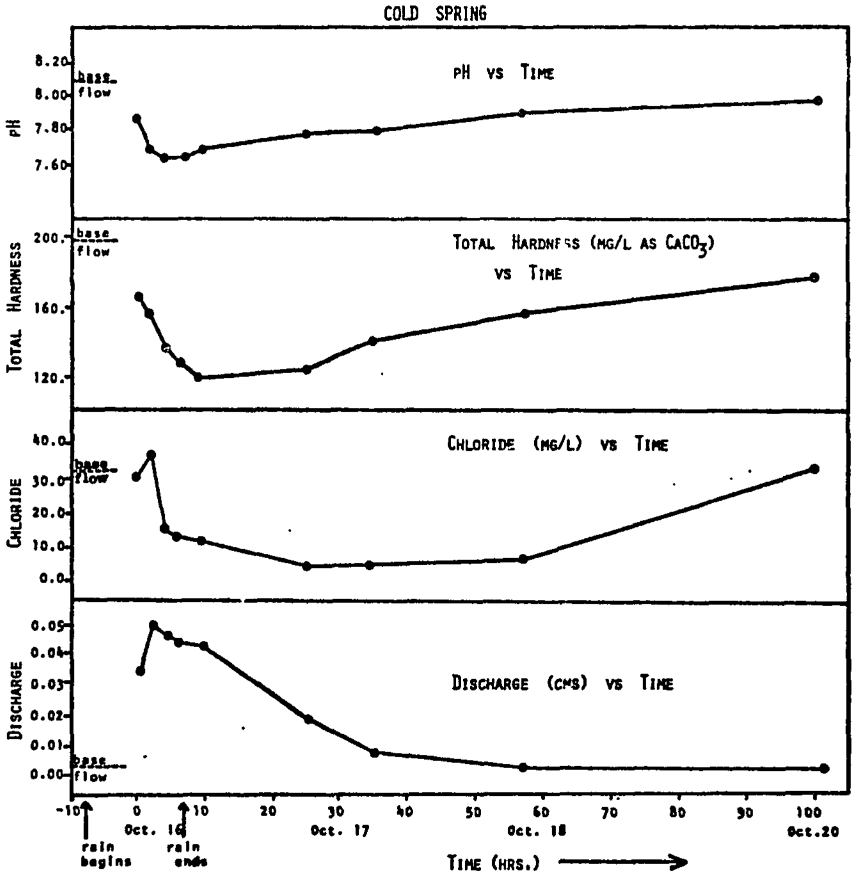

Figure 64. Plot of pH, total hardness, chloride, and discharge during and after an October storm for Cold Springs (Ogden and Rauch, in press).

The corresponding peaks of discharge and chloride concentration may be due to inflow from stockyards near the middle of the basin. There is also overland flow from two ponds carrying salts to this spring. The lags between the discharge peak and the minimum pH, hardness, and chloride concentration values were expected because of the finite time period needed to flush the old highly concentrated ground water from the cave system in response to the storm; the lag times for minimum pH and hardness (four to seven hours) indicate minimum estimates for the time span between recharge and discharge of storm waters.

The longer lag time for chloride may be a function again of the chloride-rich stockyard wastes and salt licks that continue to enter this shallow system (less than 30 ft below the surface) by diffuse flow.

McPeak's Spring

Similar plots of the chemical parameters versus time were made for McPeak's Spring in Figure 65. The pH, total hardness, and chloride concentration reached minimum values only two hours after the peak in spring discharge, while the peak discharge occurred four hours after that of Cold Spring. The delayed time arrival of peak discharge for McPeak's Spring compared to Cold Spring indicates the greater size of McPeak's Spring basin and associated longer flow times for subsurface water. Likewise, the decrease in total hardness for McPeak's Spring was about twice that of Cold Spring in response to the storm. This is believed

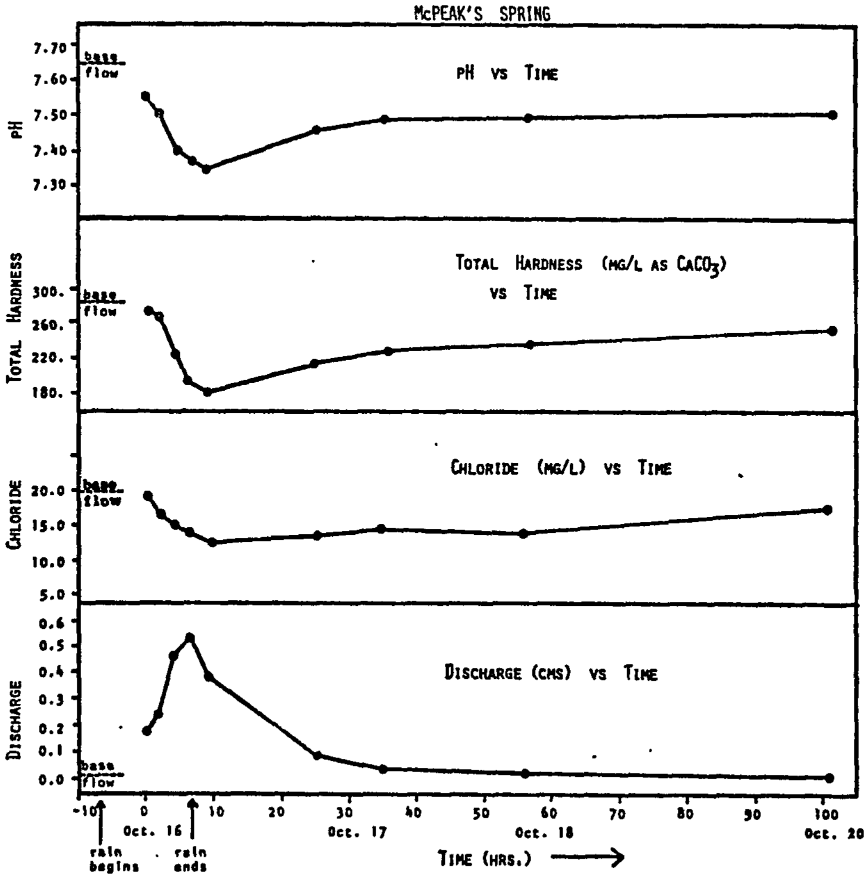

Figure 65. Plot of pH, total hardness, chloride, and discharge during and after an October storm for McPeak's Spring (Ogden and Rauch, in press).

to be caused in part by the direct dilution of the spring by surface waters. The range (maximum minus minimum values) in pH was only 0.30 pH units, while the range in total hardness was 103.0 mg/l and the range in chloride concentration was 6.6 mg/l.

Walters' Spring

Unlike the other two springs, the data for Walters' Spring (Figure 66) show a rise in pH, total hardness, and chloride concentration with increased discharge. The peaks in chloride concentration and total hardness represent old ground water in storage being flushed from the cave system. These two peaks occur nearly the same time as peak discharge. Later minimum values for chloride concentration, total hardness, and pH did not occur until nearly 50 hours after peak discharge. This extreme lag is explained by the large basin size and slower flow rates relative to the other two basins which exhibit mostly vadose (open channel) flow.

Walters' Spring had the lowest range (maximum minus minimum values) in pH, total hardness, and chloride concentration for the three springs studied. The total hardness range was only 23.5 mg/l, while the range in pH was 0.19 pH units, and the chloride concentration ranged just 1.0 mg/l. The narrow ranges in these quality variables compared with those ranges for Cold and McPeak's springs indicate the effective buffering action on these variables due to the extensive size and ground water storage of Walters' Spring basin.

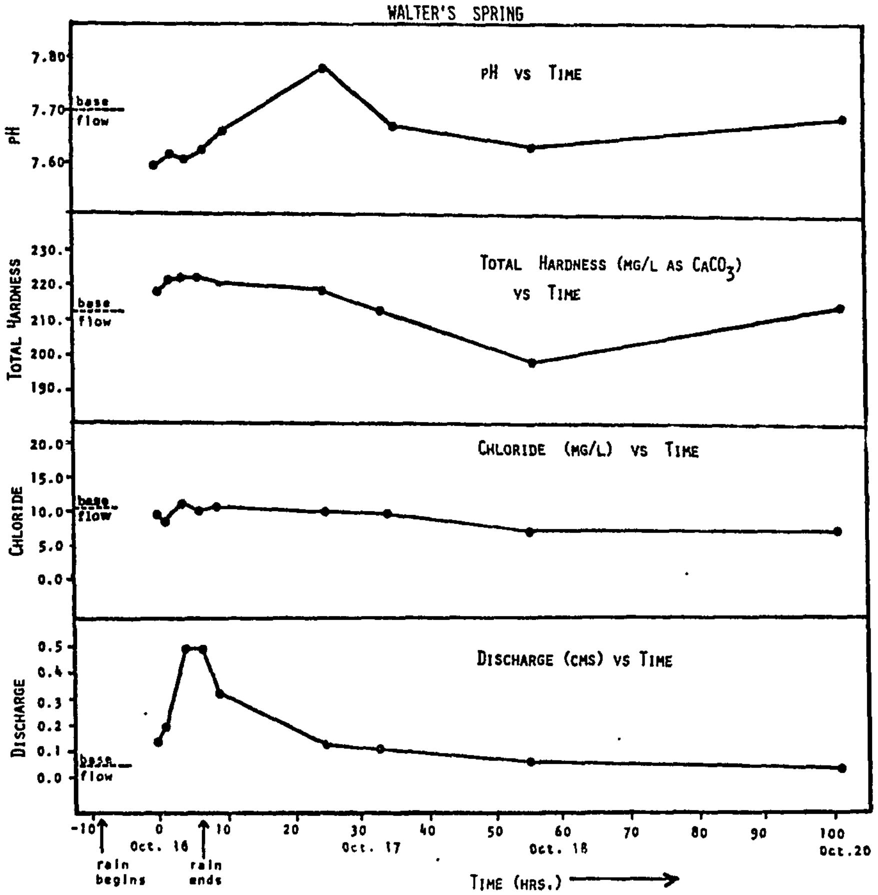

Figure 66. Plot of pH, total hardness, chloride, and discharge during and after an October storm for Walters' Spring (Ogden and Rauch, in press).

Conclusions

Table 10 shows the approximate relationships of basin size and average storm discharge to other variables. In general, as basin size and average discharge increase, there are decreases in the range in pH, total hardness, and chloride concentration as well as a decrease in the ratio of peak to base discharge during a storm. These results show that the greater the volume of ground water in storage (which is dependent on basin area), the more uniform are the discharge and water chemistry of the spring, at least during storms.

In addition, the storm lag time between the peak spring discharge and later minimum values in pH, hardness, and chloride concentrations may be explained by spring basin area and type of subsurface flow. These storm lag times should be greater for larger basins having longer flow paths and residence times for cave waters. Also phreatic (closed channel) flow, which is common in the Walters' Spring basin, represents slower flow rates in caves than does vadose (open channel) flow.

Exceptions to the above generalizations occur for the data of McPeak's Spring, which exhibit a greater range in total hardness, a higher ratio of peak to base flow, and shorter storm lag times than expected. This is probably explained in part by the dilution of spring water by surface runoff during storms and by the influence of the polluted waters that run through the system.

Table 10

Summary and Generalizations from Storm Response Data for Walters', McPeak's, and Cold Springs

Variable	Walters' Spring	McPeak's Spring	Cold Spring
Relative average discharge	highest	intermediate	lowest
Relative basin size	largest	intermediate	smallest
Relative ratio of peak to base discharge	lowest	highest	intermediate
Relative pH range	lowest	intermediate	highest
Relative total hardness range	lowest	highest	intermediate
Relative chloride range	lowest	intermediate	highest
Relative lag time between maximum discharge and minimum hardness	highest	lowest	intermediate

Karst Denudation Rates

Introduction

A topic of interest to many karst researchers is the rate at which a karst terrain is lowered by solution. The karst denudation rate has been determined in different climatic regions of the world by both direct and indirect means. The direct method generally entails measuring the lowering of an exposed limestone surface in reference to a non-erodable object. Coward (1971) used stainless steel rods imbedded in bedrock and measured the rate of surface lowering with an accurate micrometer. He found a mean value of 1.2 mm/yr for a Hughes Creek Cave in Pocahontas County, West Virginia.

The indirect method for determining denudation rates uses spring water hardness and discharge data to determine the amount of dissolved carbonate being carried from a spring basin. Corbel (1959) derived a formula for indirect denudation calculations and this was improved by Williams (1963) and Douglas (1964). Williams' (1963) formula for a basin with flow-gage records is:

$$X = FQTn/10^{12}AD \qquad (16)$$

where X = thickness of limestone removed from the basin in mm per specified period

Q = mean discharge over the period (cfs or cms)

T = the mean total hardness of the water in mg/l over the period

A = area of the basin in km^2

D = the density of the limestone or dolomite (gm/cc)

1/n = the area of limestone as a fraction of the total area of the basin

F = a conversion factor; 28.3 if Q is in cubic ft, or 1000 if Q is in cubic meters.

Methods and Results

The carbonate leaching rate was calculated for three spring basins in the study area, for each sampling time. This was determined with the formula:

$$\text{Carbonate Leaching Rate (gms } CaCO_3\text{/sec)} = \text{Total Hardness (mg/l as } CaCO_3\text{)} \times \text{Discharge (cfs)} \times \text{Conversion Factor} \quad (17)$$

The conversion factor is 0.0283 l-gm/mg-ft^3. The carbonate leaching rate for Dickson, Walters' and Cold springs are plotted in Figures 67-69. These figures clearly show that more limestone is removed in the winter and spring months when discharge is highest, even though the total hardness is lower then. This is probably largely because the carbonate dissolution rate increases with increasing flow velocity, as verified experimentally by Wentzler (1971) and many others. Another explanation for these trends is the increased submerged area of limestone in cave systems with increased discharge.

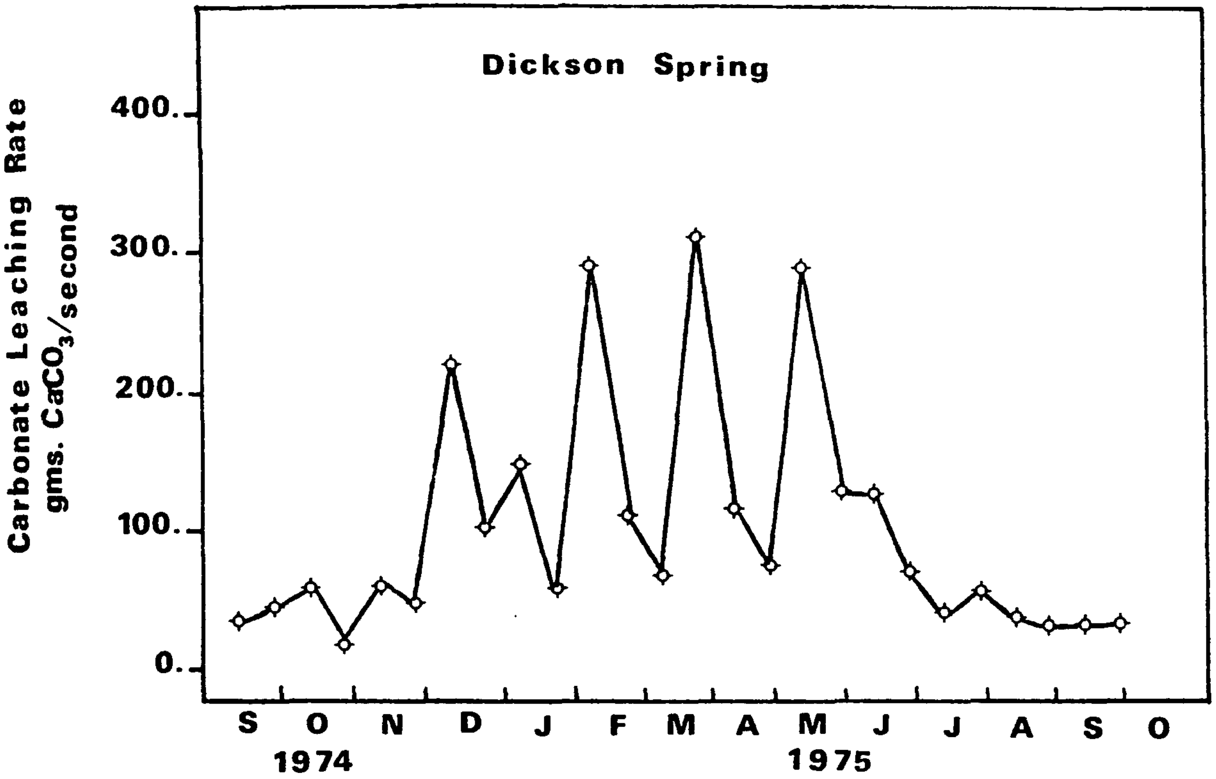

Figure 67. Carbonate leaching rate versus time for Dickson Spring.

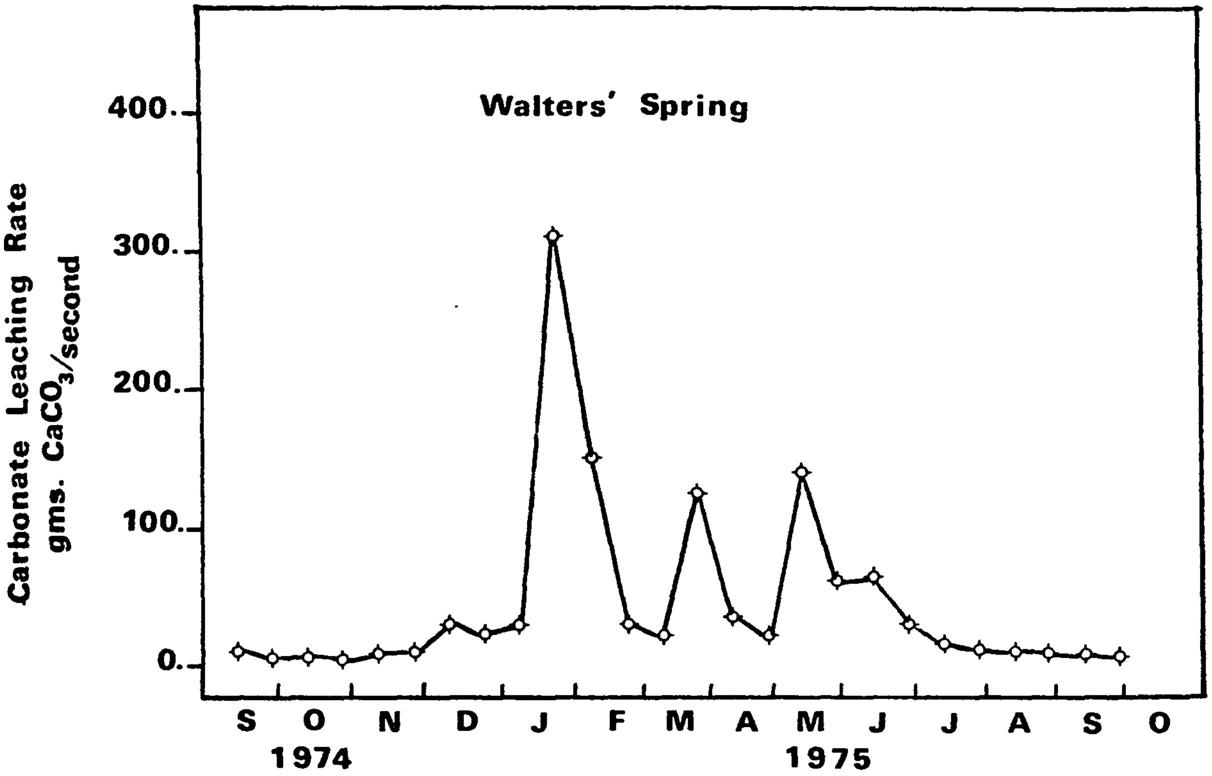

Figure 68. Carbonate leaching rate versus time for Walters' Spring.

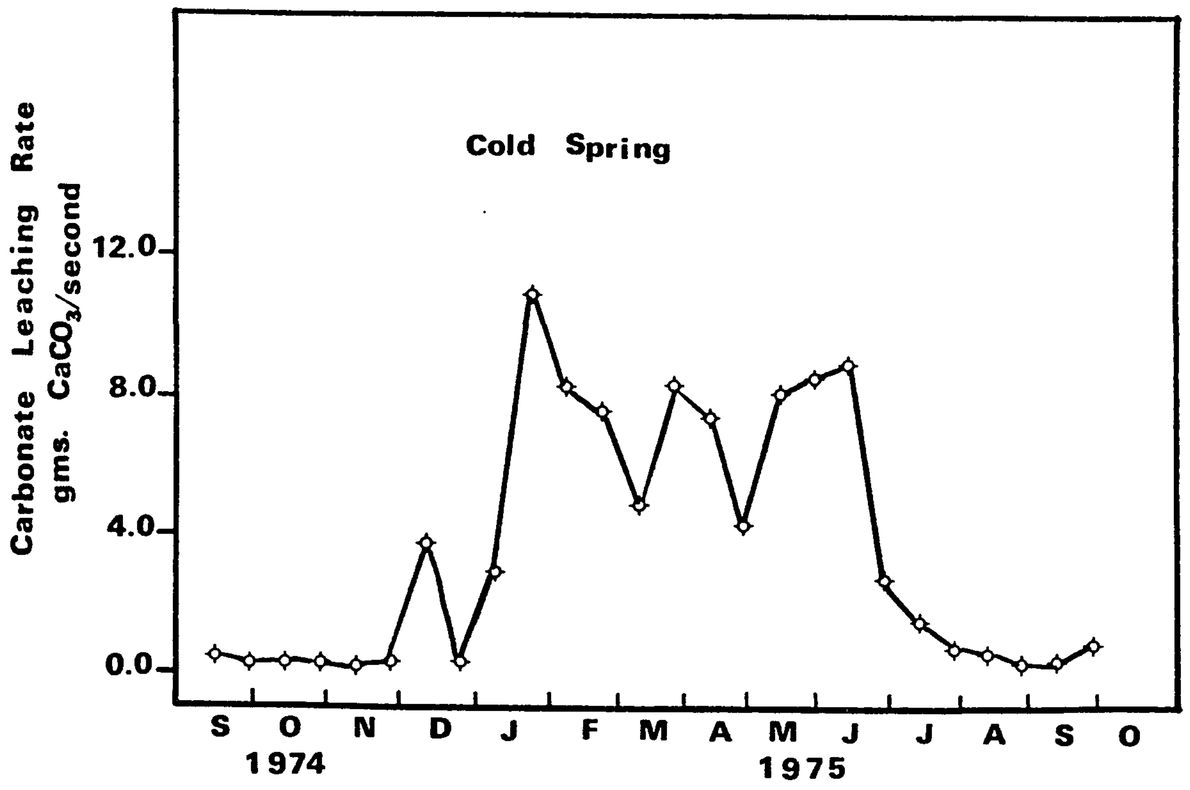

Figure 69. Carbonate leaching rate versus time for Cold Spring.

The karst denudation rate was then determined for each of these spring basins by the formula:

$$D = \overline{L}C/\rho A \tag{18}$$

where D = the denudation rate in cc $CaCO_3$/yr-km^2

$\overline{L}$ = the mean carbonate leaching rate (average for all sampling times) in grams $CaCO_3$/sec

ρ = the bulk density of the Greenbrier Limestone in gm/cc, 2.65 (West Virginia Geological Survey Subsurface File)

A = the basin area in km^2

C = constant to convert from seconds to a year.

The resulting values are as follows: (1) 1.89 ± (0.72) x 10^7 cc $CaCO_3$/km^2-yr for Cold Spring; (2) 2.011 ± (0.47) x 10^7 cc $CaCO_3$/km^2-yr for Dickson Spring; and (3) 2.014 ± (0.51) x 10^7 cc $CaCO_3$/km^2-yr for Walters' Spring. These precision values were determined from the standard deviations of individual flow and hardness measurements. The vadose nature and short subsurface residence time of Cold Spring in combination with its low discharge may be responsible for its lower denudation rate. The Dickson Spring basin is over twice the size of the Walters' Spring basin, and yet they have nearly the same denudation rates. These two springs are assumed to have some closed channel (phreatic) flow in their drainage systems which may allow more limestone to be dissolved due to greater ratios of wetted exposed rock to flow volume in the cave systems.

Most denudation rates of the world have been reported in millimeters per 1000 years. The denudation rates and respective precision values from this study in these units give 18.99 ± 7.2, 20.11 ± 4.7, and 20.14 ± 5.1 mm/1000 yrs for Cold, Dickson, and Walters' springs respectively.

These values are the average values for each basin with denudation rates probably differing drastically from place to place within each basin. The most rapid denudation rates will occur in sinkholes, on bare surface karst, and in caves. Denudation rates are highly variable throughout the world, but generally are highest in areas of high precipitation. Values reported by Williams (1963), Sweeting (1973), and Pitty (1968) for areas in the United States range from less than 1 mm/1000 yrs for New Mexico to 5 mm/1000 yrs for Florida. Jennings (1971) reports values between 12-44 mm/1000 yrs for the Yucatan, Mexico, while most values reported by Sweeting (1973) and Jennings (1971) for England and Ireland are around 40 mm/1000 yrs. Therefore, the values calculated for the study area are within the expected range for West Virginia's climate. The mean of 1200 mm/1000 yrs calculated by Coward (1971) is much higher than this author's, due to his measurements being taken on a bedrock streambed in a cave where erosion is many times higher than average for a basin.

Well Water Chemistry

Introduction

Well samples were taken during two periods. The first was during the fall of 1974, which is the dry season, and the second sampling was done during the late spring of 1975 (the wet season). The objectives of this phase of the study were to (1) check for seasonal variations among aquifers, (2) test for chemical differences among aquifers, (3) locate polluted wells and suggest pollution sources, (4) test the relationship of water chemistry to photolineaments, and finally (5) determine the relationships among chemical variables by factor analysis.

The following chemical variables were measured for most sampling sites: temperature, specific conductance, pH, calcium, magnesium, total hardness, bicarbonate, sulfate, chloride, and nitrate. From these measured variables SIc, SId, Pco_2, Ca/Mg ratio, and the percent error, were calculated by the same computer program described for the spring samples. These analyses can be found in Appendix C. Sulfate was not measured during fall, 1974, because sulfate was not originally though to be of significant abundance.

A cursory comparison of the wells and springs indicate that wells generally are more concentrated with respect to many of the individual ionic species. This is due to the diffuse nature of recharge and ground water movement, which causes longer residence times for ground water (and thus more time to dissolve rock) for wells than for conduit springs. Nitrate, sulfate, and chloride are on the other hand often more concentrated for springs, since springs are more susceptible to pollution than wells. Well waters are usually more saturated with respect to calcite and dolomite, again due to longer residence times. The high SIc values for the wells indicate supersaturation for most of them, similar to the supersaturation of springs. This supersaturation may be due to degassing of some CO_2 from well waters either before or after sampling.

Nine wells were sampled and analyzed by the U.S. Geological Survey in 1971 in central Monroe County (Chisholm and Friel, 1975). Seven of these wells were resampled by this author. All of the analyses were similar to those of this study, with minor variations as expected from seasonal differences. The nine wells were analyzed for six variables not measured in this study. Table 11 is a list of these variables and their ranges found by the U.S. Geological Survey (Chisholm and Friel, 1975).

Seasonal Variations

The means and standard deviations of each chemical parameter were calculated for each aquifer and for each sampling period (Tables 12a and 12b). These data were used to test for seasonal variations of water chemistry for each major aquifer. The three main aquifers (Hillsdale-Maccrady, Patton-Taggard, and Union-Greenville) were tested using the Mann-Whitney U test (Siegel, 1956)

Table 11

Range of Measured Chemical Parameters of Chisholm and Friel (1975) For Variables Not Measured by This Author

Fluoride	0.10-0.40 mg/l
Sodium	2.80-10.00 mg/l
Potassium	0.70-1.70 mg/l
Iron	0.02-0.37 mg/l
Manganese	0.00-0.37 mg/l
Silica	6.2-15.0 mg/l

Table 12a

Well Water Quality as a Function of Aquifer Type and Season.

	Hillsdale-Maccrady Aquifer				Sinks Grove Aquifer			
	Fall, 1975		Spring, 1975		Fall, 1974		Spring, 1975	
Variable	Mean	Std.*	Mean	Std.	Mean	Std.	Mean	Std.
pH	7.47	0.18	7.50	0.15	7.46	0.10	7.46	0.21
Specific Conductance	576	412	622	487	467	376	496	104
Calcium	92.9	71.5	105.0	82.7	90.4	34.4	87.2	25.4
Magnesium	17.8	15.0	17.3	17.8	36.2	43.2	9.6	7.0
Total Hardness	306	218	334	256	374	231	257	49
SIc	0.21	0.25	0.14	0.21	0.25	0.17	0.20	0.16
SId	-0.11	0.26	-0.21	0.31	-0.01	0.32	-0.26	0.31
Chloride	4.7	5.6	5.5	3.1	8.5	8.6	13.3	13.1
Nitrate	7.6	7.9	11.9	13.0	5.8	4.4	20.9	33.0
Sulfate	+	+	107	254	+	+	24	15
Pco$_2$**	-2.15	0.23	-2.21	0.20	-2.08	0.11	-2.13	0.22
Ca/Mg Ratio	4.3	2.6	5.6	3.7	4.5	4.3	14.7	21.4

*Represents Standard Deviation.
+Not measured.
**Log to base 10 of Pco$_2$.

Table 12b

Well Water Quality as a Function of Aquifer Type and Season

	Patton-Taggard Aquifer				Union-Greenville Aquifer			
	Fall, 1974		Spring, 1975		Fall, 1974		Spring, 1975	
Variable	Mean	Std.*	Mean	Std.	Mean	Std.	Mean	Std.
pH	7.37	0.21	7.50	0.21	7.21	0.11	7.41	0.08
Specific Conductance	513	163	523	215	758	109	774	190
Calcium	87.5	30.6	93.7	28.2	106.2	15.1	112.6	17.6
Magnesium	10.3	5.6	7.6	6.7	15.3	11.8	9.0	9.9
Bicarbonate	272	50	255	55	303	47	277	30
Total Hardness	262	70	265	75	324	69	318	65
SIc	0.20	0.18	0.21	0.25	0.14	0.10	0.28	0.10
SId	-0.27	0.28	-0.29	0.27	-0.30	0.25	-0.32	0.29
Chloride	8.1	7.0	23.0	61.7	80.6	71.8	74.6	55.5
Nitrate	11.6	8.2	19.0	5.8	12.3	10.2	22.7	19.5
Sulfate	+	+	45	88	+	+	33	21
P_{CO_2}**	-2.01	0.26	-2.18	0.27	-1.79	0.18	-2.04	0.13
Ca/Mg Ratio	9.1	9.5	15.3	14.8	6.9	7.1	26.7	38.6

*Represents Standard Deviation
+Not measured
**Log_{10} of P_{CO_2}

from the NPARMWU computer procedures for comparison of variable means. The alpha probability (two-tailed) for the difference of means was determined; Tables 13a and 13b shows the calculated alpha probabilities. Any variable having an alpha probability of less than 0.10 is considered significant, indicating less than a 10 percent chance that a variable difference between the fall and spring sampling periods was due to chance. Temperature was not used because it was considered unreliable due to the samples being taken from household sinks with varying amount of piping and tank storages.

Tables 13a and 13b indicate that the Patton-Taggard and Union-Greenville aquifers show some significant seasonal variation in ground water chemistry while the Hillsdale-Maccrady aquifer does not. Hillsdale-Maccrady wells are generally 100 ft shallower than Patton-Taggard wells. The greater depth of the Hillsdale-Maccrady aquifer probably results in older ground water which is more buffered against chemical changes with time. Shallower and more rapidly moving ground water of the nearer-surface aquifers are affected by surface and hence seasonal changes. A second factor is that the shallower Union-Greenville and Patton-Taggard aquifers are known to receive part of their recharge from sinking streams or concentrated infiltration, resulting in more rapid recharge for these aquifers. The Hillsdale-Maccrady aquifer, being deeper on the average, probably has a higher percentage of diffuse recharge then the shallower aquifers.

Table 13a

Alpha Probability of Significant Well Water Quality Differences between Fall and Spring Seasons with the Two-Tailed Mann-Whitney U Test

Aquifer	Calcium	Magnesium	Total Hardness	Bicarbonate	Specific Conductance	pH
Hillsdale-Maccrady	0.24	0.32	0.64	0.32	0.46	0.66
Patton-Taggard	0.04	0.22	0.96	0.26	0.74	0.02
Union-Greenville	0.14	0.16	0.70	0.82	0.58	0.02

Table 13b

Alpha Probability of Significant Well Water Quality Differences between Fall and Spring Seasons with the Two-Tailed Mann-Whitney U Test

Aquifer	SIc	SId	Pco_2*	Chloride	Nitrate	Ca/Mg Ratio
Hillsdale-Maccrady	0.64	0.44	0.36	0.44	0.26	0.24
Patton-Taggard	0.02	0.78	0.02	0.16	0.22	0.04
Union-Greenville	0.04	0.58	0.04	0.70	0.54	0.14

*Log_{10} of Pco_2

The Patton-Taggard and Union-Greenville wells show a significant ground water increase in pH and SIc, in addition to significant decreases in Pco_2, between fall, 1974, and spring, 1975. Pco_2 in shallow ground water should be highest during the summer and early fall because of recharge of CO_2-rich soil waters; soil CO_2 concentrations are highest during the growing season because of higher temperatures and greater microbial activity, resulting in greater decay rates then. Depletion of carbonic acid in ground water by carbonate dissolution would then decrease the Pco_2 of well waters by spring. Pco_2 should not start increasing until the late spring or early summer in response to delayed recharge of diffuse waters. As Pco_2 and hence carbonic acid concentration decrease between fall and spring, the pH and degree of calcite saturation would increase as a result.

Most of the other variables do not show significant changes even at the 0.10 alpha probability level. There is a general but insignificant increase in chloride between the fall and spring which may reflect the winter road salting. Nitrate also shows a slight increase during this period. This may be caused by greater recharge of nitrate from agricultural sources through the soil zone during the non-growing months; soil nitrate would be more absorbed by plants during the growing seasons.

Differences Among Aquifers

In addition to seasonal chemical differences, chemical differences among aquifers are apparent from Tables 12a and 12b.

Significant chemical differences among aquifer well waters were tested using the spring, 1975 well data and the two-tailed Mann-Whitney U test. The results of these tests are given in Tables 14a and 14b.

The Patton-Taggard and Hillsdale-Maccrady aquifers are the most important ones and therefore were compared first (Tables 14a and 14b). At the 0.10 alpha level, the significantly differentiating variables are magnesium, chloride, nitrate, SId, and the calcium-magnesium ratio. Magnesium is more concentrated in Hillsdale-Maccrady ground water, which results in a higher SId and a lower calcium-magnesium ratio for this aquifer. This suggests that there is more dolomite in the upper Maccrady and lower Hillsdale units than in the Taggard and Patton strata. This is in agreement with a dolomitic zone in the lower Greenbrier Group described by Martens and Hoskins (1948) and observed by this author. The Patton-Taggard wells are higher in chloride and nitrate which would be expected due to their shallower depths and hence greater accessibility to polluted surface waters. There is also a higher concentration of sulfate in the Hillsdale-Maccrady wells, which is probably due to the presence of gypsum in this stratigraphic zone.

In comparing Union-Greenville and Patton-Taggard well water qualities, only chloride concentration and specific conductance show significant differences at the 0.10 alpha level; both variables are higher for the Union-Greenville aquifer wells, due to contamination by the improper storage of road salts (Wilmoth, 1971).

Table 14a

Alpha Probability of Significant Well Water Quality Differences between Aquifers with the Two-Tailed Mann-Whitney U Test

Aquifers Compared	Calcium	Magnesium	Total Hardness	Bicarbonate	Specific Conductance	pH
Patton-Taggard vs Hillsdale-Maccrady	0.96	0.02	1.00	0.24	0.96	0.72
Patton-Taggard vs Union-Greenville	0.02	0.94	0.06	0.26	0.02	0.24
Sinks Grove vs Hillsdale-Maccrady	0.20	0.48	0.26	0.12	0.14	0.44
Sinks Grove vs Patton-Taggard	0.56	0.62	0.46	0.80	.98	0.72

Table 14b

Alpha Probability of Significant Well Water Quality Differences between Aquifers with the Two-Tailed Mann-Whitney U Test

Aquifers Compared	SIc	SId	Pco_2*	Chloride	Nitrate	Ca/Mg Ratio
Patton-Taggard vs Hillsdale-Maccrady	0.74	0.02	0.96	0.02	0.10	0.02
Patton-Taggard vs Union-Greenville	0.50	0.76	0.10	0.02	0.66	0.74
Sinks Grove vs Hillsdale-Maccrady	0.48	0.50	0.36	0.38	0.84	0.20
Sinks Grove vs Patton-Taggard	0.90	0.60	0.46	0.44	0.64	0.48

*Log_{10} of Pco_2

A comparison of Sinks Grove and Hillsdale-Maccrady wells shows that sulfate is the only chemical constituent significantly different in concentration at the 0.10 alpha level; sulfate is more concentrated in Hillsdale-Maccrady wells, which again is probably indicative of the presence of gypsum.

Patton-Taggard and Sinks Grove wells show no significant differences for any variable tested. This suggests that similar lithologies exist for the two aquifers. The Sinks Grove wells generally have water qualities in between those of the Patton-Taggard and Hillsdale-Maccrady wells. Sinks Grove ground water is also less hard than Hillsdale-Maccrady ground water and has lower concentrations of chloride and nitrate than Patton-Taggard ground water.

Well Water Chemistry Factor Analysis

Factor analysis was performed to determine relationships among well water quality variables in the same manner as was done for springs. The 1975 well data were used for this analysis. The 1974 well samples were not used because sulfate had not been measured. Because there are few chemical differences between the major aquifers, all well data were combined for the analysis in a single data set; however, data for the Union-Greenville aquifer wells near Salt Sulphur Springs were excluded because salt pollution caused these wells to be significantly different from other wells in terms of quality. Data for 58 wells were analyzed with the results shown in Table 15. Five factors were required to explain 88.4 percent of the total variance of the data. Factor loadings greater than 0.33 (Mendenhall, 1971) were considered significant for interpretation of variable relationships, assuming normal data and a 0.01 alpha probability.

The first factor explaining the greatest percentage of information in the data matrix, represents the limestone dissolution factor. From Table 15, total hardness, SIc, calcium, and specific conductance are all highly associated. An increase in any one of these will generally be associated with an increase in the others. Chloride and sulfate also load significantly with this factor indicating their strong relationship to specific conductance. Sulfate probably originates from the shales in contact with limestone, from both pyrite and gypsum weathering.

The second factor is the carbonate aggressivity factor in which pH, SIc, SId, magnesium, bicarbonate, and total hardness are related. SIc, SId, bicarbonate, total hardness, and magnesium are found to increase together as carbonate rock is dissolved. The pH is also found to increase with these variables. This is similar to the relationships of Dickson and Cold springs for this factor and has similar geochemical interpretations behind it. As magnesium increases from dolomite dissolution, there will also be an increase in SId and total hardness.

Table 15

Factor Analysis Summary for Wells Showing Significantly Loaded Variables for Each Factor

Limestone Dissolution Factor	Carbonate Aggressivity Factor	Carbonic Acid Factor	Nitrate Pollution Factor	Dolomite Dissolution Factor
+(Spc. Cond.)	+(pH)	-(pH)	+(temperature)	+(HCO_3)
+(Ca)	+(Mg)	+(Ca)	+(NO_3)	+(SId)
+(Cl)	+(HCO_3)	+(HCO_3)	-(SO_4)	-(Ca/Mg)
+(SO_4)	+(Tot. Hard)	+(Tot. Hard)		
+(Tot. Hard)	+(SIc)	+(Pco_2)		
+(SIc)	+(SId)			

The third factor is defined as the carbonic acid factor in which P_{CO_2}, total hardness, bicarbonate, and calcium concentrations are all related inversely (negatively) to pH (Table 15). An increase in the P_{CO_2} will cause the calcium and bicarbonate concentrations (and hence total hardness) to increase while the pH decreases. This is expected in an open geochemical system where there are constant additions of carbonic acid to the aquifers by recharge.

The fourth factor is the nitrate pollution factor, which is similar to that of the springs. Such pollution is again believed to originate from fertilizers and animal wastes from farming activities. This factor, with high loadings for just temperature, nitrate, and sulfate, indicates independence from carbonate geochemistry. Unlike the springs, temperature and nitrate are related in a positive manner. The reasons for the temperature-nitrate association are unclear; however, temperature was probably not reliably measured, as many measured samples were probably warmer than ground water in the respective wells. The inverse relationship of sulfate to the other two variables is less clear. Sulfate is barely significant, indicating a weaker relationship.

The final factor is the dolomite dissolution factor. The Ca-Mg ratio and SId are inversely related as they were for the springs. An increase in the saturation of dolomite is associated with an increase in the magnesium concentration and a decrease in the Ca-Mg ratio.

For the most part, the two sets of factor analyses (wells and springs) are similar, with the wells' analysis being most similar to that of Salt Sulphur South Spring. This is expected since both have diffuse flow. The major difference appears to be the fact that chloride loads heavily with the limestone dissolution factor for the wells, but is an independent factor for two of the springs and the insurgence. Diffuse recharge and depth of wells tend to inhibit chloride contamination from such sources as road salt spreading. The Union-Greenville wells are naturally an exception to this.

Jacobson, et al. (1971) used four factors in an R-mode analysis of carbonate wells in central Pennsylvania. They found two factors somewhat the same to this author's; they were a limestone dissolution factor and a nitrate factor. They also found a septic tank and road salt factor in which Na^+ and Cl^- were significantly loaded. Their fourth factor was a physical factor in which depth and elevation were loaded heavily. These two variables were not included in this author's factor analysis.

Pollution of Wells

The overall quality of the carbonate well waters is good in central Monroe County, but there are some cases of ground water contamination. Wells were tested for chloride, nitrate, and sulfate since these inorganic constituents commonly indicate pollution. A few wells were found to have high concentrations of each of the constituents, and one well was found to be contaminated by gasoline.

Nitrate Contaminated Wells

The occurrence, causes, and ramifications of nitrate in wells has been previously discussed. Forty-five milligrams per liter is the U.S. Public Health Service (1962) recommended limit. This concentration was not exceeded in any of the fall season wells; some were close. As noted earlier, nitrate levels were found to increase during the winter and spring to the point that six wells exceeded 45 mg/l for spring, 1975. Three others were over 35 mg/l. Of the six contaminated wells over 45 mg/l, three (T122, T117, and T122) are in the Patton-Taggard aquifer, one (SG12) is in the Sinks Grove aquifer, one (G106) is in the Union-Greenville aquifer, and one (M122) is in the Hillsdale-Maccrady aquifer. Generally, the shallower wells contain higher nitrate concentrations. In most cases, high nitrate wells are very close to barnyards and dairies where animal wastes are concentrated.

Chloride Contaminated Wells

Only one group of wells were found to be significantly contaminated with chloride. These wells are all in the Union-Greenville aquifer, although uncased Patton-Taggard wells in the Salt Sulphur springs area also have high chloride concentrations. These wells are usually less than 150 ft deep. Wilmoth (1971) noted the effect of an uncovered road salt pile on wells in the study area from 1966 to 1970. Natural chloride concentrations are generally less than 20 mg/l, but one well (G109) increased to 7,200 mg/l in 1970 when there was a large increase in the nearby salt pile. The storage area was in an abandoned Union Limestone quarry, up gradient from the polluted wells. Ground water moved laterally towards Indian Creek through the highly permeable limestone until the whole shallow Union-Greenville aquifer was contaminated. After much local harassment, the Department of Highways moved the piles in late 1970 and made out-of-court settlements with area residents for corrosion damage to pumps, plumbing, and appliances. The monitored well (G109) decreased to 188 mg/l by the following two months.

In the early fall of 1974, this author was called to investigate the water quality of well G100 in the same area (Ogden, 1976). The owner of the well had had to replace the boiler heating systems twice in eight years for the cost of about $3,000. The well was found to contain 132 mg/l chloride indicating some presence of the original road salt. Subsequent sampling of all the wells in the area showed that the earlier contamination had been diluted but was migrating southwest toward Indian Creek (see Figure 70). This migration caused well G100 to be contaminated several years after the problem was assumed to be solved. One nearby well drilled in 1970 (T142) was cased through the shallow polluted aquifer and obtained water at a lower level with only 15 mg/l of chloride.

Only one well (T123) exceeds the 250 mg/l recommended U.S. Public Health Service (1962) limit for chloride; however, even lower chloride concentrations in other wells pose economic hardships and indirectly threaten health, as well as representing aesthetic pollution. Well G103 is used by a dairy which has monthly water standards to meet and expensive machinery to keep clean. Wells G100 and T123 have owners who are supposed to be on salt-free diets, but who were unknowingly drinking salty water; such diets in these cases are required to avoid sodium, which is associated with chloride from their common sources. The fact that the Union-Greenville aquifer has been pumpted by many families for four years since peak chloride contamination and yet is still polluted, demonstrates the long time period necessary to restore an aquifer to its original water quality.

Sulfate-Rich Wells

Sulfate was not measured in the 1974 well samples but was later found to be locally abundant. It was therefore measured on the 1975 well samples. Six wells have concentrations of over 100 mg/l of sulfate and four of these have over the 250 mg/l limit recommended by the U.S. Public Health Service (1962). All of these wells are in the Hillsdale-Maccrady aquifer. The highest value measured was 988 mg/l, for well M127.

The high-sulfate wells are all greater than 300 ft deep and appear to have no nearby source of man-made pollution. Instead

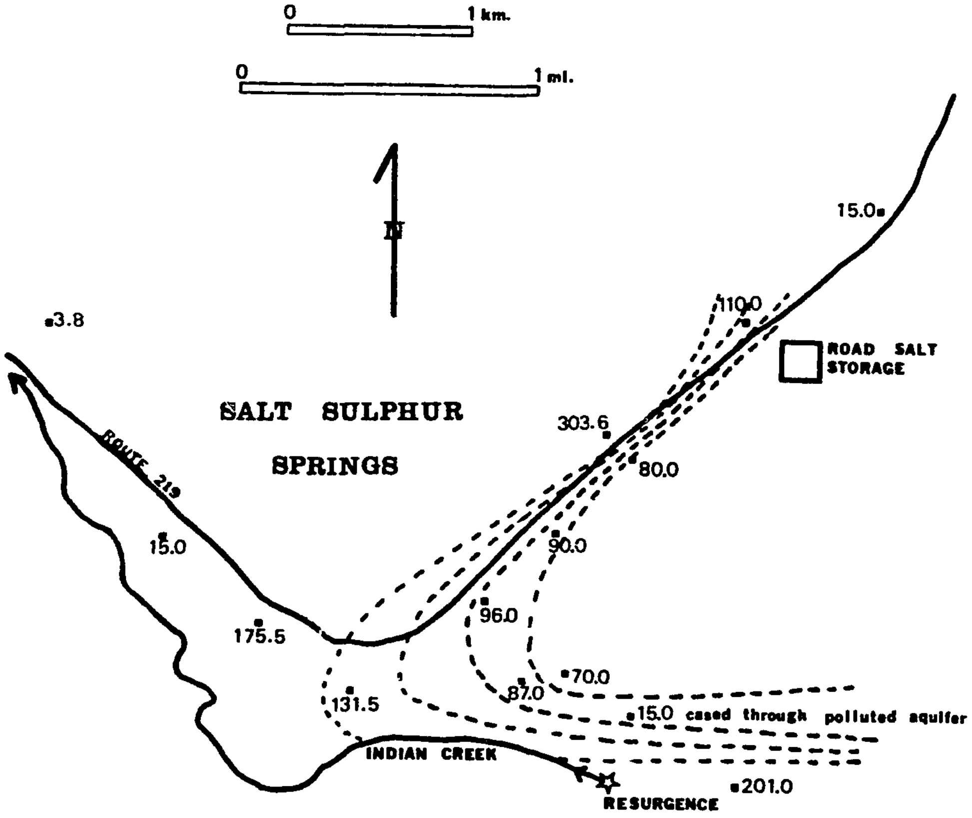

Figure 70. Isochlor map for the Union-Greenville aquifer around Salt Sulphur Springs. The numbers indicate chloride concentration of well waters in mg/l. Controu interval is equal to 20 mg/l chloride.

the contamination appears to be natural, being probably derived from gypsum-rich portions of the Hillsdale-Maccrady aquifer. The presence of gypsum in the Maccrady Shale was noted by Reger (1926) and by this author. The Ca/Mg ratios are generally lower for those wells with high sulfate concentrations. This opposes the gypsum origin for the high hardness, and suggest that pyrite weathering from the Maccrady shales may be important. These high sulfate wells generally have a lower pH (possibly from pyrite weathering) and are therefore capable of dissolving more limestone, increasing the hardness.

It was discovered during the sampling that two wells drilled near each other to nearly the same depth had remarkably different water chemistries. One well (M124) had water that was extremely hard and rich in sulfate, while the other (M106) was of the usual chemistry for the area. Well M106 was drilled to just above the Hillsdale-Maccrady boundary, while well M124 went about thirty feet into the Maccrady, intercepting beds rich in sulfur minerals. Evidence from one other site also suggests that deeper well penetration into the Maccrady aquifer yields water with higher hardness and sulfate concentrations.

It is a common practice of drillers to continue drilling once water is obtained to provide what they termed a "reservoir." This practice may be good for unconfined aquifers, but in central Monroe County the major aquifers are confined, making this extra drilling unnecessary. The additional drilling is in fact costly both initially and later for water filtration equipment. This information has been released to local drillers and is hopefully being used by them.

Relation of Water Chemistry to Photo-Lineaments

No evidence was found for fracture traces representing zones of increased ground water flow with high-yielding wells for the study area. To further test the effects of fracture traces, well water chemistry was tested as a function of lineament proximity. A study by Coughlin (1975) has shown wells on photo-lineaments in the Boone Limestone of Arkansas to have lesser concentrations of cations than wells off lineaments. These conclusions were drawn from casual observation of cation means of the two well groups (on and off photo-lineaments), but were not tested statistically. In this study the Fisher's exact probability test (Siegel, 1956) was used in a manner similar to that described for testing well yield; with two classes: (1) wells less than 100 ft versus wells greater than 100 ft from the nearest photo-lineament; and (2) wells less than 200 ft versus wells greater than 200 ft from the nearest photo-lineament. The median value of each chemical parameter was used to distinguish between high and low concentrations.

The Patton-Taggard and Maccrady-Hillsdale aquifers were the only aquifers tested due to the small sample sizes of the Sinks Grove and Union-Greenville aquifers. The calculated alpha probabilities are shown in Table 16a and 16b. Specific

Table 16a

Alpha Probability of Significant Well Water Quality Associations with Photo-Lineaments for the Patton-Taggard Aquifer, Using the Fisher Exact Probability Test

Date Tested for Well Proximity to Photo-Lineament	Number of Wells in Each Cell				Alpha Probability
	A	B	C	D	
	Specific Conductance				
Wells less than 100' vs Wells farther than 100'	2	3	6	11	0.39
Wells less than 200' vs Wells farther than 200'	10	6	6	11	0.08
	Nitrate				
Wells less than 100' vs Wells farther than 100'	5	2	9	7	0.12
Wells less than 200' vs Wells farther than 200'	7	10	9	7	0.05
	Sulfate				
Wells less than 100' vs Wells farther than 100'	5	2	8	8	0.40
Wells less than 200' vs Wells farther than 200'	7	10	8	8	0.22

Table 16a--Continued

Date Tested for Well Proximity to Photo-Lineament	Number of Wells in Each Cell				Alpha Probability
	A	B	C	D	
Chloride					
Wells less than 100' vs Wells farther than 100'	5	0	9	8	0.76
Wells less than 200' vs Wells farther than 200'	8	8	9	8	0.71
Total Hardness					
Wells less than 100' vs Wells farther than 100'	4	1	9	10	0.19
Wells less than 200' vs Wells farther than 200'	11	3	9	10	0.06

Table 16b

Alpha Probability of Significant Well Water Quality Associations with Photo-Lineaments for the Hillsdale-Maccrady Aquifer, using the Fisher Exact Probability Test

Date Tested for Well Proximity to Photo-Lineament	Number of Wells in Each Cell				Alpha Probability
	A	B	C	D	
Specific Conductance					
Wells less than 100' vs Wells farther than 100'	3	1	5	8	0.21
Wells less than 200' vs Wells farther than 200'	7	3	5	8	0.06
Nitrate					
Wells less than 100' vs Wells farther than 100'	2	2	5	8	0.80
Wells less than 200' vs Wells farther than 200'	6	4	5	8	0.20
Sulfate					
Wells less than 100' vs Wells farther than 100'	1	3	6	7	0.64
Wells less than 200' vs Wells farther than 200'	6	4	6	7	0.42

Table 16b--Continued

Date Tested for Well Proximity to Photo-Lineament	Number of Wells in Each Cell				Alpha Probability
	A	B	C	D	
Chloride					
Wells less than 100' vs Wells farther than 100'	1	3	6	7	0.35
Wells less than 200' vs Wells farther than 200'	5	5	6	7	0.30
Total Hardness					
Wells less than 100' vs Wells farther than 100'	2	2	7	5	0.28
Wells less than 200' vs Wells farther than 200'	6	5	7	5	0.32

conductance, total hardness and nitrate are the only chemical variables that are significantly related to lineament proximity at the 0.10 alpha probability for the Hillsdale-Maccrady aquifer. Specific conductance and total hardness of wells are significantly lower within 200 ft of photo-lineaments (fractures traces), while nitrate concentration is significantly higher within 200 ft of fractures traces. These results may indicate that photo-lineaments represent broad zones of increased fracture and that permeability faster movement of ground water along these zones result in lower total hardness values and therefore in lower specific conductances. These fracture zones are likewise areas that are more prone to the influx of surface pollution, as indicated by the higher nitrate concentrations.

The above conclusions are not as apparent for the Patton-Taggard aquifer. Only specific conductance is significantly different (lower) for near-lineament well waters. The primary difference between the two aquifers is average depth. The Hillsdale-Maccrady wells are usually deeper, with greater vertical and lateral distances from recharge areas. This factor may somehow explain the observed aquifer differences, but any suggested explanations would be highly speculative. The lack of significant differences for sulfate and chloride concentrations in both aquifers is puzzling in view of the original conclusions drawn from Table 16 for the Hillsdale-Maccrady aquifer. Subsequent testing of Coughlin's (1975) data by this author has shown that his conclusions cannot be substantiated statistically. Therefore, there appears to be little evidence for a strong control of lineaments on water chemistry in the study area or in the carbonates of northwest Arkansas.

SUMMARY AND CONCLUSIONS

Overview

The purpose of this study was to characterize the aquifers of the Greenbrier Limestone Group in central Monroe County by first mapping the geology and then chemically characterizing both well waters and overlying spring waters. The study area has characteristics similar to those of the braod flat-lying Mississippian limestones of Kentucky and Tennessee, as well as to the faulted and folded limestones of the Valley and Ridge Province of Pennsylvania and Virginia. The mature karst of central Monroe County is likewise similar to other Greenbrier karst regions of West Virginia.

The study was undertaken in four parts: (1) mapping of the geologic structures and Greenbrier Limestone formations; (2) investigation of aquifers by well inventorying; (3) investigation of the chemistry of aquifer waters; and (4) study of the seasonal and storm trends in spring water chemistry.

Stratigraphy, Structure, and Karst Geology

The central Monroe County karst is developed on an average of 1100 ft of Mississippian Greenbrier Limestone. Within the 65 square mile study area, there are nine major folds and several thrust faults of local extent. The folds trend in a NE-SW direction and are generally broad and of low plunge. The stratigraphic dip averages about 15 degrees but can be vertical or overturned near faults. The nine formations of the Greenbrier Group can be distinguished and were mapped in detail. The Greenville Shale and Patton Shale were mapped in with the Alderson and Sinks Grove formations respectively, due to their discontinuous nature. Shales and shaly limestones were used in most cases to separate the formations. A useful application of the map could be for determining farm pond locations on the shales and shaly limestones.

Caverns are found primarily in the Union, Patton, and Sinks Grove formations whereas areas of highest doline density are found on Union, Taggard, and Patton formation surfaces due in part to the collapse of the Taggard shales into the underlying Patton Formation. These formations are therefore least desirable for household and industrial development. Cavern orientation is not significantly related to joints, stratigraphic strike, or lineaments individually, but is related to a combination of these factors. Lineaments are nearly evenly distributed among all directions of the compass and have essentially equal densities for all formations not cropping out on mountain slopes.

Hydrogeology

Three main confined aquifers exist within the Greenbrier Limestone: (1) the Hillsdale-Maccrady aquifer; (2) the Patton-Taggard aquifer; (3) the Union-Greenville aquifer. For each aquifer, the primary aquifer unit is listed first while the prime overlying or underlying confining shale unit is given second. This listing also gives the relative order (greatest to least) of average well productivity, well depth, and use of the aquifers for water supply. The piezometric surface of each aquifer was mapped where there was sufficient well information. The gradient of the Hillsdale-Maccrady piezometric surface is relatively high, being approximately 85 ft/mile. The aquifers appear to be completely separate from the spring conduit systems with spring drainage systems both overlying and underlying the piezometric surfaces of the confined aquifers.

Well productivity (gallons per minute) is not statistically related to photo-lineaments as has been found for some other regions. This is probably due in part to the abundance of sinkholes from which the lineaments were defined; this results in many lineaments not representing joint swarms or concentrations of fractures. Some lineaments may be false alignments of randomly located dolines.

Recharge to the Hillsdale-Maccrady aquifer is primarily along Little Mountain with discharge being to the northwest along Second Creek and the Greenbrier River. The Patton-Taggard aquifer is recharged in the northeastern portion of the study area; ground water is funneled southwestward by a plunging syncline and is believed to discharge along the Burnside Branch of Indian Creek. All of the aquifers are believed to be recharged primarily by diffuse flow. From a practical standpoint the collected well information allows for the prediction of depth that an individual must drill to obtain water within the study area.

Aqueous Geochemistry

Eight springs and one insurgent stream were sampled throughout the 1974-75 academic year to test for seasonal and discharge effects on water chemistry. Generally, all chemical variables decreased during winter months except for nitrate concentration. Seasonal variations are caused by the amount of biotic activity in soils, the amount of rainfall and recharge, and the temperature.

Vadose conduit springs show the highest coefficients of variation for all variables, while phreatic conduits and/or larger springs have lower coefficients. Annual trends are shown most strongly for temperature, Pco_2, and nitrate, while significant chemical variations associated with discharge were found for total hardness for most sampling stations. A few of the springs close to highways show abnormal increases in chloride concentration which may be due to road salt spreading.

Coefficients of variation of tested parameters show general decreases downstream from insurgence points, due to buffering and residence time effects.

The two Salt Sulphur springs may be due to shallow diffuse movement of ground water rather than deep circulation, with sulfate coming from pyrite weathering. They have high coefficients of variation due to their stagnant nature. All of the sulphur springs in the area have decreased in flow dramatically in the last hundred years to the point of being mere seeps; this may have indirectly resulted from earthquakes in the region that could have sealed deep-seated fractures. The Salt Sulphur springs show strong seasonal variations for chemical parameters due primarily to dilution effects from heavy late winter and spring rains.

Karst denudation rates were determined for three drainage basins, based on spring hardness and discharge. The carbonate leaching rate (gms $CaCO_3$/sec) was first determined. This leaching rate is dependent on discharge and water hardness. Although hardness is generally lower during high discharge from dilution effects, there is much more limestone dissolved during high water periods. Karst denudation values, ranging from 19.0 ± 7.2 to 20.1 ± 5.1 mm/1000 yrs, were determined from the carbonate leaching rates.

Spring chemistry response to storms was studied for three basins. Results show that the lag times between peak discharge and later minimum values of chemical parameters are increased with basin size and degree of phreatic (closed channel) flow. In general as basin size and average discharge increase, there are decreases in the range (maximum minus minimum values) in pH, total hardness, and chloride concentration as well as a decrease in the ratio of peak to base discharge during a storm.

Chemically, the waters of aquifers can be distinguished from one another. Statistically, the Hillsdale-Maccrady aquifer has the highest hardness and sulfate concentrations. The Union-

Greenville aquifer has the highest chloride concentrations due to contamination from improperly stored road salt. The Patton-Taggard aquifer and the locally productive Sinks Grove aquifer show intermediate water qualities. Patton-Taggard wells generally have higher nitrate values with three wells exceeding 45 mg/l.

Two of the aquifers show seasonal variations as determined by two sampling periods: (1) fall (a dry season) and (2) spring (a wet season). The shallower Union-Greenville and Patton-Taggard aquifers have statistically significant increases in pH, SIc, and Pco_2 and have overall increases in the specific conductance, Ca-Mg ratio, and concentrations of calcium, chloride and nitrate between fall and spring. Hillsdale-Maccrady aquifer waters show these same trends, but they are not statistically significant, probably because of the greater average depth of this aquifer. A significant practical application of the chemistry data is found by knowing that the Hillsdale-Maccrady water is of good quality if drilling is stopped immediately upon hitting water. Continued drilling into the Maccrady intersects water very high in sulfate and total hardness.

Relationships among variables for waters of wells, springs, and an insurgence were determined using factor analysis. Five factors were used to explain the significant grouping of variables, depending on the spring or well group. These factors were labeled: (1) limestone dissolution factor, (2) carbonate aggressivity factor, (3) dolomite dissolution factor, (4) nitrate pollution factor, (5) salt pollution factor, and (6) carbonic acid factor. The springs and wells show similar relationships among variables.

Recommendations for Future Research

The observations and results of this study, as well as the distribution of time spent on each of its subdivisions, brings to light areas needing future research.

From a mapping standpoint, a regional stratigraphic study of the lower Greenbrier Group is necessary in West Virginia to better define the lower formations and to determine the depositional history of these rocks. This would tie well into a similar study by Leonard (1968) of the upper Greenbrier Group.

Now that the first detailed geologic map of the Greenbrier Limestone is available, paleontological and sedimentological studies can be performed with greater ease and accuracy. A sedimentological study of facies changes within the Greenbrier Limestone would be useful in determining the validity of formations and for deciding whether formations should be further broken down into members.

With use of the geologic map, the karst region could be better characterized morphometrically. A detailed study of lithologic controls on cave development, similar to those of

Rauch (1972) and Hempel (1974), would also be valuable from a karst geomorphic viewpoint.

Further work needs to be done with the productivity of the aquifers through many more pumping tests. These aquifers likewise need to be better characterized by using well logs and collecting rock chips during drilling.

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Explanation of Symbols for Appendices A, C, and E

☼T - Temperature in degrees Centigrade

ϕSPC - Specific conductance in micro mhos/cm^2

✱Ca^{+2} - Calcium concentration in mg/l

✱Mg^{+2} - Magnesium concentration in mg/l

✱HCO_3 - Bicarbonate concentration in mg/l

✱ Cl^- - Chloride concentration in mg/l

✱NO_3^- - Nitrate concentration in mg/l

✱SO_4^{-2} - Sulfate concentration in mg/l

♦Tot Hard - Total Hardness concentration in mg/l as $CaCO_3$

☼Discharg - Discharge in cubic feet per second

SIC - Saturation index for calcite = $\log [(Ca^{+2})(CO_3^{-2})/K_c]$

SID - Saturation index for dolomite = $\log [(Ca^{+2})(Mg^{+2})(CO_3^{-2})^2/K_d]^{1/2}$

PCO_2 - Log CO_2 pressure

Ca/Mg - Calcium/Magnesium ratio

+Perr - Percent error = $\left| \frac{(\text{Epm cations} - \text{Epm anions})}{\text{Epm cations} + \text{Epm anions}/2} \right| \times 100$

APPENDIX A
CHEMICAL ANALYSES OF NINE SAMPLING SITES

MCPEAK'S SPRING

DATE	TIME	PH	T*	SPC◊	CA^{+2}*	MG^{+2}*	HCO3^{-}*	CL^{-}*	NO3^{-}*	SO4^{-2}*	TOT HARD♦	DISCHARG♦	SIC	SID	PCO2	CA/MG	PERR^{+}
740917	1700	7.20	13.1	566	102.0	6.9	305	17.0	15	.	284	0.20	0.08	-0.44	-1.79	8.97	0.8
741006	1400	7.52	14.0	600	104.3	8.7	318	24.0	11	.	296	0.05	0.43	-0.03	-2.09	7.27	1.5
741020	1430	7.54	13.5	525	97.4	4.9	294	2.6	11	.	263	0.11	0.39	-0.18	-2.14	12.06	1.7
741103	1225	7.65	15.0	587	107.3	10.7	299	18.0	9	.	292	0.05	0.56	0.14	-2.24	6.08	5.6
741117	1345	7.70	12.2	516	93.7	8.1	261	3.4	8	.	267	0.11	0.47	0.00	-2.36	7.02	8.4
741203	1325	7.70	10.7	460	86.5	4.3	243	4.1	6	.	268	0.55	0.39	-0.97	-2.40	9.94	1.5
741215	1530	7.50	9.5	425	78.3	3.9	230	9.1	11	.	212	1.77	0.11	-0.49	-2.23	12.18	0.0
741230	1655	7.79	10.2	429	82.5	4.8	231	10.0	8	.	226	0.95	0.43	-0.13	-2.51	10.42	3.4
750111	1300	7.79	10.0	434	82.8	3.2	226	12.0	10	.	220	0.28	0.42	-0.23	-2.52	15.69	2.0
750125	1230	7.80	9.0	308	57.7	4.7	169	4.4	9	.	163	5.12	0.16	-0.34	-2.66	7.45	3.3
750208	1230	8.00	7.5	369	70.6	4.6	199	5.9	11	.	195	0.43	0.48	-0.07	-2.79	9.31	3.7
750222	1145	7.81	9.8	432	83.3	4.8	235	10.0	16	.	228	0.67	0.46	-0.11	-2.53	10.53	1.5
750304	1215	7.80	9.1	411	85.5	3.0	231	11.0	14	.	226	0.04	0.44	-0.24	-2.53	17.28	1.9
750322	1320	7.82	10.1	402	43.9	2.9	204	5.9	12	.	122	0.32	0.16	-0.38	-2.59	9.18	21.0
750406	1100	7.78	9.0	455	72.4	4.7	233	8.7	12	.	200	0.06	0.36	-0.19	-2.50	9.34	3.2
750419	1300	7.67	10.6	426	82.8	7.6	230	9.9	12	.	238	0.03	0.31	-0.15	-2.39	6.61	5.6
750503	1250	7.81	11.6	355	74.0	3.6	201	3.6	8	.	200	0.34	0.38	-0.22	-2.58	12.47	6.0
750520	1345	7.82	14.0	413	83.5	3.7	233	6.5	15	.	224	0.09	0.53	-0.08	-2.52	13.69	2.3
750603	1200	7.39	14.0	452	88.1	3.6	236	7.5	14	.	235	0.09	0.12	-0.50	-2.08	14.84	4.1
750616		7.43	13.1	575	101.0	6.7	241	11.0	13	.	256	0.03	0.21	-0.70	-2.12	7.83	6.5
750628		7.31	12.9	575	56.7	3.4	265	11.0	11	.	156	0.01	-0.10	-0.64	-1.96	10.11	22.0
750712	1300	7.23	13.5	490	91.3	7.0	214	19.0	22	.	232	0.03	-0.07	-0.98	-1.97	7.64	2.4
750725	1045	7.30	13.2	530	99.5	2.9	269	15.0	16	.	260	0.11	0.12	-0.58	-1.94	20.81	0.8
750809	1045	7.24	13.5	490	96.1	2.3	242	21.0	23	.	250	0.09	0.01	-0.73	-1.93	25.34	0.3
750823	1400	7.43	13.4	573	101.2	4.7	268	17.0	20	23	272	0.11	0.25	-0.34	-2.08	13.06	2.4
750906	1400	7.38	13.0	605	105.6	4.5	261	27.3	27	37	282	0.33	0.20	-0.42	-2.04	14.23	5.3
750919		7.36	12.7	553	108.6	4.6	262	25.0	23	43	290	0.08	0.20	-0.44	-2.10	14.32	5.5
751005	1830	7.54	12.5	579	112.1	3.1	290	20.3	14	38	293	0.06	0.42	-0.29	-2.16	21.93	4.2

APPENDIX A (CONTINUED)

DICKSON SPRING

DATE	TIME	PH	T$^{☆}$	SPC$^{◊}$	CA^{+2*}	MG^{+2*}	HCO3^{-*}	CL^{*-}	NO3^{-*}	SO4^{-2*}	TOT HARD$^{♦}$	DISCHARG$^{♦}$	SIC	SID	PCO2	CA/MG	PERR^{+}
740917	1330	7.10	13.5	359	61.7	5.5	213	3.8	8	.	176	8.50	-0.36	-0.81	-1.84	6.80	3.0
741009	1230	7.27	12.0	335	67.8	7.4	234	3.9	10	.	200	9.30	-0.14	-0.55	-1.98	5.56	1.5
741020	1315	7.28	11.5	373	69.4	5.3	215	4.4	8	.	195	12.50	-0.16	-0.65	-2.03	7.94	1.4
741103	1110	7.38	11.7	365	63.8	6.7	194	4.7	6	.	187	9.80	-0.13	-0.56	-2.17	5.78	4.5
741117	1215	7.32	11.5	373	68.4	7.1	200	4.2	6	.	200	12.50	-0.15	-0.58	-2.10	5.84	6.5
741203	1655	7.50	11.5	347	61.0	6.5	184	5.0	5	.	179	11.20	-0.05	-0.48	-2.31	5.69	4.7
741215	1730	7.42	10.5	287	53.0	3.3	145	5.1	8	.	146	61.50	-0.30	-0.85	-2.34	9.74	4.5
741230	1845	7.50	10.7	282	52.2	5.3	154	5.2	7	.	152	27.50	-0.20	-0.64	-2.39	5.97	4.1
750111	1100	7.51	10.7	317	61.7	2.3	165	4.3	9	.	163	37.00	-0.09	-0.75	-2.37	16.27	4.4
750125	1700	7.43	9.5	278	49.7	4.4	142	4.8	11	.	142	16.70	-0.34	-0.81	-2.36	6.85	3.4
750208	1630	7.55	9.0	256	44.9	3.2	125	4.8	12	.	125	95.50	-0.32	-0.85	-2.54	8.51	2.4
750222	1330	7.56	10.0	304	59.3	3.3	156	5.4	15	.	162	27.50	-0.09	-0.67	-2.45	10.90	4.2
750307	1100	7.59	10.5	292	60.6	4.1	170	5.4	13	.	168	16.50	-0.01	-0.54	-2.44	8.96	3.2
750322	1130	7.55	9.5	274	46.1	4.6	127	4.6	16	.	134	95.50	-0.29	-0.75	-2.53	6.08	3.8
750405	1800	7.56	9.5	281	52.2	4.6	151	4.1	11	.	149	32.00	-0.16	-0.64	-2.46	6.88	3.4
750419	1200	7.60	10.2	306	58.6	5.6	170	4.7	11	.	170	18.00	-0.02	-0.47	-2.45	6.35	4.0
750503	1545	7.51	11.2	222	42.9	4.0	121	4.2	10	.	124	95.50	-0.36	-0.81	-2.50	6.50	4.0
750520	2020	7.51	11.5	263	52.4	3.8	150	4.1	8	.	146	36.00	-0.18	-0.69	-2.41	8.36	3.4
750603	1100	7.48	12.0	312	66.3	5.6	169	4.4	7	.	189	27.50	-0.06	-0.54	-2.32	7.18	10.9
750616		7.35	11.2	347	69.5	1.6	181	4.6	6	.	180	16.00	-0.16	-0.92	-2.17	26.33	5.7
750624		7.33	11.7	370	65.8	5.6	191	4.7	8	.	188	9.40	-0.17	-0.65	-2.13	7.13	4.8
750712	1140	7.30	11.7	338	67.1	4.0	188	4.9	9	.	184	12.50	-0.20	-0.75	-2.10	10.17	4.2
750725	1245	7.38	11.6	347	64.7	7.9	188	4.9	8	20.0	194	8.00	-0.14	-0.54	-2.18	4.97	1.2
750809	1330	7.36	12.4	361	67.6	6.2	191	5.2	5	17.5	194	7.00	-0.13	-0.58	-2.15	6.61	1.8
750823	1230	7.33	12.6	352	68.7	6.4	195	5.0	6	23.0	198	6.60	-0.14	-0.59	-2.11	6.51	0.4
750906	1300	7.32	13.0	334	50.0	12.5	178	5.6	11	12.0	194	7.00	-0.31	-0.54	-2.14	2.43	0.1
750918	1100	7.38	12.3	334	67.0	6.4	200	4.5	8	17.0	194	107.00	-0.09	-0.54	-2.15	6.35	0.4
751004	1000	7.59	11.8	351	65.0	6.7	193	5.9	7	21.0	190	7.66	0.08	-0.35	-2.38	5.88	1.2

APPENDIX A (CONTINUED)

ROGERS' SPRING

DATE	TIME	PH	T☆	SPC◇	CA•$^{+2}$	MG•$^{+2}$	HCO3•$^{-}$	CL•$^{-}$	NO3•$^{-}$	SO4•$^{-2}$	TOT HARD♦	DISCHARG✦	SIC	SID	PCO2	CA/MG	FERB^{+}
740917	1300	7.46	12.6	295	66.0	6.0	223	2.9	10	.	190	0.23	0.04	-0.42	-2.18	6.67	1.6
741006	1200	7.68	13.2	295	66.0	7.5	230	3.0	10	.	196	0.23	0.28	-0.13	-2.39	5.34	1.6
741020	1245	7.75	12.5	334	59.3	6.6	200	3.5	7	.	175	0.24	0.24	-0.17	-2.52	5.45	0.2
741103	1015	7.85	12.5	369	68.2	12.1	215	2.9	6	.	192	0.22	0.42	0.11	-2.59	3.42	8.4
741117	1140	7.99	12.3	378	67.3	7.6	215	2.3	9	.	199	0.22	0.55	0.14	-2.73	5.37	3.1
741203	1600	8.09	12.0	352	71.6	4.4	215	3.8	5	.	197	0.23	0.68	0.13	-2.83	9.87	2.6
741215	1135	8.00	10.8	325	63.0	5.7	196	2.8	9	.	181	2.00	0.48	0.01	-2.79	6.70	2.5
741230	1745	7.92	11.0	343	65.0	5.4	94	3.4	10	.	185	0.75	0.11	-0.38	-3.02	7.30	34.0
750111	945	8.10	10.5	343	65.5	7.3	196	3.4	10	.	194	1.00	0.59	0.16	-2.89	5.44	5.3
750125	1500	7.75	10.0	261	51.0	5.3	146	3.1	10	.	149	82.00	0.01	-0.43	-2.66	5.84	5.8
750208	1410	7.92	10.0	300	56.7	10.9	211	3.6	13	.	156	6.40	0.37	0.06	-2.68	3.16	0.8
750222	1300	8.03	10.2	330	62.8	4.1	180	4.0	13	.	174	1.31	0.46	-0.08	-2.86	9.29	2.6
750307	1145	8.10	10.3	315	63.6	5.4	197	4.9	11	.	181	0.39	0.58	-0.09	-2.89	7.14	0.7
750322	1230	7.86	10.5	317	55.3	9.4	161	4.2	12	.	154	3.60	0.20	-0.13	-2.73	3.57	8.8
750406	1730	7.88	10.4	334	61.0	4.6	181	4.0	10	.	171	1.35	0.31	-0.20	-2.70	8.04	2.5
750419	1115	7.86	10.4	319	52.0	10.6	192	4.1	9	.	173	0.39	0.24	-0.05	-2.66	2.98	0.8
750503	1500	7.97	11.8	295	57.3	4.1	172	2.9	6	.	160	3.50	0.37	-0.14	-2.81	8.48	3.0
750520	1930	8.00	12.0	332	58.5	12.0	198	3.0	8	.	195	1.45	0.46	0.18	-2.78	2.96	5.9
750603	1100	8.10	12.5	353	71.3	2.8	195	4.1	8	.	190	0.42	0.65	0.01	-2.88	15.44	4.8
750616		7.89	12.0	317	75.0	1.2	199	4.0	8	.	192	0.25	0.46	-0.37	-2.67	37.88	4.4
750628		7.81	11.8	361	71.4	2.4	199	3.8	8	.	188	0.21	0.36	-0.31	-2.59	18.04	3.4
750712	1120	7.81	12.1	338	74.5	3.8	200	5.0	6	.	188	0.19	0.39	-0.68	-2.58	10.93	2.9
750725	1230	7.55	12.5	355	68.4	5.3	203	4.7	7	.	192	0.18	0.10	-0.39	-2.31	7.83	3.5
750809	1330	7.67	12.1	355	67.0	6.7	202	5.0	5	8	195	0.18	0.20	-0.24	-2.44	6.07	2.4
750823	1230	7.57	12.0	352	70.5	4.8	204	5.1	5	6	196	0.18	0.13	-0.39	-2.34	8.91	2.8
750906	1230	7.62	12.7	315	60.0	3.2	171	4.9	13	8	163	0.20	0.05	-0.52	-2.46	11.37	1.1
750918	1300	7.63	12.5	290	61.7	3.0	198	5.1	7	8	166	0.21	0.13	-0.46	-2.40	12.47	5.1
751005	1230	7.59	12.2	334	68.6	2.9	199	4.2	11	7	183	0.22	0.13	-0.50	-2.37	14.40	0.7

APPENDIX A (CONTINUED)

WALTERS' SPRING

DATE	TIME	PH	T☆	SPC◊	CA^{+2}	MG^{+2}	HCO_3^{-}	CL^{-}	NO_3^{-}	SO_4^{-2}	TOT HARD♦	DISCHARG♦	SIC	SID	PCO2	CA/MG	PERR+
740917	1730	7.64	13.7	369	77.2	4.9	247	6.5	7	.	213	2.50	0.34	-0.19	-2.32	9.56	1.1
741006	1445	7.70	15.2	447	71.8	12.8	230	7.0	8	.	232	0.93	0.35	0.06	-2.40	3.40	5.9
741020	1445	7.68	13.5	369	67.0	7.0	214	7.4	6	.	196	1.15	0.26	-0.16	-2.42	5.81	1.2
741103	1200	7.90	15.0	429	79.0	4.2	237	8.8	9	.	214	0.84	0.61	0.05	-2.59	11.41	0.0
741117	1415	7.90	12.3	429	83.5	5.4	238	8.8	6	.	231	1.37	0.59	0.06	-2.60	9.38	4.1
741203	1345	7.99	11.2	403	77.7	3.4	236	7.8	4	.	208	1.85	0.63	0.01	-2.70	13.86	0.0
741215	1445	8.11	8.6	355	71.0	5.2	210	6.0	6	.	198	6.70	0.63	0.11	-2.88	8.28	3.3
741230	1715	8.00	10.0	360	70.2	4.6	209	6.7	5	.	194	5.00	0.54	0.00	-2.76	9.26	2.2
750111	1315	8.00	10.5	386	71.8	6.6	220	6.6	8	.	206	6.00	0.57	0.11	-2.74	6.60	2.5
750125	1330	8.03	9.5	425	65.4	4.3	187	5.9	9	.	181	70.00	0.49	-0.06	-2.84	9.22	3.1
750208	1245	7.93	8.0	339	64.7	3.4	179	5.3	11	.	176	35.00	0.34	-0.26	-2.77	11.54	3.3
750222	1135	8.00	9.7	365	70.3	4.3	204	7.0	12	.	193	6.20	0.52	-0.03	-2.77	9.92	1.4
750304	1230	7.95	9.5	367	74.5	5.6	214	7.5	12	.	209	4.00	0.51	0.00	-2.71	8.07	3.1
750322	1330	7.86	9.5	334	60.1	6.2	184	5.7	11	.	176	29.00	0.27	-0.17	-2.68	5.88	1.8
750406	1115	8.20	8.7	403	48.6	4.7	204	6.1	9	.	168	10.00	0.56	0.10	-2.98	6.27	13.4
750419	1315	7.80	10.0	374	73.2	5.8	212	7.2	8	.	207	4.50	0.36	-0.14	-2.56	7.65	3.9
750503	1310	7.89	12.3	332	65.0	4.0	190	4.4	8	.	179	32.00	0.39	-0.15	-2.68	9.86	2.7
750520	1410	8.00	13.2	352	59.8	8.7	206	5.6	8	.	185	13.50	0.51	0.16	-2.75	4.17	0.1
750603	1230	7.80	14.1	370	79.1	4.8	206	4.7	7	.	217	12.00	0.44	-0.10	-2.55	9.99	9.0
750616		7.81	13.6	430	79.9	5.1	216	4.3	5	.	205	5.60	0.47	-0.34	-2.54	10.14	4.3
750624		7.89	12.7	447	83.3	6.5	224	7.4	6	.	210	2.85	0.57	-0.48	-2.61	8.65	2.5
750712	1330	7.67	13.5	387	76.6	4.9	220	8.5	5	.	211	2.15	0.31	-0.21	-2.40	9.48	3.4
750725	1100	7.70	13.8	385	76.1	4.4	213	9.0	6	.	208	1.85	0.33	-0.21	-2.44	10.49	3.7
750809	1030	7.55	13.3	367	72.6	4.7	223	10.0	4	11.0	200	1.60	0.17	-0.35	-2.27	9.37	3.0
750823	1420	7.87	13.9	352	67.3	13.0	225	9.5	6	9.0	222	1.45	0.47	0.18	-2.59	3.14	1.9
750906	1400	7.59	13.8	334	59.6	4.2	170	9.4	9	18.5	166	1.85	0.03	-0.48	-2.42	8.61	4.0
750918	1500	7.67	13.0	382	80.4	3.1	227	10.0	6	10.0	213	1.60	0.33	-0.30	-2.39	15.73	0.8
751004	1845	7.83	12.8	395	77.5	4.3	227	8.3	6	14.0	210	1.60	0.48	-0.08	-2.55	10.93	1.6

APPENDIX A (CONTINUED)

COLD SPRING

DATE	TIME	PH	T☼	SPC◊	CA^{+2}	MG^{+2}	HCO3^{-}	CL^{-}	NO3^{-}	SO4^{-2}	TOT HARD♦	DISCHARG♦	SIC	SID	PCO2	CA/MG	PERR^{+}
740917	1630	7.93	15.4	391	70.2	5.5	215	31	9	.	198	0.11	0.55	0.08	-2.66	7.74	7.3
741006	1530	8.14	15.1	403	67.4	3.3	195	26	13	.	182	0.07	0.70	0.13	-2.91	12.39	7.0
741020	1530	7.99	14.5	408	59.3	7.0	178	32	10	.	177	0.09	0.45	0.06	-2.80	5.14	6.2
741103	1300	8.15	15.5	386	59.7	4.7	160	26	10	.	168	0.08	0.59	0.12	-3.00	7.70	2.5
741117	1530	8.03	13.0	300	44.1	3.1	140	32	6	.	123	0.09	0.26	-0.26	-2.95	8.63	15.0
741203	1230	8.10	10.8	359	48.7	5.2	130	25	6	.	143	0.10	0.30	-0.13	-3.06	5.68	1.9
741215	1555	8.04	7.3	399	61.8	5.1	161	29	13	.	175	0.89	0.37	-0.13	-2.93	7.35	2.7
741230	1940	8.06	8.0	482	70.5	5.3	184	48	10	.	198	0.07	0.51	-0.01	-2.89	8.07	7.0
750111	1500	8.05	8.2	512	68.9	6.2	226	41	17	.	198	0.60	0.58	0.09	-2.79	6.74	13.3
750125	1800	7.22	6.5	343	48.1	3.4	119	31	16	.	134	3.60	-0.25	-1.23	-2.24	8.58	7.1
750208	1145	7.61	6.0	378	61.2	3.8	151	27	20	.	168	2.00	-0.11	-0.68	-2.53	9.77	3.0
750222	1400	7.79	8.6	429	70.8	4.5	189	23	20	.	195	1.60	0.26	-0.29	-2.60	9.54	2.5
750304	1320	8.05	7.7	343	60.9	4.6	159	22	16	.	171	1.20	0.38	-0.14	-2.94	8.03	1.5
750322	1350	7.68	10.3	379	64.4	4.5	166	19	23	.	179	1.90	0.09	-0.44	-2.54	8.68	0.9
750406	1020	7.89	8.2	411	65.0	5.7	179	19	14	.	186	1.65	0.30	-0.19	-2.73	6.92	0.1
750419	1330	7.89	10.2	336	59.8	5.1	158	21	12	.	170	1.05	0.25	-0.23	-2.77	7.11	0.1
750503	1230	7.55	13.7	355	66.5	3.4	167	17	16	.	180	1.85	0.02	-0.55	-2.39	11.86	1.7
750520	1430	7.65	16.1	399	73.0	4.2	191	18	17	.	201	1.75	0.25	-0.28	-2.42	10.54	0.4
750603	1330	7.58	17.8	436	79.0	9.4	185	24	14	.	236	1.55	0.22	-0.15	-2.36	5.10	8.8
750616		7.61	15.9	447	68.0	2.8	165	30	9	.	181	0.66	0.12	-0.49	-2.45	14.73	1.1
750628		7.68	15.4	395	96.6	2.0	141	22	8	.	250	0.25	0.25	-0.51	-2.59	29.29	23.3
750712	1400	7.59	17.0	383	51.1	6.9	150	29	18	.	156	0.22	-0.04	-0.39	-2.46	4.49	7.1
750725	1145	7.80	16.4	415	72.7	4.3	175	34	10	.	199	0.15	0.36	-0.16	-2.61	10.25	0.2
750809	1115	7.95	15.6	403	63.4	4.8	175	30	9	6.0	178	0.09	0.45	-0.03	-2.76	8.01	5.9
750823	1330	7.95	15.4	445	72.2	4.3	192	35	16	7.0	198	0.08	0.53	0.00	-2.73	10.18	7.0
750906	1600	7.89	15.0	449	65.7	2.2	192	32	13	12.5	173	0.24	0.43	-0.23	-2.67	18.11	13.5
750918	1030	7.85	14.7	395	64.4	4.0	197	40	10	49.0	177	0.12	0.38	-0.15	-2.62	9.76	22.1
751005	0930	7.89	14.3	401	58.1	5.5	160	47	9	15.0	168	0.07	0.29	-0.14	-2.75	6.41	13.8

APPENDIX A (CONTINUED)

REHOBETH CHURCH INSURGENCE

DATE	TIME	PH	T☼	SPC◊	CA*+2	MG*+2	HCO3*	CL*	NO3*	SO4*2	TOT HARD†	DISCHARG*	SIC	SID	PCO2	CA/MG	PERR+
740917	1300	8.30	16.4	612	64.6	32.6	331	1.8	2	.	295	0.20	1.06	1.00	-2.84	1.20	3.4
741006	1630	8.03	17.7	642	109.4	22.4	397	1.7	1	.	365	0.32	1.10	0.85	-2.49	2.96	5.1
741020	1630	7.91	8.0	429	61.4	19.6	257	3.7	0	.	234	0.40	0.44	0.23	-2.59	1.90	3.7
741103	1330	8.08	17.0	557	76.4	26.1	316	1.6	1	.	298	0.32	0.90	0.76	-2.63	1.78	6.2
741117	1630	7.95	5.5	434	65.7	17.7	246	3.4	1	.	237	0.46	0.45	0.19	-2.66	2.25	6.4
741203	1250	7.87	2.7	278	38.0	12.2	146	4.1	1	.	145	0.37	-0.10	-0.34	-2.81	1.89	6.4
741215	1645	7.51	3.5	194	26.3	7.2	89	4.4	3	.	95	0.51	-0.80	-1.07	-2.66	2.22	7.3
741230	2020	7.57	6.0	235	31.7	9.1	115	3.5	3	.	117	0.46	-0.52	-0.76	-2.60	2.11	6.5
750111	1630	7.81	8.0	185	25.2	8.1	84	2.6	4	.	96	0.70	-0.47	-0.68	-2.97	1.89	11.4
750125	1830	7.26	4.0	117	16.0	4.0	44	2.9	7	.	65	3.50	-1.54	-1.82	-2.71	2.43	8.5
750208	1000	7.65	1.0	176	23.4	7.3	130	2.8	6	.	88	0.70	-0.59	-0.84	-2.64	1.94	13.4
750222	1530	7.96	9.0	264	40.7	8.2	142	5.3	5	.	134	0.18	0.10	-0.20	-2.89	3.01	2.7
750304	1000	7.93	3.8	299	71.3	11.0	171	2.3	2	.	223	0.18	0.29	-0.10	-2.80	3.93	21.0
750322	1415	7.62	9.8	205	26.8	7.4	94	3.3	5	.	97	0.19	-0.56	-0.79	-2.72	2.20	5.7
750406	1000	8.15	1.8	317	46.8	8.1	155	2.3	1	.	150	0.15	0.27	-0.10	-3.07	3.50	6.5
750419	1355	7.96	11.6	270	45.2	9.4	155	2.8	1	.	152	0.37	0.22	-0.06	-2.84	2.92	6.7
750503	1200	7.87	13.2	185	35.1	5.2	99	2.5	2	.	109	1.20	-0.13	-0.48	-2.93	4.09	11.1
750520	1500	8.10	20.5	245	46.1	6.9	149	2.0	2	.	144	0.60	0.49	0.18	-2.95	4.05	5.9
750603	1500	7.87	18.0	310	55.8	7.0	181	1.8	2	.	168	0.45	0.37	0.02	-2.65	4.83	4.7
750616		7.98	19.1	387	65.2	15.0	228	2.0	1	.	224	0.51	0.65	0.43	-2.66	2.64	7.9
750628		6.92	19.8	281	39.4	2.4	91	5.4	1	.	108	4.50	-0.05	-1.47	-1.98	9.95	12.9
750712	1430	8.03	20.5	407	74.2	10.8	243	3.6	0	.	230	0.32	0.80	0.49	-2.67	4.17	5.6
750725	1000	8.02	18.5	558	81.9	24.6	319	1.8	0	.	306	0.20	0.90	0.74	-2.56	2.02	7.2
750809	1430	8.21	22.0	609	91.6	25.9	337	2.9	0	.	336	0.29	1.21	1.05	-2.71	2.15	8.8
750823	1015	8.25	19.5	609	79.8	33.7	353	2.3	0	65	338	0.29	1.16	1.08	-2.74	1.44	3.3
750906	1700	7.90	18.3	604	54.3	11.4	361	6.8	1	27	182	0.40	0.67	0.42	-2.38	2.89	29.6
750918	1600	8.21	13.8	490	90.7	14.9	313	6.3	1	6	288	0.40	1.06	0.74	-2.79	3.69	2.5
751005	1000	8.02	9.8	588	101.6	18.7	380	3.7	0	69	330	0.20	0.92	0.60	-2.54	3.30	8.1

APPENDIX A (CONTINUED)

SPROUSES' SPRING

DATE	TIME	PH	T$^{☆}$	SPC$^{◊}$	CA^{*+2}	MG^{*+2}	HCO3^{*-}	CL^{*-}	NO3^{*-}	SO4^{*-2}	TOT HARD†	SIC	SID	PCO2	CA/MG	PERB^{+}
740919	1600	7.86	13.1	516	90.5	5.3	255	12.2	23	.	248	0.62	0.07	-2.53	10.36	0.4
741021	1600	7.60	9.5	429	81.5	3.7	257	11.8	19	.	219	0.27	-0.35	-2.28	13.36	5.5
741118	1645	7.62	9.0	457	86.2	1.5	247	11.8	13	.	221	0.29	-0.54	-2.32	34.84	2.0
7412L6	1630	7.65	6.5	339	62.3	4.8	165	10.9	14	.	175	-0.01	-0.54	-2.53	7.87	3.7
750111	1600	8.13	11.5	325	65.5	0.8	165	9.6	8	.	167	0.57	-0.33	-2.99	49.61	3.3
750208	1015	7.95	7.5	291	54.0	4.2	138	8.9	18	.	152	0.17	-0.34	-2.90	7.80	3.9
750307	1020	7.61	7.9	347	66.2	4.1	184	10.5	16	.	182	0.04	-0.53	-2.44	9.79	0.9
750406	1830	7.75	6.8	399	62.0	3.4	199	9.2	12	.	169	0.17	-0.43	-2.55	11.06	4.9
750503	1145	7.83	13.4	334	63.8	3.9	173	9.3	12	.	175	0.30	-0.24	-2.66	9.92	3.0
750603	1445	7.60	18.5	397	75.6	2.1	190	10.0	13	.	198	0.25	-0.43	-2.36	21.83	4.1
750624		7.08	21.4	387	44.1	1.5	104	11.0	15	.	195	-0.12	-1.30	-2.07	17.82	1.1
750725	1015	7.94	15.3	449	87.3	3.6	245	12.3	21	.	233	0.70	0.09	-2.61	14.71	0.8
750823	2100	8.25	16.2	458	90.7	4.4	246	12.4	20	5	244	1.04	0.47	-2.91	12.50	0.6
750918	2100	8.21	15.0	379	76.1	4.9	251	12.9	20	36	210	0.91	0.40	-2.87	9.42	14.0

SALT SULPHUR SOUTH SPRING

DATE	TIME	PH	T$^{☆}$	SPC$^{◊}$	CA^{*+2}	MG^{*+2}	HCO3^{*-}	CL^{*-}	NO3^{*-}	SO4^{*-2}	TOT HARD†	SIC	SID	PCO2	CA/MG	PERB^{+}
740919	1845	6.81	17.4	1070	198.4	18.2	277	41.5	6	323	570	-0.06	-0.48	-1.43	6.61	4.8
741021	1510	6.93	13.0	1006	163.4	24.4	336	38.9	0	230	508	0.00	-0.34	-1.49	4.06	5.8
741118	1240	6.96	9.5	954	159.2	13.0	400	36.1	0	173	451	0.05	-0.44	-1.46	7.43	10.8
741216	1335	7.13	6.0	725	139.2	9.0	280	29.9	0	145	348	-0.03	-2.57	-1.80	8.85	9.8
750111	1410	6.90	6.8	808	137.8	2.5	302	36.7	0	167	354	-0.22	-1.06	-1.53	33.42	14.5
750208	1255	7.10	4.5	683	129.9	3.2	281	35.2	1	197	338	-0.12	-0.90	-1.77	24.62	18.1
750307	1300	7.10	5.2	614	72.7	23.0	280	32.8	4	130	276	-0.35	-0.57	-1.77	1.92	20.1
750406	1120	7.11	6.3	910	118.7	9.2	266	35.8	4	230	334	-0.14	-0.66	-1.80	7.83	21.0
750503	1345	7.00	12.7	660	118.4	8.7	268	26.6	1	80	300	-0.14	-1.11	-1.65	7.43	6.6
750603	1300	6.91	15.5	910	149.3	3.2	283	24.7	1	115	396	-0.07	-0.82	-1.53	28.29	0.3
750624	1200	7.40	19.0	967	152.2	12.0	401	35.0	2	200	430	0.62	0.17	-1.85	7.69	15.7
750725	1130	6.93	19.0	1012	157.1	8.1	427	39.1	7	295	426	0.18	-0.36	-1.35	11.76	25.7
750823	1440	7.25	21.0	1113	254.4	16.2	391	42.2	1	580	530	0.66	0.17	-1.71	9.53	16.8
750918	2130	6.97	17.0	1152	202.5	12.7	350	35.4	0	357	558	0.20	-0.31	-1.49	9.67	12.0

APPENDIX A (CONTINUED)

SALT SULPHUR NORTH SPRING

DATE	TIME	PH	T^{*}	$SPC^{\diamond}$	CA^{*+2}	MG^{*+2}	$HCO3^{*-}$	CL^{*-}	$NO3^{*-}$	$SO4^{*-2}$	$TOT\ HARD^{\diamond}$	SIC	SID	PCO2	CA/MG	$PERR^{+}$
740919	1830	7.03	17.4	3000	230.9	169.1	427	58.2	8	1580	1273	0.38	0.41	-1.47	0.83	47.3
741021	1500	7.10	13.0	3090	372.3	80.3	408	50.9	2	1250	1260	0.57	0.31	-1.59	2.81	49.9
741118	1230	7.12	9.5	2550	384.6	83.5	270	54.2	0	1350	1304	0.38	0.10	-1.80	2.79	61.3
741216	1325	7.10	6.0	1350	210.8	21.0	286	31.7	1	1990	613	0.12	-0.35	-1.76	6.09	34.0
750111	1415	7.02	6.8	1990	304.2	39.7	275	45.6	4	1025	923	0.17	-0.23	-1.70	4.65	50.5
750208	1240	7.18	4.5	848	140.3	4.0	235	29.2	2	270	367	-0.06	-0.81	-1.92	21.27	21.0
750307	1245	7.16	5.2	836	144.2	9.6	197	27.3	2	425	365	-0.13	-1.14	-1.97	9.43	27.5
750406	1135	7.25	6.3	1480	236.0	18.9	232	36.9	8	590	667	0.23	-0.28	-2.00	7.57	44.5
750503	1330	7.07	12.7	1232	193.8	4.3	251	31.1	1	410	502	0.11	-0.65	-1.75	27.33	32.4
750603	1315	7.00	15.5	1480	203.4	32.4	324	33.4	1	515	641	0.20	-0.12	-1.56	3.81	33.5
750624	1215	7.30	19.0	3080	428.5	134.1	206	37.7	1	1305	1622	0.61	0.46	-2.05	1.94	74.5
750725	1115	7.27	19.0	3105	455.1	99.1	245	40.5	0	1095	1544	0.68	0.45	-1.94	2.79	70.3
750823	1455	7.33	21.0	2900	464.5	60.8	218	55.3	5	1240	1410	0.74	0.41	-2.04	4.63	67.4
750918	2145	6.80	17.0	2740	430.4	76.1	272	51.2	0	1250	1388	0.21	-0.07	-1.44	3.43	63.6

Explanation of Symbols for Appendix B

+ Driller -	A	Andrew Anderson
	H	B. Hylton
	TS	Tri-State Drilling Company
¢ Quad. -	GM	Gap Mills 7 1/2" Topo. quadrangle
	U	Union 7 1/2" Topo. quadrangle
	FS	Fort Spring 7 1/2" Topo. quadrangle
	R	Ronceverte 7 1/2" Topo. quadrangle
* Water - Level	Measured as feet below ground surface	
# Source of - Level Info	O	Owner
	TA	This author
	D	Driller
	USGS	U.S. Geological Survey

APPENDIX B
PHYSICAL CHARACTERISTICS OF THE INVENTORIED WELLS

Hillsdale-Maccrady Aquifer

Well Number	Owner	Driller[+]	Quad.[c]	Altitude (ft)	Well Depth (ft)	Water Level (ft)[*]	Date of Level	Source of Level Info.[#]	Yield (gpm)	Remarks
M100	A. Wickline		GM	2340	100	20		O		
M101	William Sibold		GM	2252	195	+1	10/1/74	TA		Flowing well
M102	Jon Duncan	A	U	2250	485	365		D	12	
M103	Al Gelderman	A	U	2220	360	138		TA	20	Cave stream at 130'
M104	James Erskin		FS	2110	457	327		O	5	
M105	George Irons		R	2265	485					
M106	Henry hancock	H	GM	2450	220					
M107	R.O. McBrayer	A	GM	2300	303	158	10/27/74	TA		
M108	Roy Burwell		FS	2180	310					
M109	Robert Dunbar	A	U	2250	225	170	10/19/75	TA	10	
M110	G.C. Shanklin		U	2300	518					
M111	Vernon Kittle		GM	2385	425					
M112	C.P. Crosier		GM	2450	289					
M113	Leroy Kaufman	A	GM	2315	465	185		D	30	
M114	Frank McClung	TS	R	2270	475	315	10/15/75	D		
M115	Berle McClung	A	R	2190	594	414		D	10	
M116	Melvin Hoke		FS	2300	470					
M117	Minnie Weikle	A	FS	2230	385	185		D	30	
M118	J.F. Atkins		FS	2185	368					
M119	John Burns	TS	R	2230	456	256		D		
M120	S. Edwards	A	FS	2280	140	62	10/11/75	A	30	
M121	R. Miller		FS	2150	205	105		D	6	
M122	R. Canterbury		FS	2180	244					
M123	W.A. Daniels		FS	2150	192				2	
M124	R. Miller	A	GM	2400	305	162	11/25/74	TA		
M125	V. Atkins		GM	2360	231	135		USGS		
M126	Rehobeth Church	A	U	2275	285	120		D	20	
M127	W. Faulkner	A	U	2340	350	120		D	50	
M128	Darrell Echols	A	GM	2390	170	130		D	25	
M129	Francis Pence	A	FS	2240	425	275		D	100	
M130	C.V. Kessel		GM	2375						
M131	Earl Booth		GM	2370	280					
M132	Leona Dunbar	A	U	2295	305	155		D	40	Cave at 130'
M133	Jack Neel		U	2345	340	80		O		1970 Earthquake broke casing
M134	P. Powers		GM	2240	400					
M135	J. McNeel		FS	2285	505	225		O		
M141	L. Caldwell		U	2340	344	158	1/5/76	TA		Hit 4' cave
M142	Bostic		GM	2390	205	94	1/5/76	TA	25	
M143	R. Thomolson	A	U	2290	425	180		D	40	
M144	V. Baldwin		U	2270	475	150		O		
M145	Bill Sibold		GM	2440	385	245		O		
M146	James Karnes	TS	GM	2360	75	20	10/9/74	TA		
M147	Lee McClung	A	R	200	525	282	10/28/74	TA	40	No pump
M148	Richard Burwell	TS	R	2190	550	410	10/27/74	TA		No pump
M150	P. Lemon	A	FS	2310	180					Hit 30' cave
M151	T. Sizemore	A	FS	2325	225				30	
M152	James Christie	A	FS	2345	90					
M153	R. Miller		FS	2145	170	131	5/20/75	TA		No pump

APPENDIX B (CONTINUED)

TAGGARD -PATTON AQUIFER

Well Number	Owner	Driller+	Quad c	Altitude (ft)	Well Depth (ft)	Water Level* (ft)	Date of Level	Source of Level Info*	Yield (gpm)	Remarks
T100	[illegible]	A	L	2120	145	20	9/20/74	TA	5	
T101	[illegible]	A	L	2170	180	9		D	20	
T102	David White	TS	FS	2220	272	84	10/2/74	TA	5	
T103	[illegible] (town)	H	L	2055	425	30		O	200	
T104	Mark Killcollin	A	FS	2270	345	159	8/21/74	TA		
T105	B [illegible]ickles	TS	R	2205	320					
T106	Emmitt Walker	A	L	2125	160	8		O	25	
T107	C R Ripley	H	L	2225	105	15		O		
T108	Dale Beckett		FS	2250	153	20		O		
T109	Paul Gilchrist	A	FS	2230	285	70	8/15/74	TA		
T110	Mason Barton	A	R	2275	345	185		D	8	Hit red shale several times
T111	Bob White	B	L	2080	103	38		O		Red shale at 20'
T112	V Dixon	B	U	2200	112	40		D		
T113	I Canterbur		L	2060	172	2		O	200	
T114	J Amos		FS	2310	250				1	
T115	W Harvey	A	FS	2225	182	102		D	18	Water in yellowish shaly limestone
T116	Beckett Park		FS	2205	256	81		USGS		
T117	Lemon's Dairy	A	FS	2205	176	40			8	
T118	Pickaway P O	A	FS	2205	215	85		D	100	
T119	Sam's Auto Shop		L	2205	285	100		O		
T120	Nevitt Allen		L	2240	256	80			5	Red shale at 200', water hit at 170'
T121	R Riner	H	L	2175	130	53		TA-O	5	
T122	Clay Portifield		FS	2245	129	27		O		
T123	Sue Washington	A	U	1910	225	73	11/2/74	TA		Salt polluted
T124	Larry Weikle	TS	FS	2200	273					
T125	David Kraft	A	FS	2220	305	55		D	5	
T127	Harris Talbott	A	L	2160	226	75		O		
T128	M Bullington	A	L	2110	220	70		D	30	
T129	John Brown		L	2220	145				3	
T130	Bud Cooke	A	U	2170	385	185		D	100	
T131	Arnold Wickline	TS	FS	2265	355	274	10/25/75	TA		
T132	M T Pomphrey	F	FS	2235	100	30		O		
T135	Doc Reed	A	FS	2165	200	60		D	30	
T136	W Shafer	A	L	2160	105	30		D	7	
T137	A Walker	A	U	2130	205				15	
T138	J Benjamin		U	2185						
T139	G Wylie		U	2185						
T140	C Broyles	A	U	2120						
T141	F Brown		U	1925						
T142	Robert Hill		R	2200						
T143	F Lewis	A	FS	2160	235	165			25	
T144	Kyle Nickols		FS	2210						
T145	W Dixon		FS	2235						

Appendix B (continued)

Well Number	Owner	Driller^{+}	Quad.^{c}	Altitude (ft)	Well Depth (ft)	Water Level* (ft)	Date of Level	Source of Level Info.$^{\#}$	Yield (gpm)	Remarks
SINKS GROVE AQUIFER										
SG10	Robert Ash		U	2090	290	60		O		1970 earthquake broke casing, cave at 30'
SG11	Dept. of Hi.		U	2200	375					
SG12	C.E. Lemon	A	FS	2210	285	15		D	6	
SG13	Roy Ash		U	2240	193	93				
SG14	Tom McCraw		FS	2135	280					
SG15	M. Shirey		U	2160	130					
SG16	Ralph Mann			2180	215					
SG17	Charles Allen	A	FS	2200	172	72		D	25	
SG18	Harry Walker		U	2180	205					
SG20	T. Nickels		R	2210	137	55		TA		
UNION-GREENVILLE AQUIFER										
G100	Dixie Dransfield		U	1850	68	8	10/13/74	TA		Salt polluted
G101	Cody McPeak		U	1800	103	5		O		
G102	K. Brown		U	1895	79	30		O		Salt polluted
G103	Arby Dransfield		U	1930	270	200		O		Salt polluted
G104	D.H. Dunbar	A	U	1915	245	76	10/4/74	TA		
G105	Brown's Gas Sta.	H	U	1895						Salt polluted
G106	M. Taylor	H	U	1915	120	76		D		
G107	Willow Bend P. O.		U	1930	75	27		USGS		
G108	Jerry Brown	A	U	1895	200				12	Salt polluted
G109	Harry Ellison		U	1905	72					Salt polluted
G110	Elwood McPeak	H	U	1830	81	+1	10/3/74	TA		Salt polluted, flowing well
G111	E. Dowdy	A	U	1910	160				15	Salt polluted
G112	Ted Brown		U	1890						Salt polluted
G113	Ed Fisher	H	U	1810	100					Salt polluted
WELLS IN CAVES										
C1	D. Ripley	H	U	2205	98					
C2	J. Taylor	H	U	1935	35					
WELLS IN ALLUVIUM										
A100	William Dickson		R	1850	30	10	10/2/74	TA		Dug Well

APPENDIX C
CHEMICAL ANALYSES OF WELL WATERS

HILLSDALE-MACCRADY AQUIFER (1974)

SAMPLE	DATE	TIME	PH	T☼	SPC◊	CA^{+2}*	MG^{+2}*	HCO3^{-}*	CL^{-}*	NO3^{-}*	SO4^{-2}*	TOT HARD♦	SIC	SID	PCO2	CA/MG	PERR^{+}
M100	740922	1430	7.63	19.9	291	50.5	5.3	167	4.0	10	.	148	0.09	-0.30	-2.43	5.78	1.1
M101	740922	1530	7.54	17.5	447	59.6	20.2	246	1.0	1	.	232	0.18	0.03	-2.19	1.79	6.2
M102	740922	1610	7.72	15.1	516	66.2	24.4	272	1.4	2	.	266	0.40	0.26	-2.35	1.65	7.9
M103	741001	1930	7.60	17.5	425	67.0	13.6	260	1.8	4	.	223	0.31	0.06	-2.23	2.99	0.8
M104	741002	1730	7.51	17.3	333	65.5	11.4	243	7.3	8	.	210	0.18	-0.11	-2.17	3.49	1.4
M105	741002	1830	7.49	18.1	499	89.8	18.4	285	10.0	16	.	300	0.36	0.11	-2.08	2.96	6.7
M106	741004	1330	7.26	17.5	295	54.0	4.7	172	4.1	9	.	154	-0.28	-0.71	-2.06	6.97	0.1
M107	741118	1415	7.36	16.0	470	83.9	11.5	232	.	0	.	257	0.09	-0.26	-2.05	4.43	14.8
M108	741004	1530	7.72	19.0	399	61.8	15.5	217	9.2	14	.	218	0.34	0.14	-2.42	2.42	3.5
M109	741004	1600	7.81	18.6	212	39.4	2.7	131	3.0	5	.	110	0.06	-0.43	-2.72	8.85	3.3
M110	741017	1200	7.11	14.4	641	98.2	12.4	215	29.0	.	.	296	-0.16	-0.53	-1.84	4.80	15.2
M111	741017	1300	7.37	13.7	566	78.5	29.3	410	1.0	2	.	316	0.26	0.12	-1.83	1.63	3.6
M112	741028	1320	7.41	15.5	495	84.7	14.4	350	14.0	1	.	272	0.30	0.00	-1.93	3.57	6.5
M113	741017	1830	7.19	15.5	1982	301.1	63.5	248	6.6	2	.	1013	0.42	0.17	-1.87	2.88	65.0
M114	741021	1800	7.35	12.0	429	82.8	5.3	269	1.2	15	.	228	0.08	-0.45	-2.00	9.48	1.3
M115	741026	1415	7.71	11.5	600	101.2	15.8	239	1.9	1	.	318	0.46	0.11	-2.42	3.89	22.6
M116	741026	1430	7.39	14.0	512	88.3	7.7	313	4.4	12	.	252	0.24	-0.22	-1.96	6.96	4.1
M117	741026	1445	7.45	13.5	465	74.5	13.9	259	4.4	25	.	243	0.14	-0.16	-2.11	3.25	0.8
M118	741026	1500	7.59	13.0	556	63.3	33.8	351	0.7	1	.	297	0.32	0.25	-2.12	1.14	1.1
M119	741016	1600	7.56	16.0	386	71.8	7.0	253	2.0	12	.	208	0.27	-0.15	-2.21	6.22	2.9
M120	741028	1400	7.63	12.5	334	51.4	11.9	232	1.2	4	.	177	0.12	-0.14	-2.34	2.62	5.1
M121	741101	1545	7.60	15.5	1272	161.0	54.0	215	2.7	1	.	624	0.52	0.37	-2.34	1.81	55.0
M122	741101	1600	7.70	16.0	473	76.1	7.8	240	1.6	30	.	222	0.41	0.00	-2.38	5.92	0.3
M123	741101	1630	7.35	16.0	360	63.4	4.9	182	5.3	24	.	178	-0.12	-0.59	-2.14	7.85	0.4
M124	741118	1345	7.15	15.0	912	117.1	51.2	367	1.4	1	.	503	0.16	0.07	-1.66	1.39	24.6
M125	741115	1230	7.36	11.5	557	72.5	32.8	387	1.5	1	.	316	0.16	0.05	-1.86	1.34	0.8
M126	741115	1245	7.62	12.0	421	74.0	12.5	256	1.7	0	.	236	0.28	-0.04	-2.29	3.59	5.2
M127	741115	1330	7.12	13.5	1955	395.0	24.5	230	8.0	1	.	1087	0.40	-0.13	-1.85	9.78	68.8
M128	741118	1330	7.48	12.0	365	71.8	7.2	219	2.9	3	.	209	0.07	-0.36	-2.21	6.05	5.5
M129	741123	1350	7.57	13.5	365	60.2	10.5	192	5.7	8	.	194	0.05	-0.25	-2.35	3.48	5.9
M130	741123	1420	7.43	12.0	516	75.8	22.3	352	0.7	6	.	281	0.22	0.02	-1.97	2.06	2.5
M131	741123	1445	7.55	15.5	386	72.4	5.5	216	4.0	7	.	204	0.19	-0.29	-2.27	7.98	3.7

APPENDIX C (CONTINUED)

PATTON-TAGGARD AQUIFER (1974)

SAMPLE	DATE	TIME	PH	T✲	SPC◊	CA^{+2}●	MG^{+2}●	$HCO3^{-}$●	CL^{-}●	$NO3^{-}$●	$SO4^{-2}$●	TOT HARD♦	SIC	SID	PCO2	CA/MG	PERR⁺
T100	740322	1810	7.43	16.6	378	54.6	14.2	239	2.4	6	.	195	0.01	-0.19	-2.10	2.33	2.5
T101	740322	1810	7.50	17.5	495	73.0	20.7	297	5.2	2	.	268	0.29	0.11	-2.08	2.14	2.7
T102	741002	1700	7.52	15.2	343	63.8	15.6	260	1.1	2	.	223	0.17	-0.05	-2.17	2.48	1.5
T103	740322	1200	8.02	18.9	529	90.2	12.2	246	14.0	12	.	276	0.84	0.51	-2.67	4.49	8.6
T104	741004	1630	7.45	19.2	566	91.3	15.0	287	16.0	12	.	290	0.34	0.05	-2.03	3.69	3.8
T105	741004	1800	7.20	19.0	541	92.4	7.9	357	1.3	2	.	263	0.19	-0.24	-1.69	7.09	6.0
T106	741006	1530	7.34	17.5	563	101.7	6.3	303	12.0	39	.	280	0.28	-0.23	-1.91	9.79	3.3
T107	741016	1830	7.22	15.8	570	86.0	20.0	354	1.6	13	.	297	0.12	-0.11	-1.73	2.61	1.2
T108	741123	1425	7.00	13.0	641	118.2	3.7	357	3.7	13	.	310	0.00	-0.68	-1.53	19.37	0.2
T109	741017	1315	7.45	11.9	421	63.4	15.6	244	3.1	19	.	222	0.03	-0.22	-2.14	2.47	0.4
T110	741017	1330	7.24	11.5	1161	199.6	9.9	262	1.3	1	.	539	0.29	-0.30	-1.91	12.23	42.2
T111	741028	1200	7.45	12.5	464	81.2	11.3	276	0.6	11	.	249	0.19	-0.18	-2.09	4.36	2.6
T112	741101	1330	7.11	12.0	641	127.5	3.4	363	14.0	21	.	332	0.13	-0.59	-1.64	22.74	0.5
T113	741113	1230	7.11	16.0	516	95.5	2.8	293	14.0	6	.	250	-0.01	-0.69	-1.70	20.68	3.0
T114	741113	1245	7.46	15.0	412	75.8	9.0	265	3.8	6	.	226	0.19	-0.19	-2.10	5.11	0.5
T115	741113	1300	7.40	14.2	382	66.0	7.9	194	7.1	16	.	197	-0.06	-0.45	-2.18	5.07	4.0
T116	741113	1315	7.69	14.5	425	58.9	18.2	248	2.1	1	.	211	0.28	0.10	-2.36	1.96	3.1
T117	741113	1330	7.27	15.5	408	67.0	10.6	210	6.9	13	.	251	-0.14	-0.45	-2.00	3.83	4.3
T118	741113	1345	7.31	16.3	465	80.7	12.0	235	7.5	6	.	251	0.03	-0.29	-1.99	4.08	9.2
T119	741115	1200	7.55	14.5	352	54.9	11.7	190	5.9	9	.	185	0.01	-0.25	-2.33	2.85	3.5
T120	741115	1315	7.49	14.5	566	100.6	1.5	283	15.0	16	.	257	0.36	-0.48	-2.11	40.66	1.9
T121	741117	1500	7.23	15.0	557	94.8	2.9	279	26.0	11	.	249	0.07	-0.61	-1.85	19.82	5.2
T122	741123	1330	7.18	13.5	516	96.9	4.1	270	20.0	15	.	259	-0.01	-0.61	-1.82	13.67	0.6

APPENDIX C (CONTINUED)

UNION-GREENVILLE AQUIFER (1974)

SAMPLE	DATE	TIME	PH	T✡	SPC◊	CA^{+2}●	MG^{+2}●	HCO3^{-}●	CL^{-}●	NO3^{-}●	SO4^{-2}●	TOT HARD♦	SIC	SID	PCO2	CA/MG	PERR^{+}
G100	740922	1230	7.20	16.0	871	120.6	21.9	294	132	2	.	391	0.15	-0.13	-1.80	3.34	4.7
G101	740922	1330	7.08	17.8	604	105.2	5.8	390	4	3	.	287	0.14	-0.39	-1.54	11.00	6.9
G102	741016	1030	7.23	18.5	725	78.2	18.9	331	.	21	.	273	0.11	-0.10	-1.75	2.51	2.8
G103	741016	1230	7.40	15.5	1145	116.5	39.5	269	250	26	.	453	0.28	0.13	-2.04	1.79	13.5
G104	741024	1330	7.21	16.0	892	110.0	17.1	276	92	.	.	345	0.10	-0.22	-1.83	3.90	1.7
G105	741113	1445	7.15	16.5	808	124.6	10.0	286	96	10	.	323	0.11	-0.34	-1.76	7.56	3.6
G106	741113	1455	7.29	16.5	553	96.1	5.9	242	15	20	.	264	0.10	-0.42	-1.96	9.88	5.5
G107	741113	1515	7.05	12.0	607	99.5	3.9	334	25	1	.	262	-0.06	-0.70	-1.61	15.32	8.6
G108	741114	1300	7.45	12.0	395	.	.	.	26	.	.	.					
G109	741114	1330	7.12	12.0	769	.	.	.	60	.	.	.					
G110	741114	1400	7.26	11.5	1065	.	.	.	176	.	.	.					
G111	741117	1400	7.23	14.0	766	.	.	.	70	.	.	.					
G112	741117	1415	7.18	14.5	766	.	.	.	87	.	.	.					
G113	741117	1430	7.15	14.5	641	.	.	.	15	.	.	.					

SINKS GROVE AQUIFER (1974)

SAMPLE	DATE	TIME	PH	T✡	SPC◊	CA^{+2}●	MG^{+2}●	HCO3^{-}●	CL^{-}●	NO3^{-}●	SO4^{-2}●	TOT HARD♦	SIC	SID	PCO2	CA/MG	PERR^{+}
SG10	741001	1800	7.48	16.5	412	33.6	11.3	285	4.0	8	.	255	0.30	-0.05	-2.08	4.49	1.6
SG11	741016	1500	7.47	18.5	477	88.4	4.8	260	14.0	10	.	240	0.31	-0.22	-2.10	11.17	0.4
SG12	741123	1220	7.32	12.5	579	100.6	11.0	268	21.0	1	.	296	0.13	-0.29	-1.97	5.55	8.3
SG13	741028	1100	7.46	15.0	1312	137.6	107.7	330	1.6	3	.	786	0.48	0.51	-2.02	0.78	48.0
SG14	741123	1300	7.61	13.5	457	42.0	46.3	261	1.8	.	.	295	0.04	0.14	-2.27	0.55	15.2

STREAM ALLUVIUM (1974)

SAMPLE	DATE	TIME	PH	T✡	SPC◊	CA^{+2}●	MG^{+2}●	HCO3^{-}●	CL^{-}●	NO3^{-}●	SO4^{-2}●	TOT HARD♦	SIC	SID	PCO2	CA/MG	PERR^{+}
A100	741002	1800	7.34	15.2	421	52.5	9.2	226	12	39	.	169	-0.14	-0.44	-2.04	3.46	16.2

APPENDIX C (CONTINUED)

HILLSDALE-MACCRADY AQUIFER (1975)

SAMPLE	DATE	TIME	PH	T✲	SPC♦	CA^{+2}●	MG^{+2}●	HCO3^{-}●	CL^{-}●	NO3^{-}●	SO4^{-2}●	TOT HARD♦	SIC	SID	PCO2	CA/MG	PERR^{+}
M100	750521	2200	7.50	12.0	276	55.1	3.4	157	7.1	16	.	152	-0.15	-0.69	-2.37	9.83	0.3
M101	750524	1945	7.65	13.5	421	66.6	15.9	226	2.0	1	44.0	232	0.23	-0.01	-2.37	2.54	0.8
M102	750524	1730	7.45	13.0	448	86.7	6.7	246	6.5	24	10.0	244	0.17	-0.31	-2.13	7.85	0.5
M103	750526	1430	7.60	15.2	325	59.9	8.7	196	2.1	5	10.0	186	0.12	-0.22	-2.37	4.18	1.7
M104	750521	1500	7.62	14.0	367	65.5	7.7	206	11.0	8	5.0	195	0.18	-0.21	-2.37	5.16	0.7
M105	750524	1120	7.41	13.0	479	85.7	6.1	232	12.0	27	9.6	239	0.10	-0.40	-2.12	8.52	0.2
M106	750523	1245	7.21	12.0	295	58.6	4.5	154	6.5	13	9.0	165	-0.43	-0.92	-2.10	7.90	2.8
M107	750522	1545	7.60	14.0	432	75.6	9.8	217	4.7	9	44.0	229	0.22	-0.15	-2.33	4.68	2.2
M108	750521	1000	7.63	15.0	414	67.6	14.0	195	10.0	12	36.0	226	0.18	-0.09	-2.40	2.93	0.7
M109	750522	1520	7.57	14.0	182	39.6	2.6	116	3.2	4	.	110	-0.30	-0.82	-2.56	9.24	2.6
M110	750524	1700	7.30	13.5	383	71.9	4.1	178	8.0	36	19.0	197	-0.18	-0.73	-2.12	10.64	2.6
M111	750524	1750	7.41	12.5	558	79.9	27.6	380	1.0	4	4.5	313	0.26	0.09	-1.91	1.76	1.3
M112	750524	1920	7.50	13.2	490	79.3	18.7	324	0.9	1	4.5	275	0.30	0.05	-2.06	2.57	0.3
M113	750521	1530	7.42	14.0	2064	314.1	80.4	234	7.1	1	905.0	1115	0.54	0.32	-2.15	2.37	1.4
M114	750521	1550	7.51	14.5	440	76.1	13.7	251	7.6	21	5.0	246	0.21	-0.09	-2.18	3.37	1.4
M115	750524	1200	7.62	13.5	481	71.9	17.1	224	4.8	4	81.0	250	0.21	-0.03	-2.34	2.55	5.4
M117	750521	1015	7.65	14.6	495	73.5	18.5	263	8.0	31	8.4	260	0.35	0.13	-2.30	2.41	0.4
M118	750521	1430	7.58	14.0	593	85.2	26.0	355	3.1	1	41.0	320	0.44	0.26	-2.11	1.99	3.0
M119	750521	1130	7.64	13.0	370	62.6	10.9	228	3.1	10	0.0	201	0.20	-0.11	-2.35	3.48	0.4
M121	750521	1515	7.70	13.5	1450	215.1	32.6	208	3.9	1	118.0	671	0.69	0.36	-2.47	4.00	38.2
M122	750522	1900	7.81	15.0	488	93.2	5.3	228	4.6	44	23.0	255	0.56	0.01	-2.52	10.67	0.0
M123	750526	1000	7.41	15.1	303	73.7	5.3	158	6.9	24	10.5	206	-0.08	-0.57	-2.27	8.43	9.6
M124	750523	1135	7.25	13.5	1500	229.5	74.8	308	4.8	0	135.0	881	0.42	0.25	-1.85	1.86	37.5
M125	750723	1430	7.41	14.0	596	79.8	25.8	387	7.0	0	7.0	306	0.29	0.12	-1.90	1.88	4.7
M126	750523	1115	7.65	13.5	403	60.6	19.0	252	1.2	1	23.6	229	0.24	0.06	-2.32	1.93	1.1
M127	750523	1030	7.21	14.5	2060	410.2	19.5	227	7.5	0	988.0	1105	0.43	-0.15	-1.95	12.76	5.2
M128	750523	1200	7.37	15.0	410	78.2	5.3	249	3.3	8	4.5	217	0.09	-0.41	-2.03	8.95	0.7
M129	750521	1445	7.65	13.5	343	61.7	9.1	189	7.8	8	18.3	192	0.13	-0.21	-2.44	4.11	0.4
M130	750524	1900	7.44	12.5	531	96.8	23.0	355	3.0	9	0.0	336	0.34	0.09	-1.97	2.55	5.1
M131	750523	1050	7.55	13.5	365	68.9	4.1	206	5.1	16	10.0	189	0.12	-0.42	-2.30	10.19	3.0
M132	750726	1200	7.57	12.5	1441	251.6	10.6	243	5.3	0	670.0	673	0.64	0.02	-2.28	14.40	14.8
M133	750723	1330	7.33	12.5	607	78.7	33.7	387	1.2	0	18.5	335	0.17	0.05	-1.83	1.42	0.5
M134	750605	1100	7.41	15.2	532	92.9	8.8	267	8.8	44	50.0	268	0.21	-0.22	-2.05	6.40	8.8

APPENDIX C (CONTINUED)

PATTON-TAGGARD AQUIFER (1975)

SAMPLE	DATE	TIME	PH	T✿	SPC◊	CA^{+2}●	MG^{+2}●	$HCO3^{-}$●	CL^{-}●	$NO3^{-}$●	$SO4^{-2}$●	TOT HARD⧫	SIC	SID	PCO2	CA/MG	PERR+
T100	750723	1400	7.59	12.3	347	70.0	3.7	206	3.7	4	2.0	190	0.14	-0.43	-2.34	11.47	2.6
T102	750521	1300	7.71	13.5	386	69.4	14.7	239	3.4	2	.	234	0.34	0.07	-2.40	2.96	6.9
T103	750522	1340	7.96	14.0	453	95.6	0.9	243	12.0	17	96.0	242	0.72	-0.22	-2.65	64.36	15.7
T104	750522	2100	7.49	12.5	558	86.6	15.0	257	15.0	12	61.0	278	0.21	-0.11	-2.16	3.50	4.8
T105	750524	1230	7.31	14.0	553	103.5	2.0	331	2.2	4	18.0	267	0.24	-0.54	-1.86	31.38	5.5
T106	750526	1200	7.58	13.5	424	104.4	2.5	285	12.0	28	30.0	271	0.44	-0.30	-2.20	25.32	6.1
T107	750522	1500	7.35	14.0	579	99.2	12.8	324	7.0	10	.	300	0.25	-0.12	-1.91	4.70	2.8
T108	750522	1700	7.20	14.5	614	108.9	1.9	310	31.0	27	0.0	280	0.13	-0.67	-1.78	34.75	6.8
T110	750521	1530	7.34	12.5	1070	177.2	9.1	247	2.3	0	357.0	480	0.30	-0.27	-2.04	11.81	9.4
T111	750605	1420	7.66	13.0	447	91.0	5.3	259	5.6	8	26.0	249	0.42	-0.13	-2.32	10.41	1.1
T112	750526	1400	7.01	14.8	694	140.0	3.6	366	21.0	27	5.3	364	0.11	-0.61	-1.52	23.58	0.8
T113	750521	930	7.44	13.5	464	100.8	5.1	258	13.0	13	7.9	272	0.25	-0.33	-2.10	11.99	4.4
T115	750524	1500	7.58	14.0	357	60.4	11.3	181	8.1	28	.	197	0.05	-0.24	-2.39	3.24	3.6
T116	750521	945	7.48	13.5	504	72.4	16.2	307	1.8	2	.	248	0.23	-0.03	-2.06	2.71	1.9
T117	750524	1550	7.71	13.8	481	87.9	8.0	204	9.2	53	.	252	0.37	-0.08	-2.47	6.66	5.9
T118	750524	1620	7.35	13.0	446	86.0	8.3	254	11.0	12	.	249	0.08	-0.35	-2.02	6.28	3.0
T119	750522	1350	7.35	13.5	292	55.1	5.1	163	5.0	11	3	158	-0.26	-0.71	-2.20	6.55	1.6
T120	750523	930	7.42	14.5	490	98.4	2.1	266	9.0	22	.	254	0.25	-0.51	-2.06	28.41	1.0
T122	750522	1620	7.39	13.0	511	89.5	2.0	233	21.0	47	10	232	0.10	-0.65	-2.10	27.13	7.6
T123	750723	1530	7.79	13.0	1184	133.0	29.4	320	304.0	13	69	453	0.75	0.49	-2.36	2.74	26.2
T124	750524	1300	7.85	14.5	264	51.3	3.7	149	7.1	9	2	143	0.19	-0.31	-2.73	8.41	0.4
T125	750606	1500	7.62	13.2	395	81.1	2.9	234	3.2	11	8	214	0.30	-0.35	-2.32	16.96	0.2
T129	750605	1000	7.51	14.5	524	92.9	10.1	216	18.0	68	21	274	0.22	-0.19	-2.24	5.58	1.3

APPENDIX C (CONTINUED)

UNION-GREENVILLE AQUIFER (1975)

SAMPLE	DATE	TIME	PH	T✡	SPC◊	CA^{+2}●	MG^{+2}●	HCO3^{-}●	CL^{-}●	NO3^{-}●	SO4^{-2}●	TOT HARD♦	SIC	SID	PCO2	CA/MG	PERR^{+}
G100	750605	1230	7.30	14.8	820	135.5	5.9	321	83.0	1	30	363	0.32	-0.28	-1.87	13.93	6.6
G101	750522	1300	7.35	13.0	575	86.0	3.5	271	3.8	6	23	229	0.11	-0.51	-1.99	14.90	5.8
G103	750523	900	7.52	14.5	1057	121.9	27.5	250	146.0	37	.	418	0.38	0.14	-2.20	2.69	2.8
G104	750605	1155	7.39	12.5	869	99.6	12.5	291	118.0	16	70	300	0.20	-0.18	-2.01	4.83	24.1
G105	750522	1330	7.40	13.5	774	112.1	3.6	290	79.0	22	16	295	0.29	-0.39	-2.01	18.88	13.3
G106	750605	1130	7.49	14.5	549	120.6	0.7	240	17.0	53	25	304	0.35	-0.69	-2.18	104.36	2.3

SINKS GROVE AQUIFER (1975)

SAMPLE	DATE	TIME	PH	T✡	SPC◊	CA^{+2}●	MG^{+2}●	HCO3^{-}●	CL^{-}●	NO3^{-}●	SO4^{-2}●	TOT HARD♦	SIC	SID	PCO2	CA/MG	PERR^{+}
SG11	750522	1400	7.48	15.0	495	85.4	7.8	250	26.0	12	.	245	0.23	-0.21	-2.15	6.64	1.4
SG12	750524	1530	7.09	14.5	707	133.0	5.7	265	33.0	94	35	356	0.02	-0.58	-1.74	14.15	2.9
SG14	750522	1730	7.80	13.0	447	70.8	21.5	259	1.7	0	43	265	0.45	0.26	-2.46	2.00	0.7
SG15	750723	1300	7.47	11.5	385	55.4	15.5	234	4.0	2	22	202	-0.01	-0.21	-2.17	2.17	4.9
SG16	750523	1000	7.46	12.5	520	91.3	4.6	270	20.0	11	.	247	0.24	-0.35	-2.11	12.04	2.5
SG17	750526	1130	7.56	13.5	422	71.8	11.4	243	2.2	5	16	226	0.21	-0.12	-2.25	3.82	0.6
SG18	750605	1020	7.39	13.8	499	102.5	1.0	288	4.9	20	7	260	0.26	-0.67	-2.00	62.12	1.3

Appendix D

Precipitation Data from the Union Station, U.S. Weather Bureau

	1974				1975									
(Days)	September	October	November	December	January	February	March	April	May	June	July	August	September	October
1				.05	.21	.53			.13	1.11			1.10	
2	.05			T	T	.30			.51					.02
3	.21					T	.10	.09				.03		
4	.12				.05	.15			T		T	T		
5	T		.05			.75			.06		.28	.07		
6		T				.16				.48		.67	.30	
7					T	T	T				.03	T	.50	
8	.08			.05			.44		.03					
9	.18				.07	T			.57		.70			.38
10	T			T			.43	.22	T		.03			
11	.11				.24		T	.03		.31	.11	.04		.03
12	.38		.27	.05		.82	.06			.20	.37	.25	.10	
13	.20		.15		.35		.43		.76	.38	.03		.50	
14					T		1.00		.06		.03	.03		
15			.15	T	T			.30			T	.85		
16		1.80		.15	T			T	.50	.15	.05			.01
17		.12	.04	T		.15	.32		.20			.11		.38
18	.04		.05	.05		T		.03			.50		.08	1.36
19	.27			T	T		.70	.24	T		.24		.20	
20	.20	.03	.50		.24		.26			.03	.05			.03
21			.08		.04						.24	.16	.07	
22													T	
23				T			.18		.47				1.30	
24						.15		.07	.28		.13		.30	
25		.05	.06	.09	.27		.17	1.15		.04	.05	.30		
26	.03				.33			.32	.28	.02				
27	.10									T				.19
28	.43		T	.38			.79	.30		.55				
29	T						.49	.33	T	.12				
30				T				1.09	.12					.10
31		T		.08	.11				.27					
Total Inches	2.40	2.00	1.35	.90	1.91	3.01	5.37	4.17	4.24	3.39	2.84	2.51	4.45	2.50

APPENDIX E
CHEMICAL ANALYSES OF COLD, MCPEAK'S, AND WALTERS'SPRINGS DURING A STORM PULSE

COLD SPRING

DATE	TIME	PH	T*	SPC◊	CA*+*	MG*+*	HCO3*-	CL*-	NO3*-	TOT HARD♦	DISCHARG	SIC	SID	PCO2	CA/MG	PERR+
741016	845	7.87	15.0	425	56.5	6.0	172	30.0	.	166	1.220	0.31	-0.10	-2.69	5.71	5.5
741016	1045	7.70	15.5	386	43.4	11.3	134	37.0	.	155	1.750	-0.07	-0.28	-2.62	2.33	2.8
741016	1245	7.65	15.5	447	41.7	7.6	157	14.0	.	135	1.650	-0.06	-0.35	-2.50	3.33	5.2
741016	1515	7.65	15.5	435	40.0	7.6	143	12.0	.	131	1.570	-0.12	-0.40	-2.55	3.19	1.5
741016	1815	7.71	15.5	360	36.7	6.6	121	11.0	.	119	1.520	-0.16	-0.45	-2.67	3.37	0.9
741017	915	7.79	15.5	334	40.7	5.5	127	2.5	.	124	0.620	-0.01	-0.37	-2.73	4.49	6.9
741017	1815	7.80	15.5	352	50.0	3.9	144	3.7	.	140	0.230	0.13	-0.34	-2.69	7.78	6.5
741018	1645	7.90	15.2	394	51.2	6.5	171	5.2	.	154	0.098	0.30	-0.06	-2.72	4.78	2.3
741020	1500	7.99	14.5	408	59.3	7.5	176	32.0	.	178	0.092	0.45	0.08	-2.81	4.80	3.2

MCPEAK'S SPRING

DATE	TIME	PH	T*	SPC◊	CA*+*	MG*+*	HCO3*-	CL*-	NO3*-	TOT HARD♦	DISCHARG	SIC	SID	PCO2	CA/MG	PERR+
741016	815	7.55	13.3	558	98.0	8.3	321	19	.	279	5.50	0.44	-0.03	-2.12	7.16	2.1
741016	1015	7.55	13.0	512	94.3	8.5	306	16	.	270	6.90	0.40	-0.06	-2.14	6.73	0.8
741016	1215	7.41	13.0	430	78.8	7.5	248	15	.	228	14.00	0.10	-0.34	-2.09	6.37	0.6
741016	1445	7.38	13.5	373	67.4	6.4	207	14	.	195	16.00	-0.05	-0.49	-2.13	6.39	1.2
741016	1775	7.35	13.0	369	65.0	5.1	208	12	.	183	11.50	-0.10	-0.59	-2.10	7.73	1.3
741017	845	7.46	13.0	430	80.3	4.3	254	13	.	218	2.50	0.17	-0.39	-2.13	11.33	2.2
741017	1745	7.49	13.0	469	87.1	4.1	271	14	.	234	1.15	0.26	-0.33	-2.13	12.88	1.8
741018	1615	7.50	12.5	495	88.6	5.2	291	14	.	242	0.34	0.30	-0.25	-2.11	10.33	3.3
741020	1430	7.54	12.5	525	97.4	4.9	320	18	.	263	0.18	0.41	-0.17	-2.11	12.06	4.6

WALTERS' SPRING

DATE	TIME	PH	T*	SPC◊	CA*+*	MG*+*	HCO3*-	CL*-	NO3*-	TOT HARD♦	DISCHARG	SIC	SID	PCO2	CA/MG	PERR+
741016	830	7.60	13.0	447	75.3	7.2	270	9.0	9	219	4.00	0.31	-0.13	-2.24	6.34	5.4
741016	1030	7.68	13.0	434	76.7	7.0	275	9.1	8	221	6.00	0.40	-0.05	-2.31	6.65	5.4
741016	1230	7.60	13.2	434	79.0	6.2	277	9.9	11	223	15.00	0.34	-0.14	-2.23	7.73	5.9
741016	1500	7.62	11.0	438	81.2	5.1	281	10.0	9	224	15.00	0.38	-0.16	-2.24	9.66	6.1
741016	1800	7.65	13.0	434	79.3	5.3	273	10.0	10	220	9.40	0.39	-0.13	-2.29	9.07	5.9
741017	900	7.77	12.0	438	76.6	6.7	261	9.9	9	219	3.40	0.46	-0.01	-2.43	6.93	3.8
741017	1800	7.66	13.5	399	74.3	6.1	252	9.6	9	211	2.30	0.34	-0.13	-2.33	7.39	4.0
741018	1630	7.63	13.0	386	71.6	4.4	238	9.3	6	197	1.60	0.27	-0.27	-2.32	9.87	4.2
741020	1445	7.68	12.5	369	79.0	4.2	214	7.4	6	214	1.15	0.31	-0.26	-2.42	11.41	5.7

APPENDIX F
FACTOR ANALYSIS MATRIX DATA
for
Dickson Spring

Percent Variation Explained

Factor	Eigen Values	Percent Variation Explained	Cumulative Percent Variation Explained
1	6.98	49.84	49.84
2	2.56	18.28	69.12
3	1.91	13.68	81.80
4	0.85	6.05	87.85
5	0.66	4.68	92.53

Rotated Factor Matrix

	1	2	3	4	5
pH	0.796	0.502	0.084	0.228	-0.214
T	-0.654	-0.080	-0.345	-0.038	0.533
SPC	-0.889	0.210	-0.066	0.095	0.226
Ca	-0.806	0.451	0.176	-0.063	0.259
Mg	-0.376	0.006	-0.862	0.180	0.080
HCO_3	-0.902	0.247	-0.173	-0.145	0.177
Cl	0.077	0.170	-0.110	0.940	-0.006
NO_3	0.387	-0.137	-0.042	-0.001	-0.870
TH	-0.850	0.349	-0.230	0.066	0.237
D	0.715	-0.196	0.034	-0.363	0.015
SIc	-0.184	0.961	0.050	0.153	0.080
SId	-0.204	0.730	-0.618	0.177	0.085
Pco_2	-0.909	-0.227	-0.127	-0.191	0.238
Ca/Mg	-0.078	-0.008	0.944	0.034	0.040

Commualities

Variable	Communalities
pH	0.991
T	0.840
SPC	0.900
Ca	0.957
Mg	0.924
HCO_3	0.958
Cl	0.932
NO_3	0.928
TH	0.958
D	0.684
SIc	0.991
SId	0.996
Pco_2	0.989
Ca/Mg	0.902

APPENDIX F (CONTINUED)
for
Cold Spring
Percent Variation Explained

Factor	Eigen Values	Percent Variation Explained	Cumulative Percent Variation Explained
1	5.10	36.42	36.42
2	3.22	23.02	59.44
3	2.07	14.77	74.21
4	1.28	9.16	83.37
5	1.11	7.93	91.30

Rotated Factor Matrix

	1	2	3	4	5
pH	0.991	-0.023	0.061	0.014	0.092
T	-0.034	0.274	0.061	0.893	-0.058
SPC	0.111	0.743	0.106	-0.097	0.547
Ca	-0.048	0.901	-0.299	0.139	-0.132
Mg	0.038	0.145	0.918	0.072	0.005
HCO_3	0.320	0.737	0.279	0.066	0.229
Cl	0.194	-0.023	0.060	0.120	0.944
NO_3	-0.395	0.258	0.202	-0.690	-0.209
TH	-0.038	0.925	-0.070	0.157	-0.130
D	-0.677	-0.080	0.052	-0.584	-0.316
SIc	0.868	0.374	0.048	0.156	0.153
SId	0.848	0.315	0.335	0.230	0.085
Pco_2	-0.945	0.262	0.026	0.042	-0.047
Ca/Mg	-0.128	0.353	-0.886	0.183	-0.103

Communalities

Variable	Communalities
pH	0.996
T	0.881
SPC	0.885
Ca	0.940
Mg	0.872
HCO_3	0.781
Cl	0.948
NO_3	0.785
TH	0.904
D	0.910
SIc	0.945
SId	0.992
Pco_2	0.966
Ca/Mg	0.971

APPENDIX F (CONTINUED)
for
Salt Sulphur South Spring
Percent Variation Explained

Factor	Eigen Values	Percent Variation Explained	Cumulative Percent Variation Explained
1	6.02	44.23	44.23
2	3.12	17.89	62.12
3	2.21	12.20	74.32
4	1.02	11.11	85.43
5	0.58	5.08	90.51

Rotated Factor Matrix

	1	2	3	4	5
pH	-0.005	0.958	0.059	-0.066	0.261
T	0.503	-0.153	-0.012	0.108	0.773
SPC	0.704	-0.271	0.310	0.017	0.486
Ca	0.911	-0.105	0.059	-0.131	0.348
Mg	0.154	-0.083	0.890	-0.039	0.082
HCO_3	0.232	0.019	0.249	0.016	0.819
Cl	0.617	-0.032	0.560	0.350	0.072
NO_3	-0.009	-0.116	0.170	0.964	0.042
SO_4	0.869	0.124	0.264	0.182	0.232
TH	0.767	-0.337	0.336	-0.133	0.337
SIc	0.541	0.395	0.060	-0.082	0.728
SId	0.191	0.004	0.645	0.113	0.608
Pco_2	0.189	-0.930	0.053	0.078	0.250
Ca/Mg	-0.194	-0.098	-0.902	-0.121	-0.122

Commualities

Variable	Commulities
pH	0.995
T	0.886
SPC	0.903
Ca	0.984
Mg	0.831
HCO_3	0.788
Cl	0.824
NO_3	0.974
SO_4	0.928
TH	0.948
SIc	0.991
SId	0.837
Pco_2	0.973
Ca/Mg	0.892

APPENDIX F (CONTINUED)
for
Rehobeth Church Insurgence

Percent Variation Explained

Factor	Eigen Values	Percent Variation Explained	Cumulative Percent Variation Explained
1	7.82	55.83	55.83
2	2.72	19.43	75.26
3	1.03	7.34	82.60
4	0.06	6.16	88.71

Rotated Factor Matrix

	1	2	3	4	5
pH	0.606	-0.748	-0.120	0.110	0.170
T	0.452	0.122	-0.173	-0.161	0.851
SPC	0.792	0.064	0.224	0.134	0.094
Ca	0.942	-0.063	-0.070	-0.065	0.116
Mg	0.788	-0.098	-0.296	0.404	0.122
HCO_3	0.939	-0.063	0.056	0.206	0.185
Cl	-0.066	0.178	0.940	-0.098	-0.053
NO_3	-0.816	0.080	0.080	0.431	-0.029
TH	0.948	-0.075	-0.167	0.114	0.127
D	-0.402	0.778	-0.024	-0.257	0.121
SIc	0.895	-0.236	-0.022	-0.125	0.331
SId	0.858	-0.400	-0.076	0.095	0.288
Pco_2	0.285	0.876	0.241	0.075	0.072
Ca/Mg	0.110	0.467	0.165	0.809	0.201

Communalities

Variable	Communalities
pH	0.983
T	-.976
SPC	0.709
Ca	0.915
Mg	0.897
HCO_3	0.967
Cl	0.934
NO_3	0.867
TH	0.963
D	0.849
SIc	0.983
SId	0.994
Pco_2	0.919
Ca/Mg	0.954

APPENDIX F (CONTINUED)
for
1975 Sampled Wells
Percent Variation Explained

Factor	Eigen Values	Percent Variation Explained	Cumulative Percent Variation Explained
1	4.85	34.60	34.60
2	3.16	22.60	37.20
3	1.96	14.00	71.20
4	1.34	9.50	80.70
5	1.08	7.70	88.40

Rotated Factor Matrix

	1	2	3	4	5
pH	-0.076	0.385	-0.913	-0.040	0.046
T	-0.146	0.119	-0.054	0.762	-0.136
SPC	0.146	0.315	0.294	0.021	0.078
Ca	0.826	0.158	0.379	0.110	-0.322
Mg	0.116	0.585	0.109	-0.231	0.702
HCO_3	0.210	0.737	0.627	-0.071	0.016
Cl	0.614	0.120	-0.136	0.156	0.301
NO_3	0.239	-0.290	0.112	0.761	-0.108
SO_4	0.769	-0.075	-0.165	-0.399	-0.153
TH	0.799	0.431	0.392	-0.017	0.062
SIc	0.393	0.833	-0.292	0.079	-0.159
SId	0.184	0.790	-0.259	-0.081	0.483
Pco_2	0.157	0.057	0.981	0.024	-0.047
Ca/Mg	0.094	0.036	0.070	0.123	-0.931

Communalities

Variable	Communalities
pH	0.991
T	0.638
SPC	0.980
Ca	0.968
Mg	0.914
HCO_3	0.988
Cl	0.567
NO_3	0.746
SO_4	0.808
TH	0.984
SIc	0.966
SId	0.966
Pco_2	0.994
Ca/Mg	0.865

VITA

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Parents: Charles Ogden
May Ogden

Birth Place: Phoenixville, Pennsylvania

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Date

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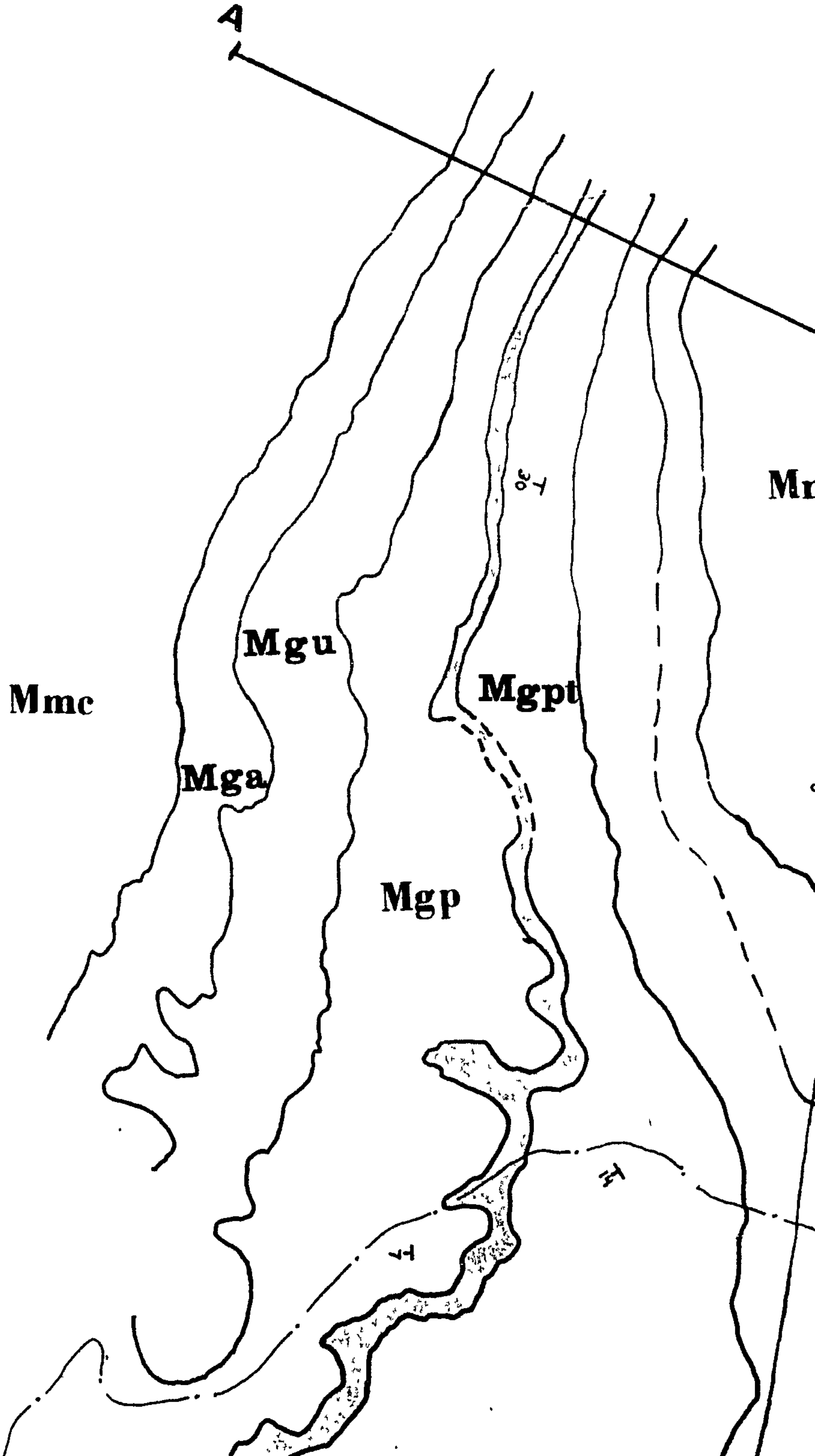
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Mr
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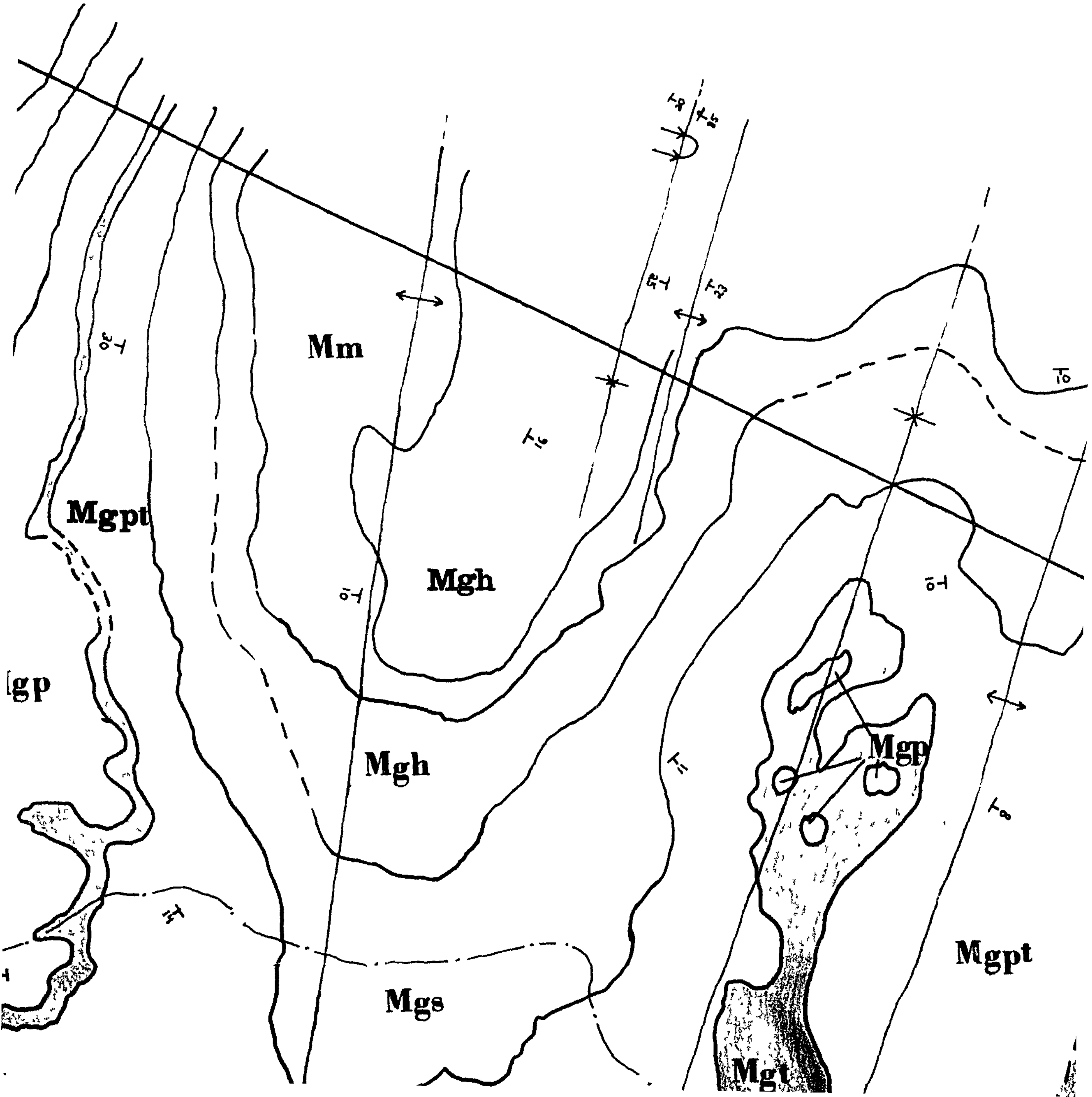
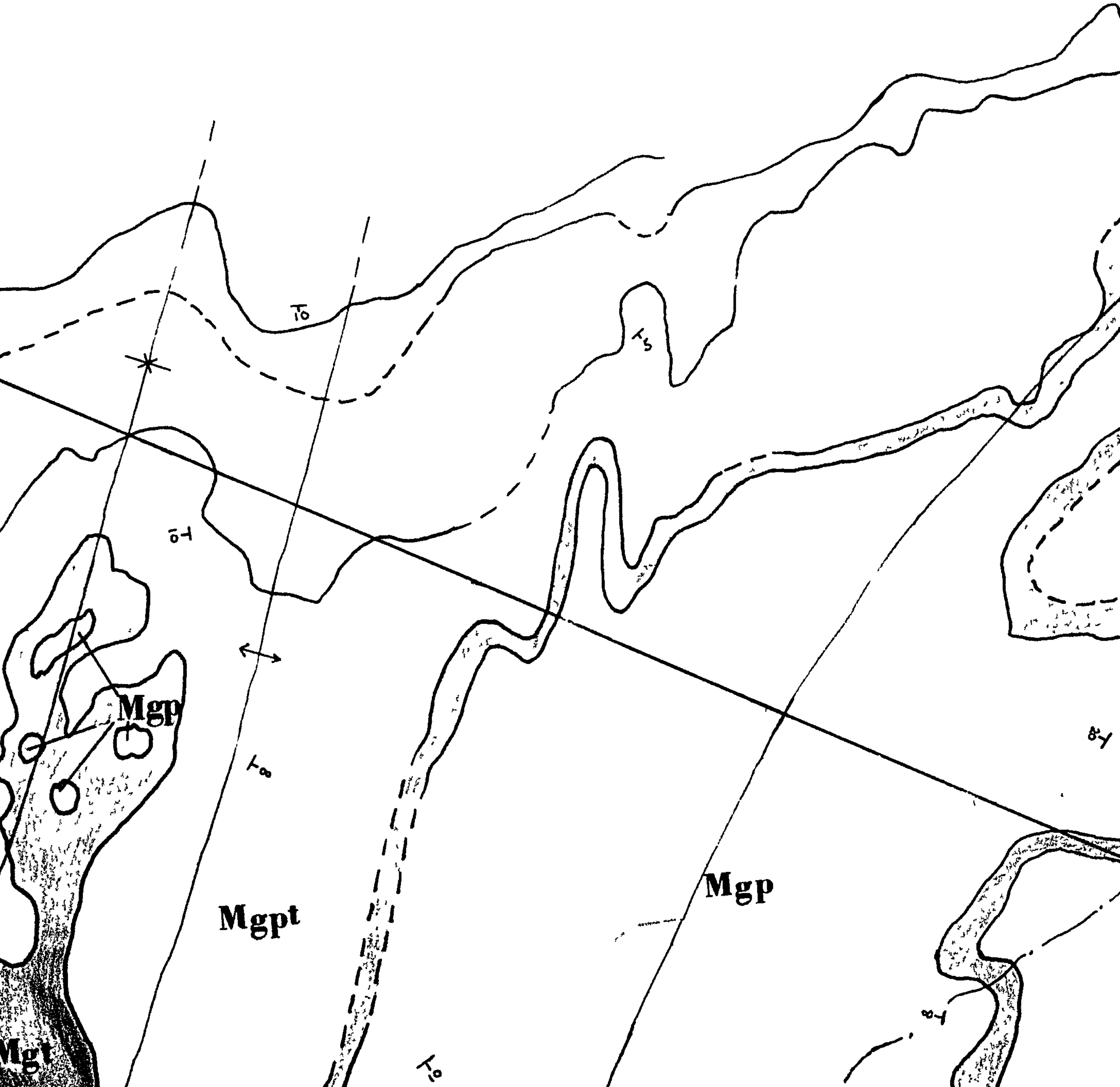
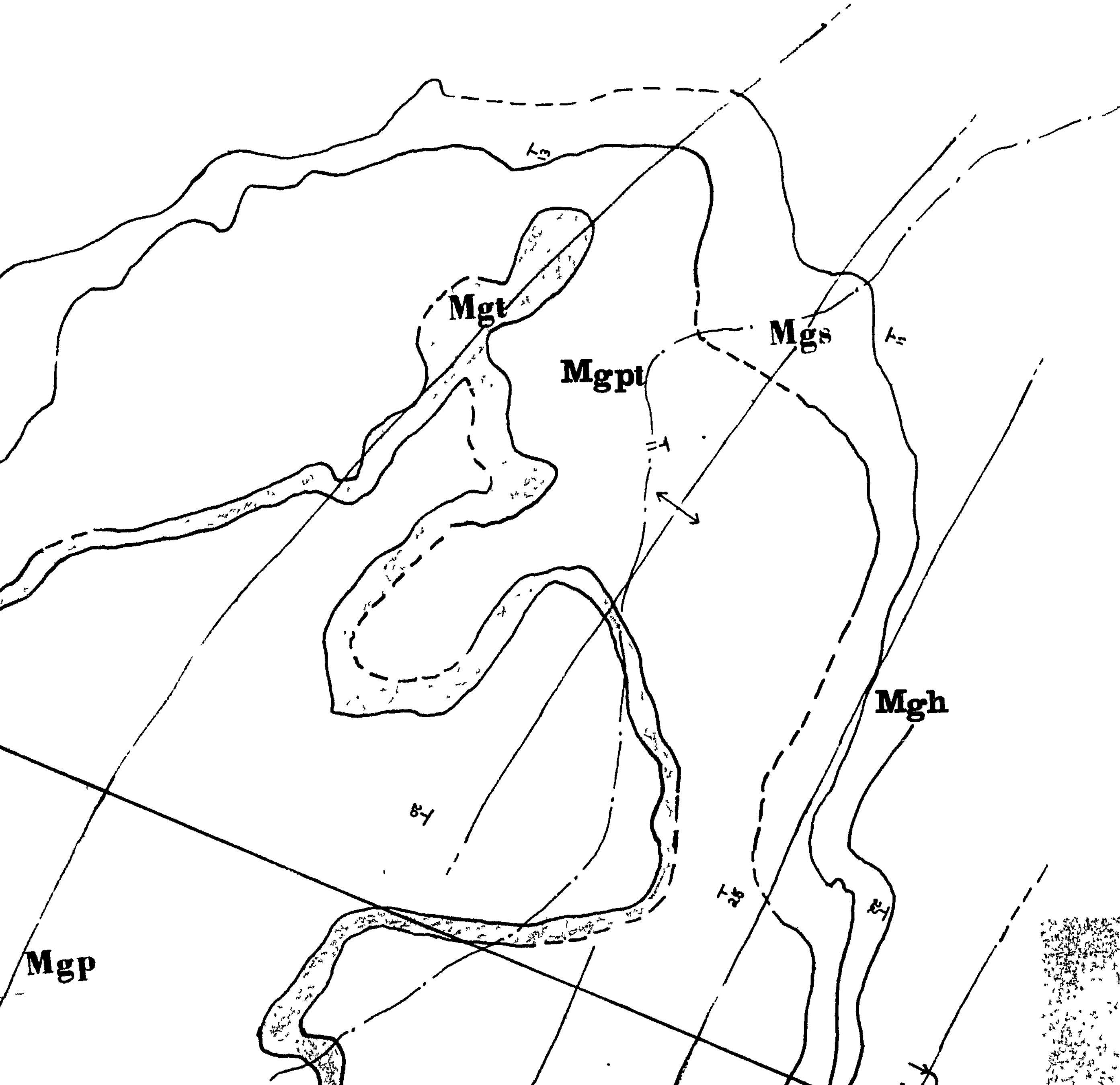
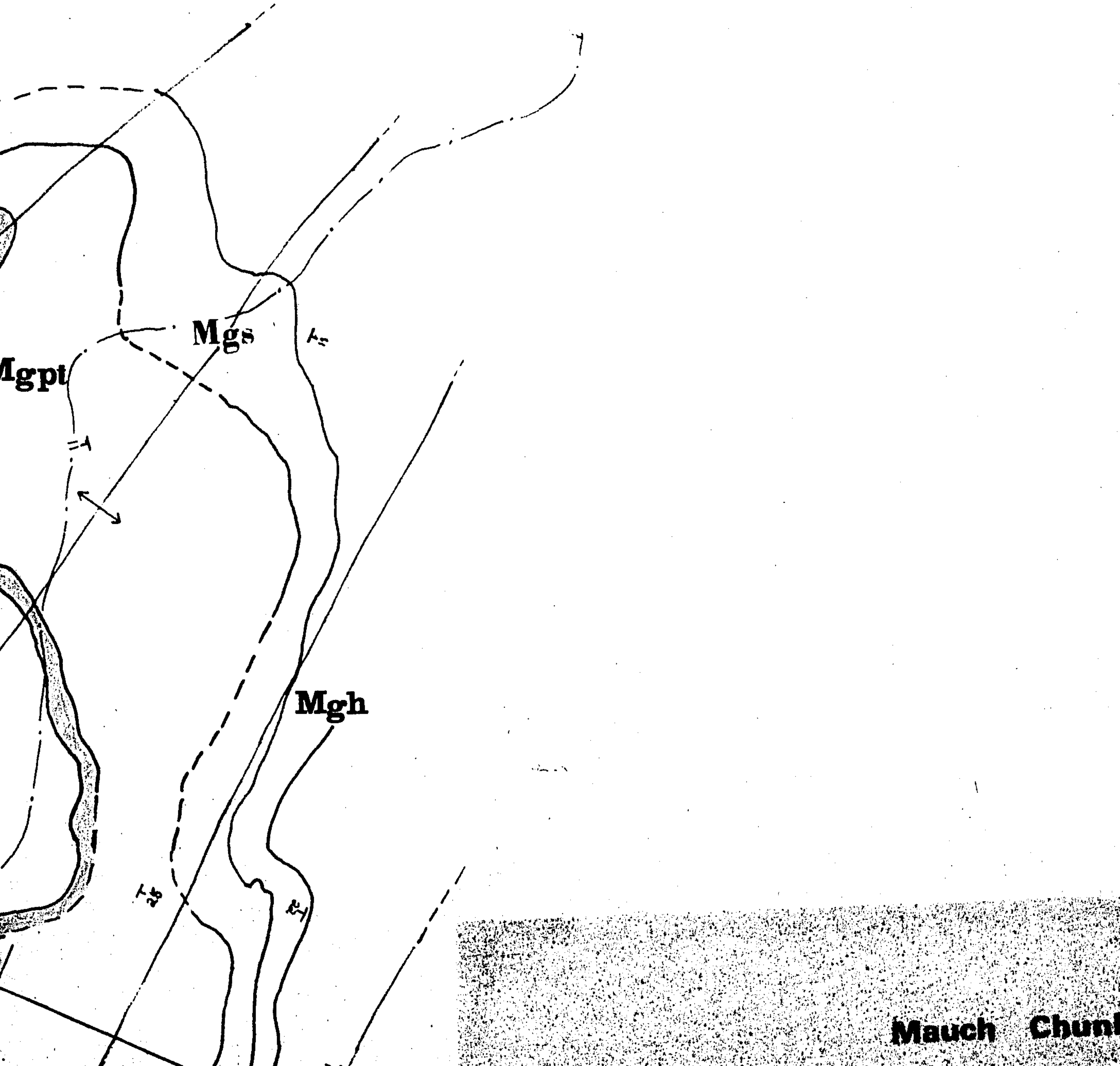
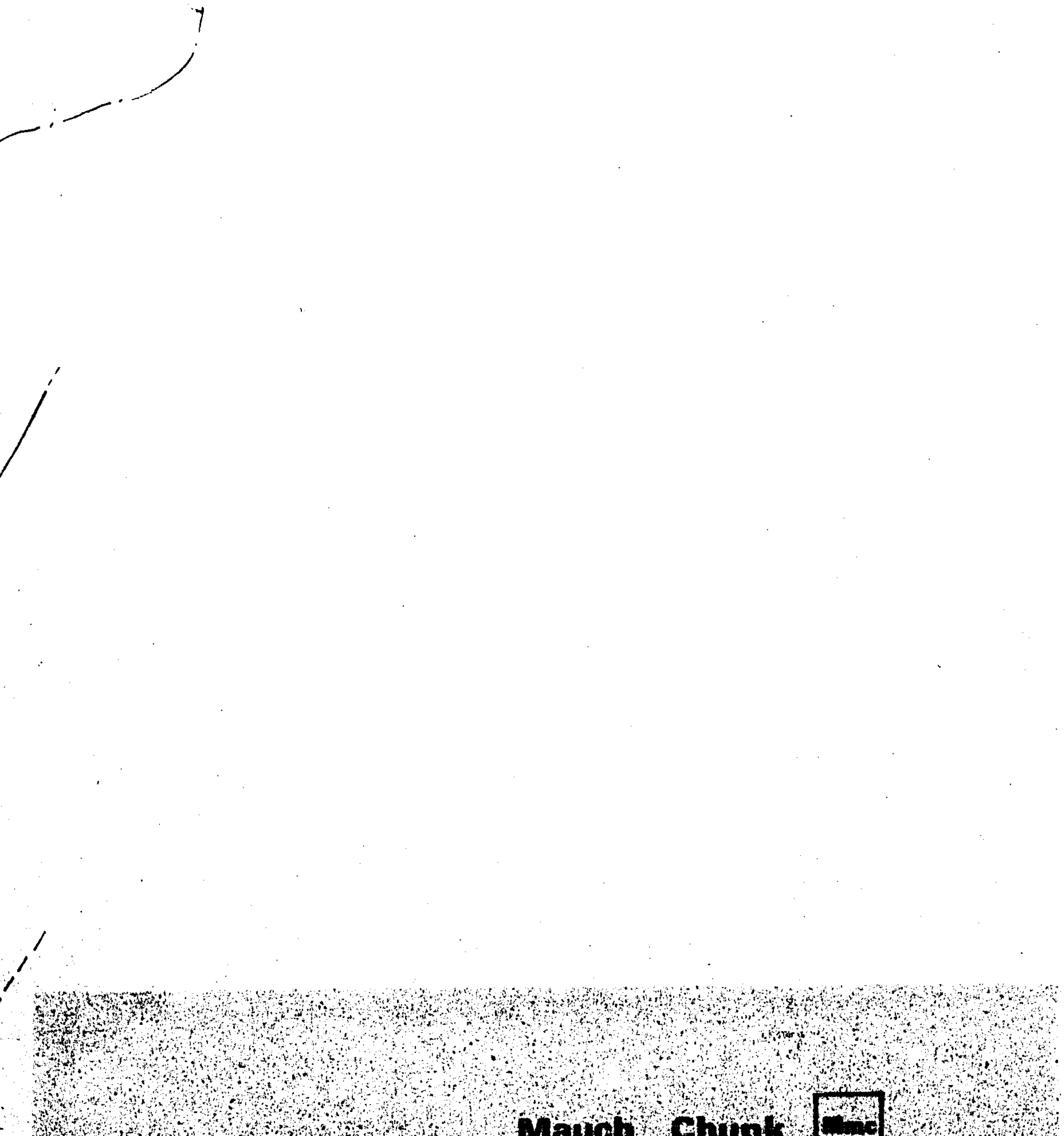
Mga
Mgp


Mm
Mgpt
Mgh
gp
Mgh
Mgp
Mgs
Mgpt
Mgt
30
25
23
16
10
10
10
11
14
8
8
25

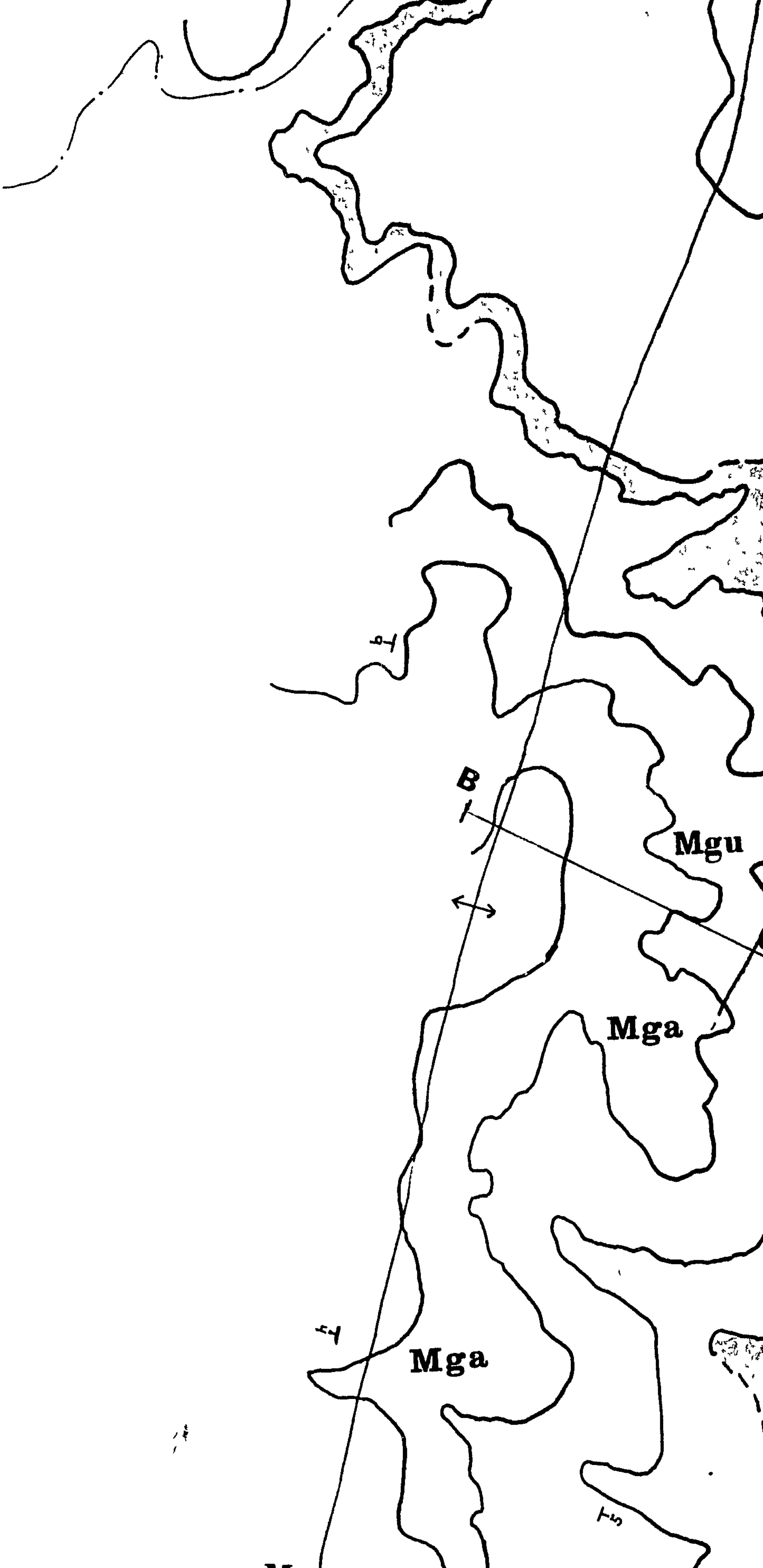

10
5
10
Mgp
8
Mgpt
Mgp
8
8
Mgt
10

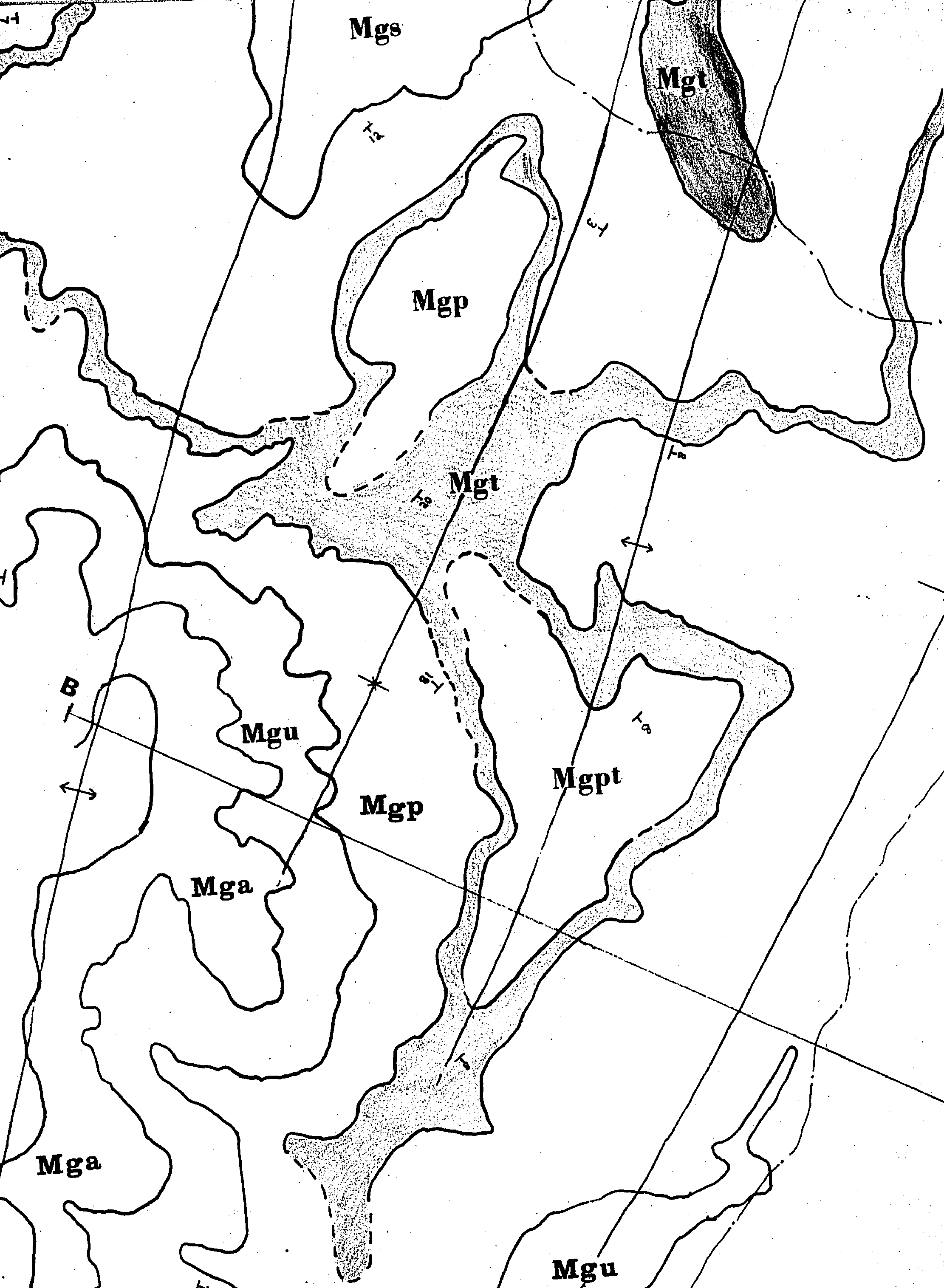

Mgt
Mgpt
Mgs
Mgh
Mgp

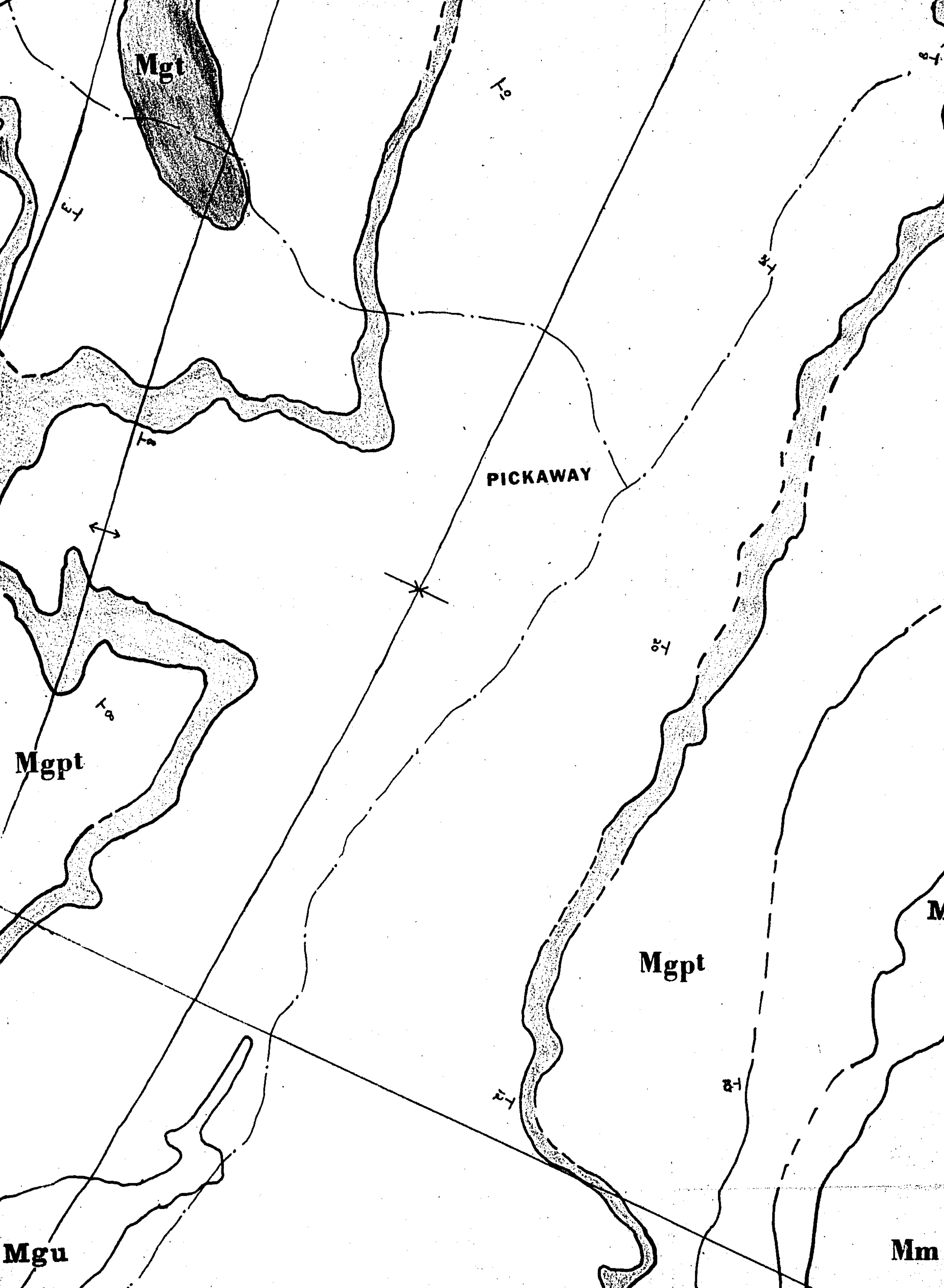

Mgs
Mgpt
Mgh
Mauch Chun

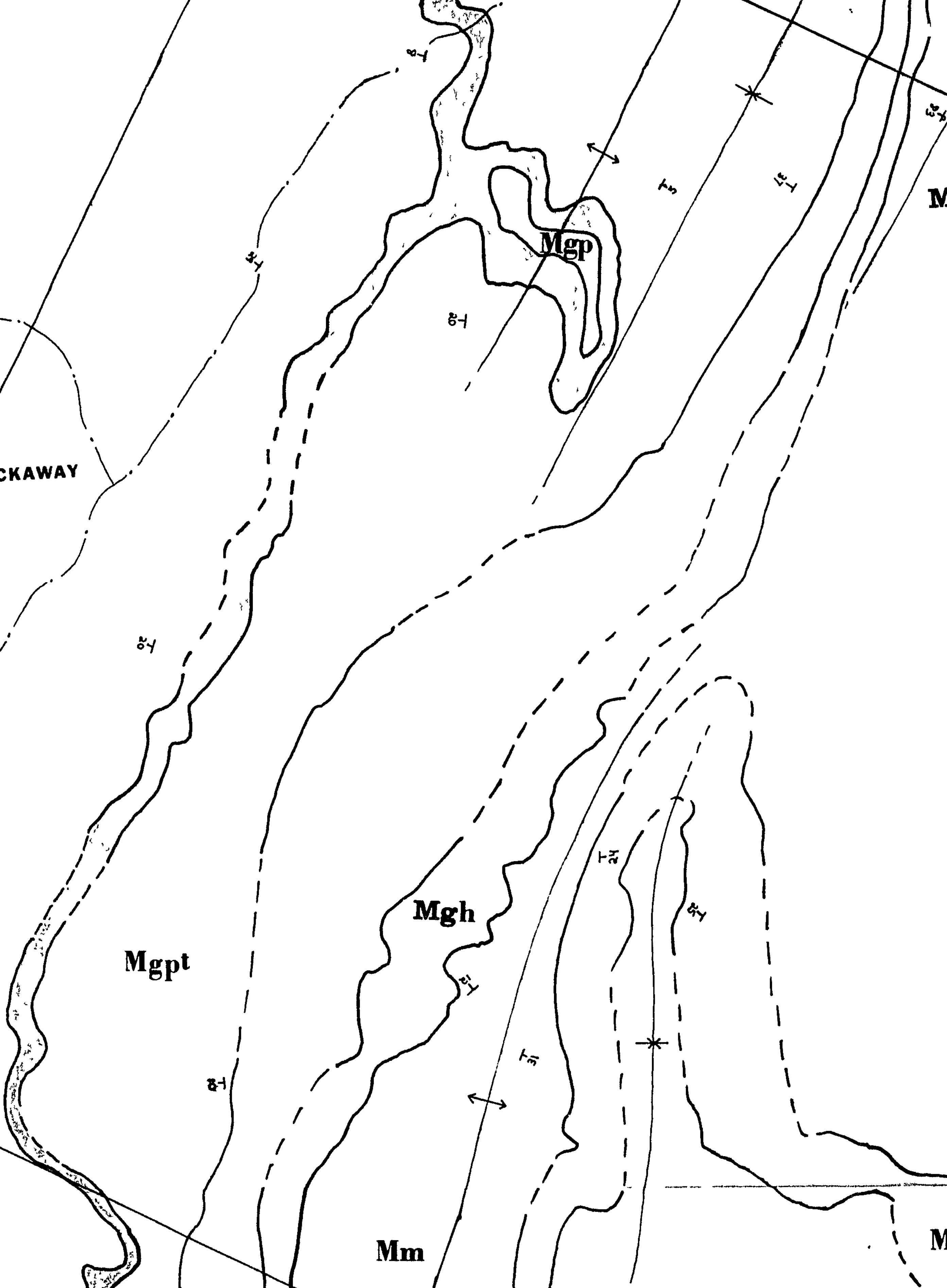


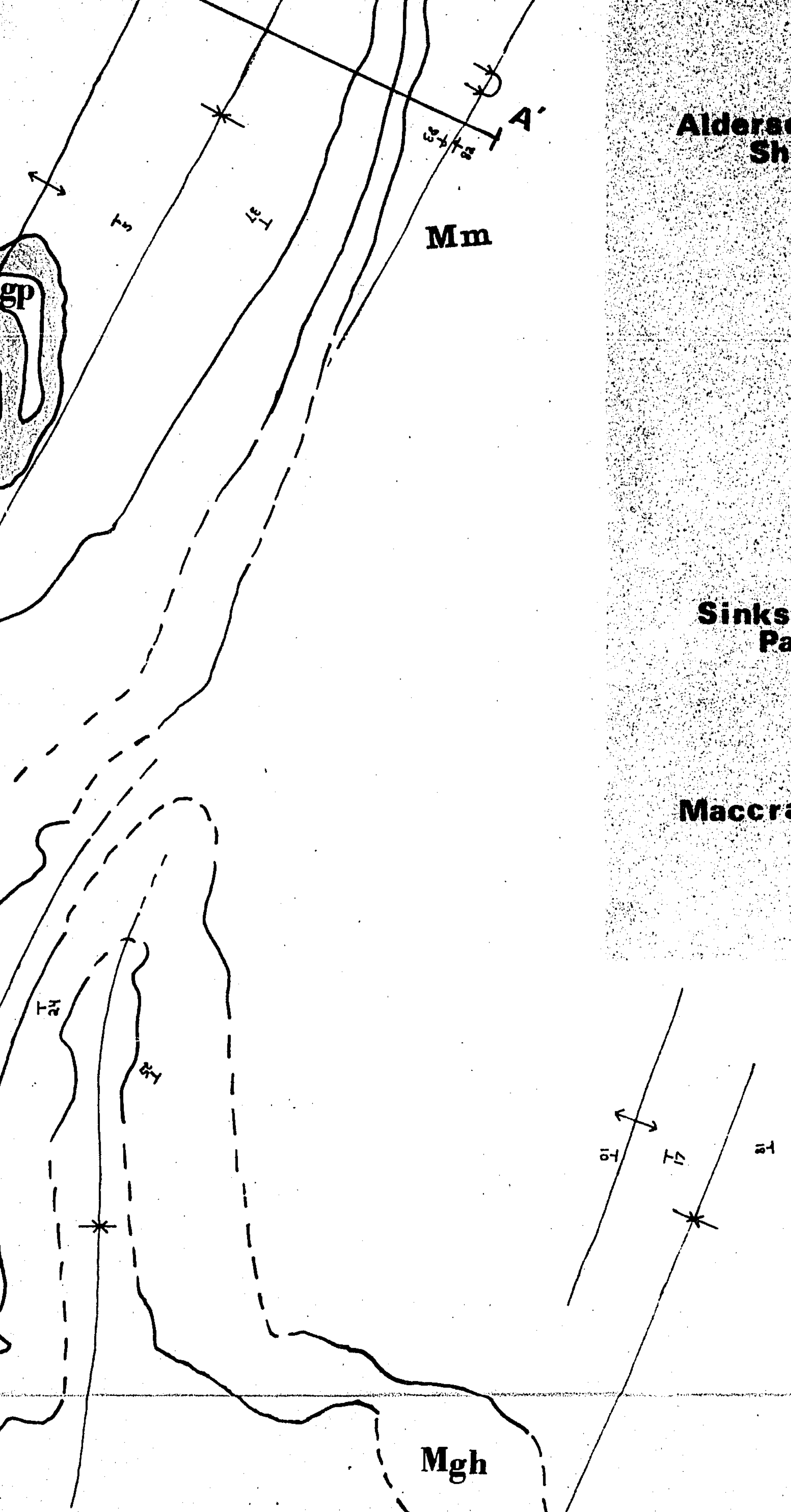
Mauch Chunk
Mmc


B
Mgu
Mga
Mga


Mgs
Mgt
Mgp
Mgt
B
Mgu
Mgp
Mgpt
Mga
Mga
Mgu


Mgt
PICKAWAY
Mgpt
Mgpt
M
Mgu
Mm


Mgp
CKAWAY
Mgpt
Mgh
Mm
M
M



Mau

Alderson Ls. with thin
Shale at base when

Pic

Taggard L

Sinks Grove Ls. with o
Patton Sh. when p

Hi

Maccrady and older fo

PLA

Mauch Chunk	Mmc
Alderson Ls. with thin Greenville Shale at base when present	Mga
Union Ls.	Mgu
Pickaway Ls.	Mgp
Taggard Ls. and Sh.	Mgt
Patton Ls.	Mgpt
Sinks Grove Ls. with overlying Patton Sh. when present	Mgs
Hillsdale Ls.	Mgh
Maccrady and older formations	Mm

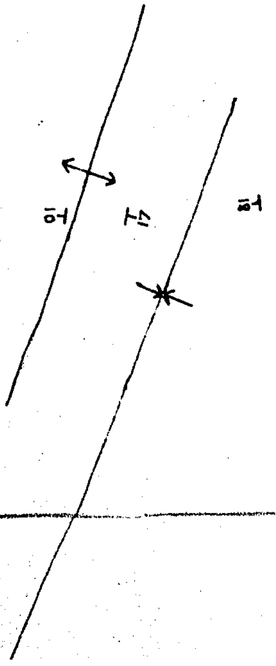
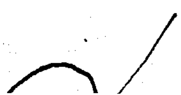
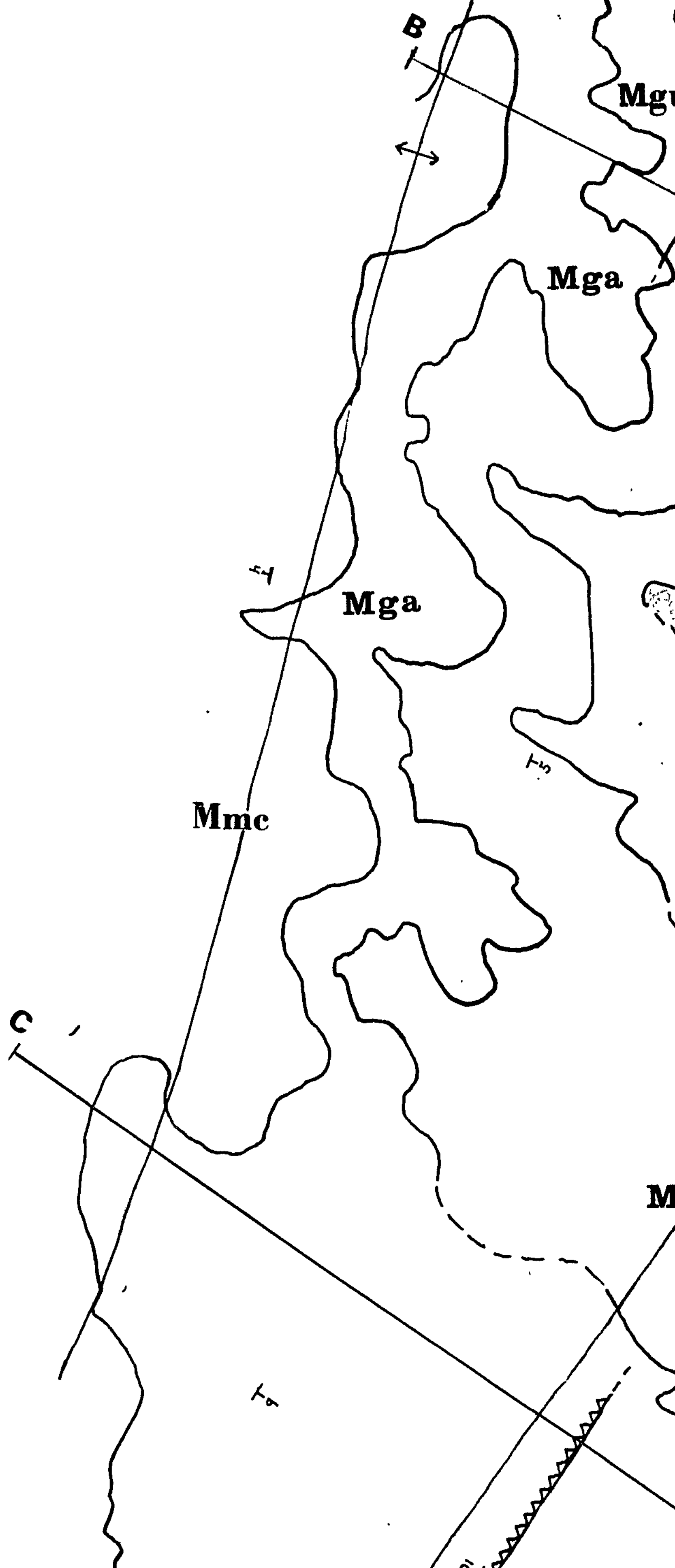
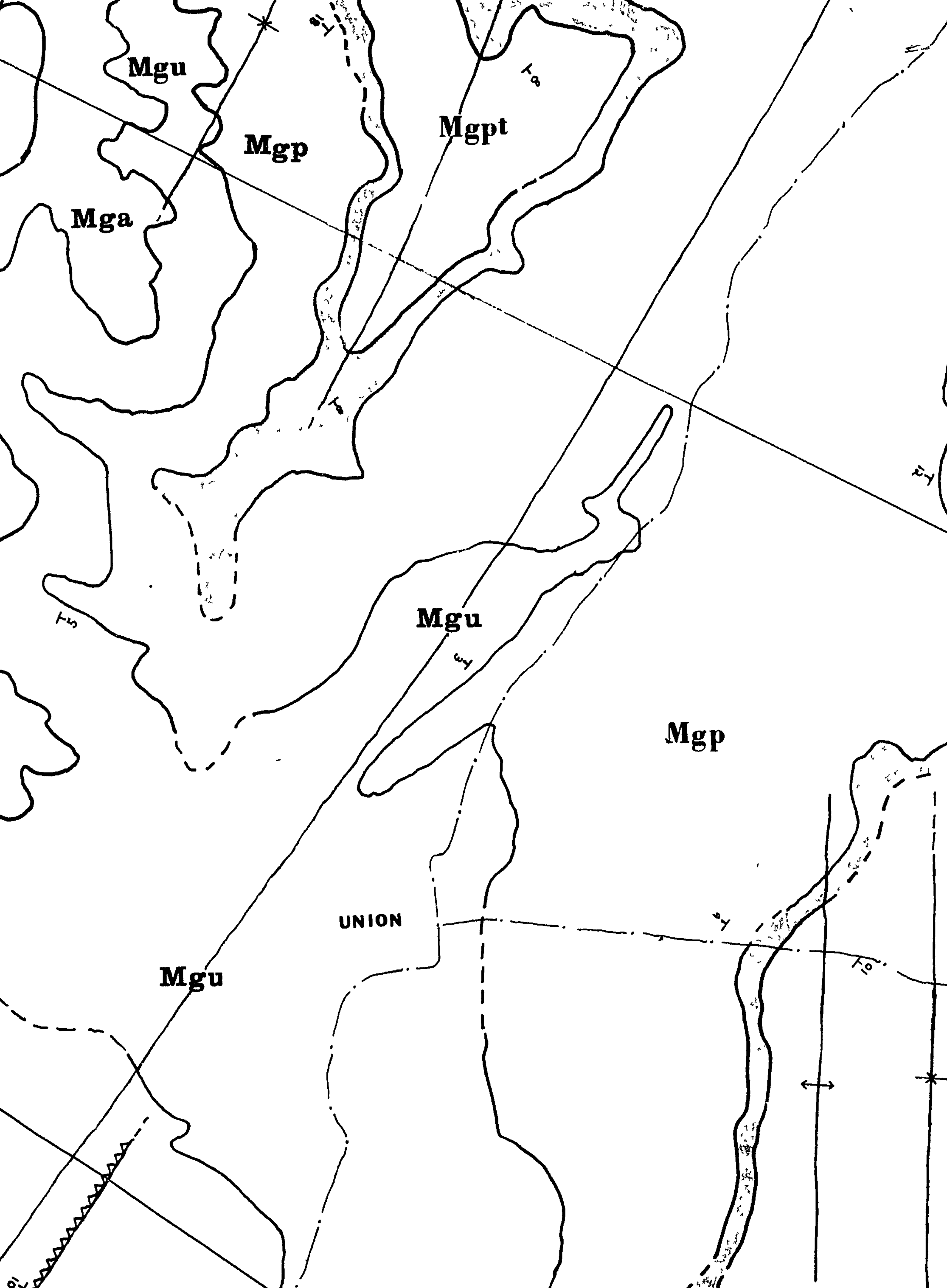
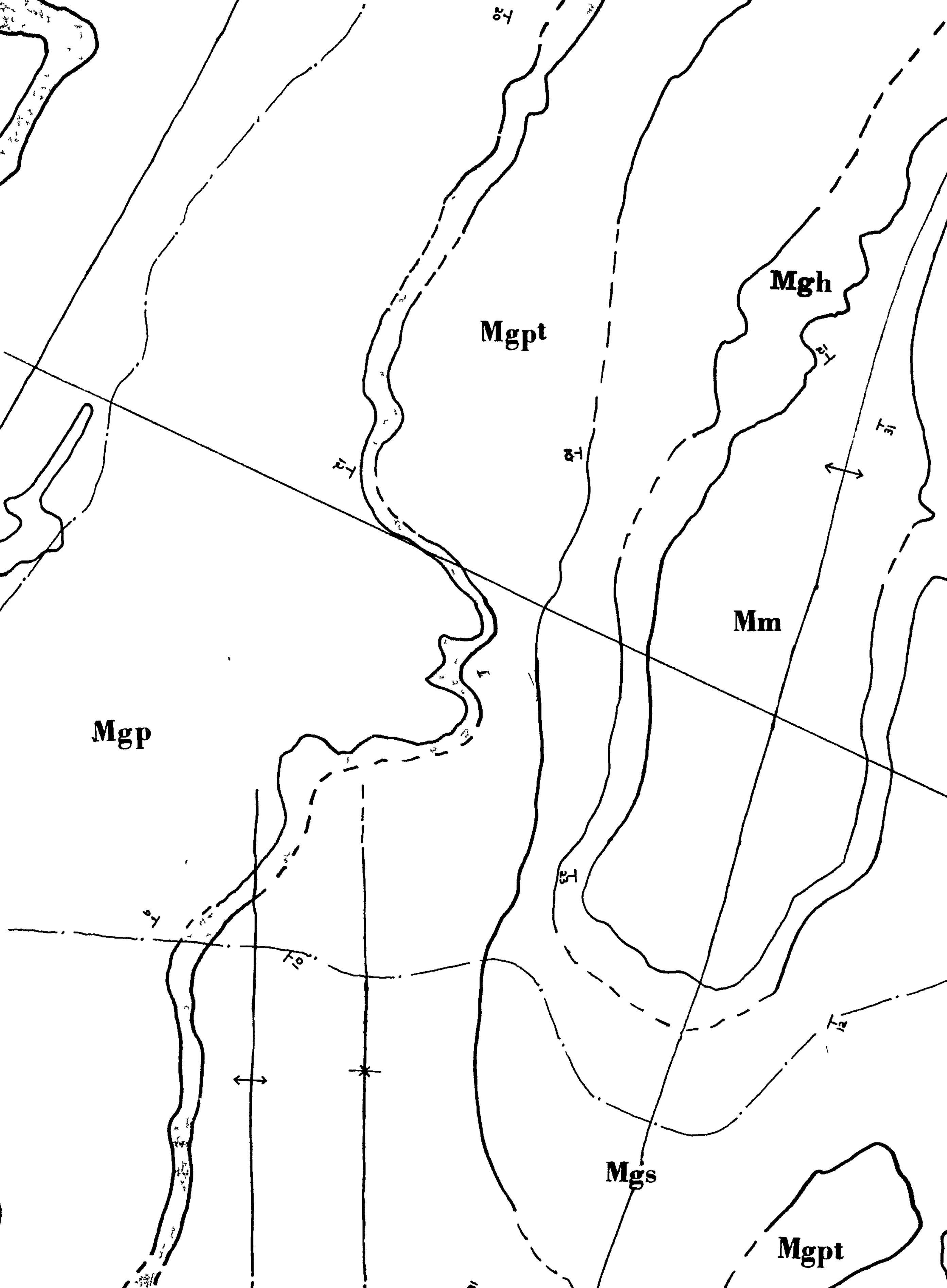


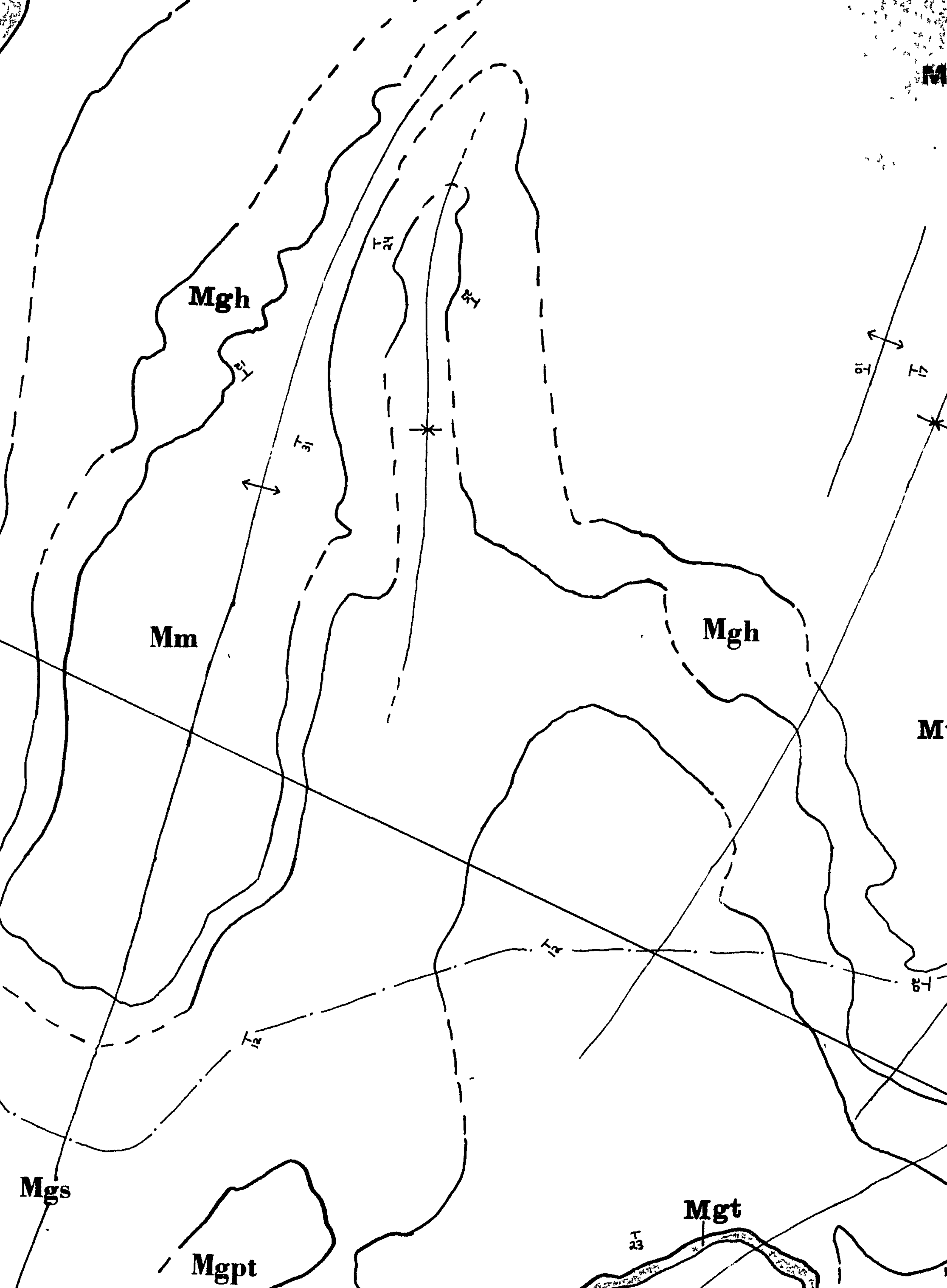
PLATE 1

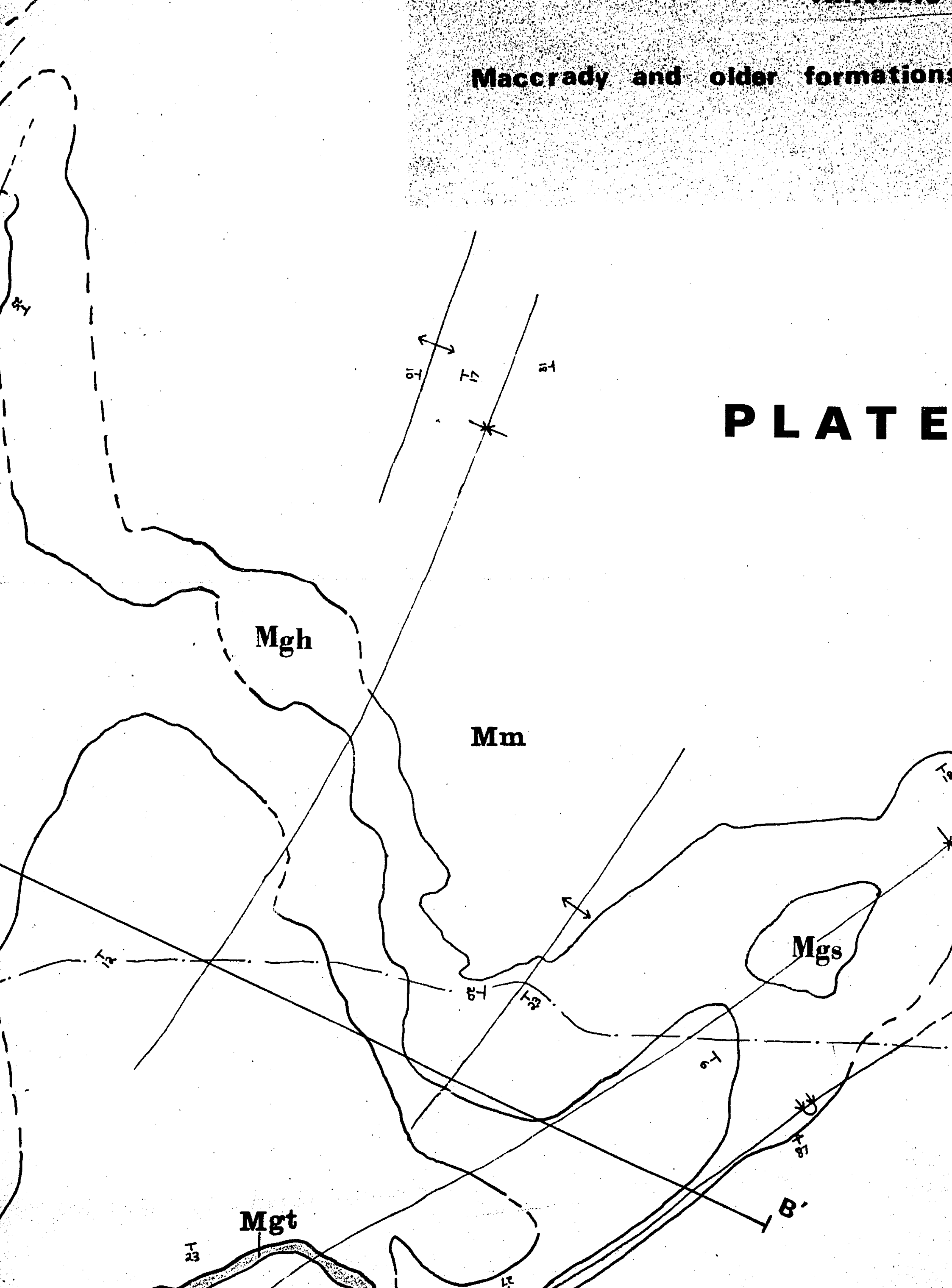



B
Mgu
Mga
Mga
Mmc
C
M


Mgu
Mgp
Mgpt
Mga
Mgu
Mgp
UNION
Mgu


Mgh
Mgpt
Mm
Mgp
Mgs
Mgpt


Mgh
31
Mm
Mgh
12
12
Mgs
Mgpt
Mgt
23

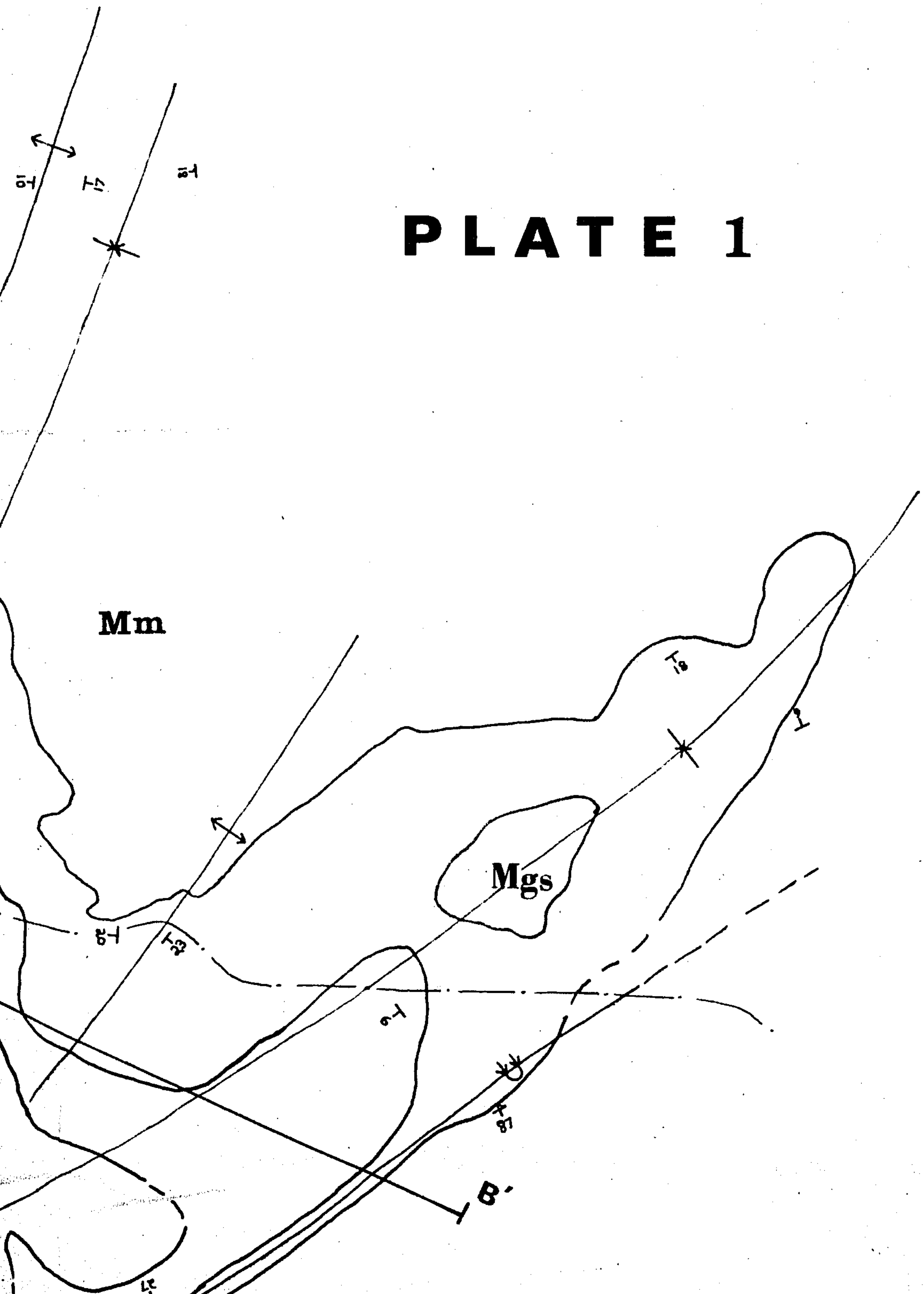

Maccrady and older formations
Mgh
Mm
Mgs
Mgt
B'
10
17
12
33
6
87
23

PLATE

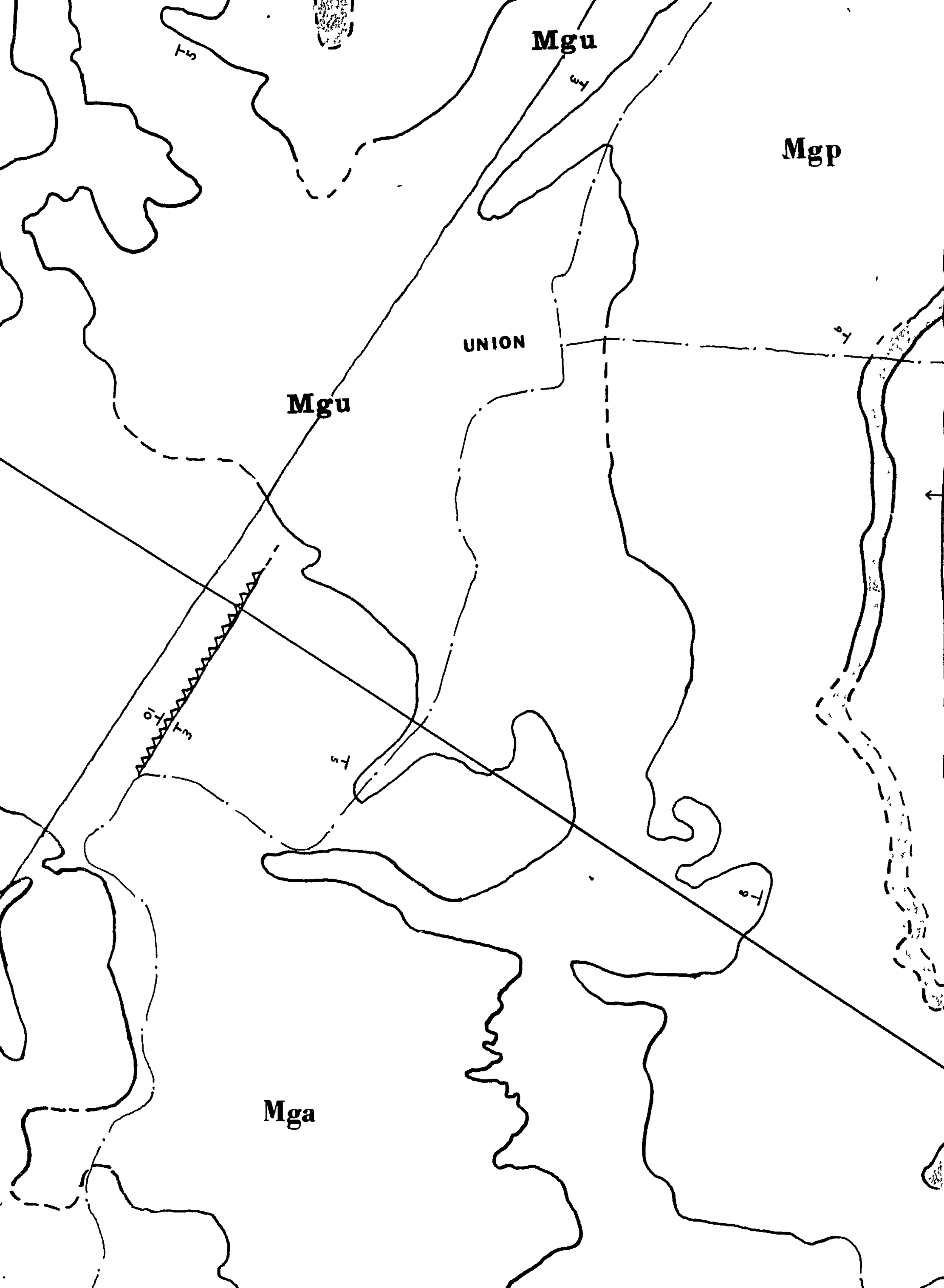
Hillsdale Ls. **Mgh**

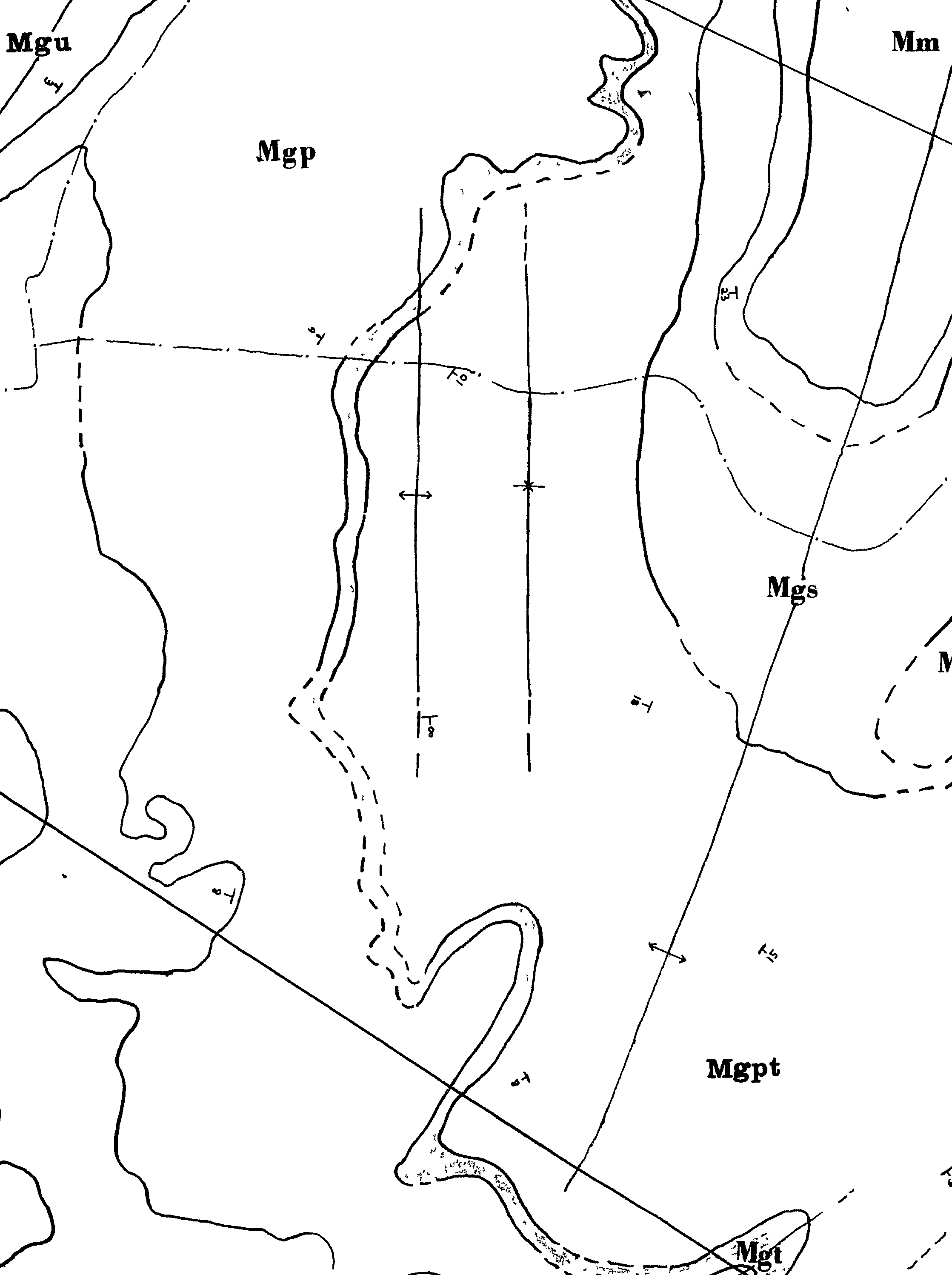
Maccrady and older formations **Mm**

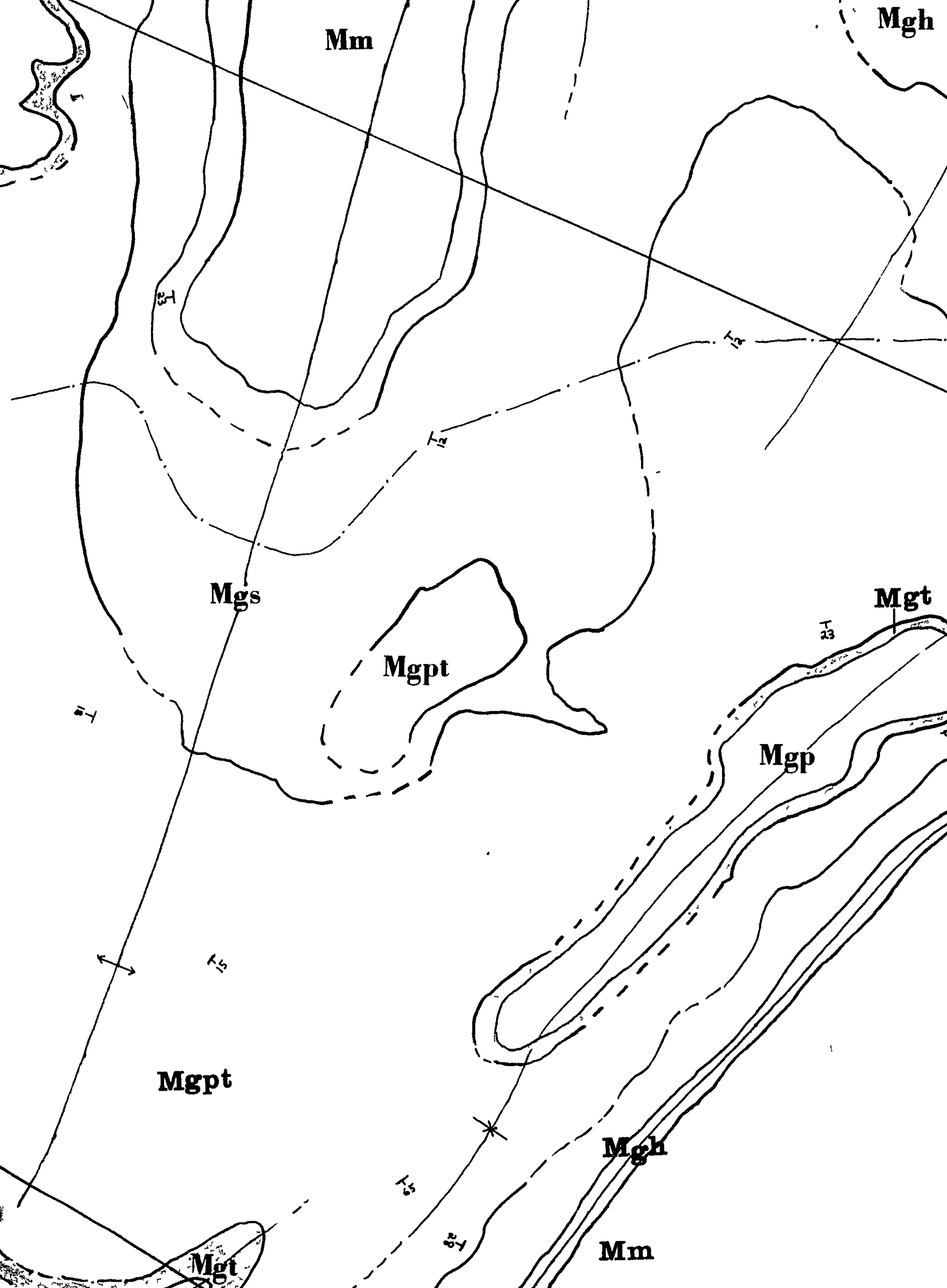
PLATE 1

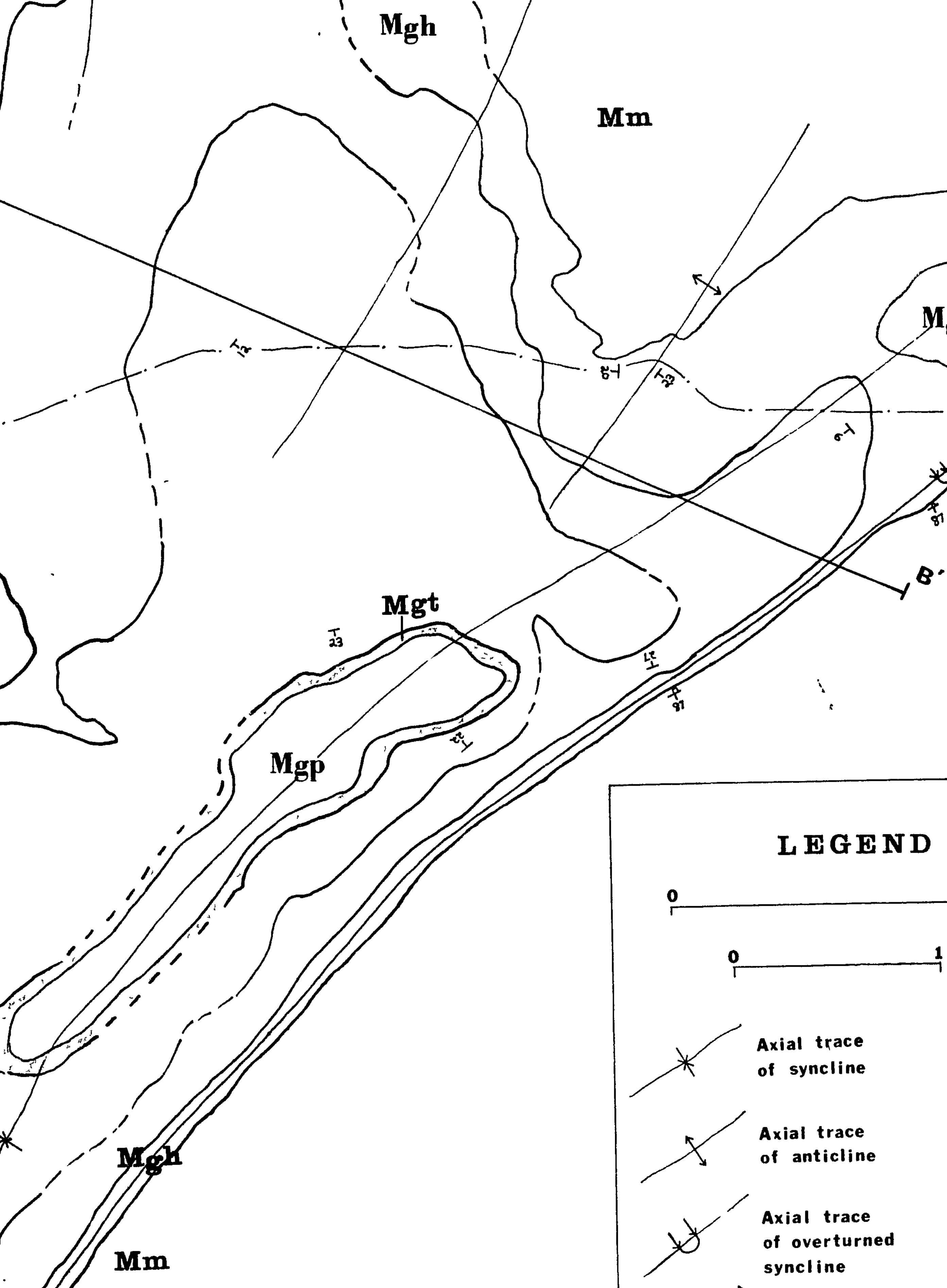


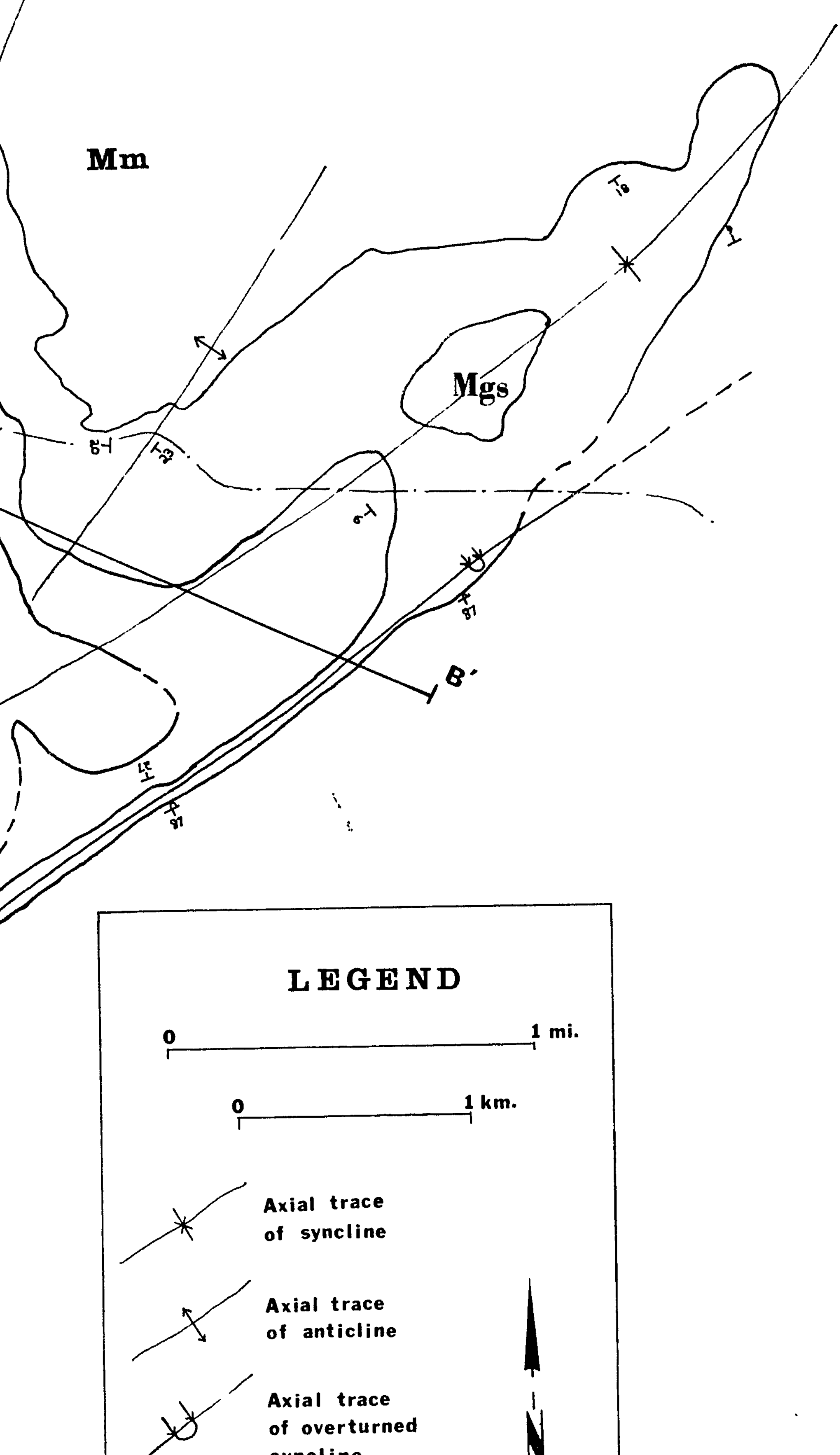

Mmc
C
9
10
3
Mmc
Mg

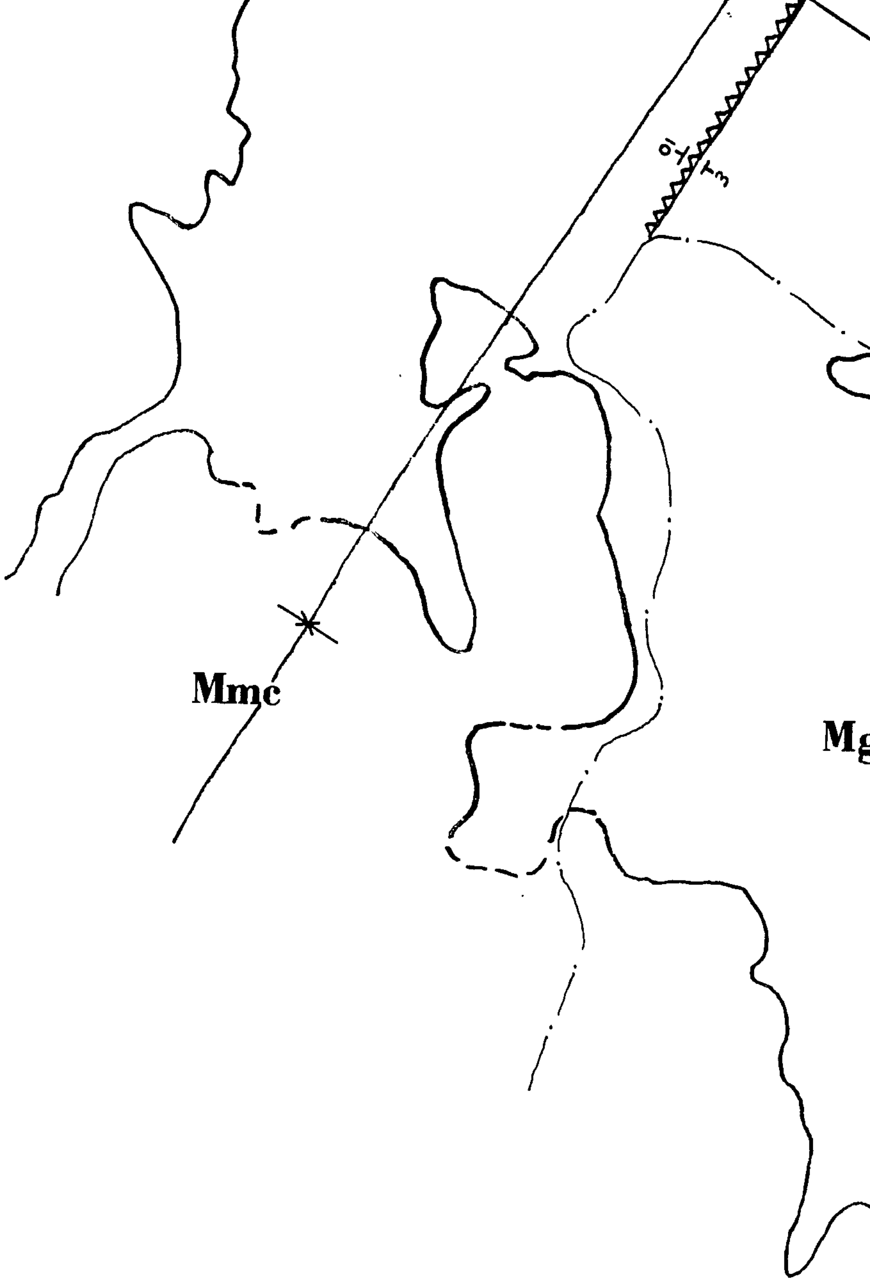

Mgu
Mgp
UNION
Mgu
Mga
5
3
10
3
5
8

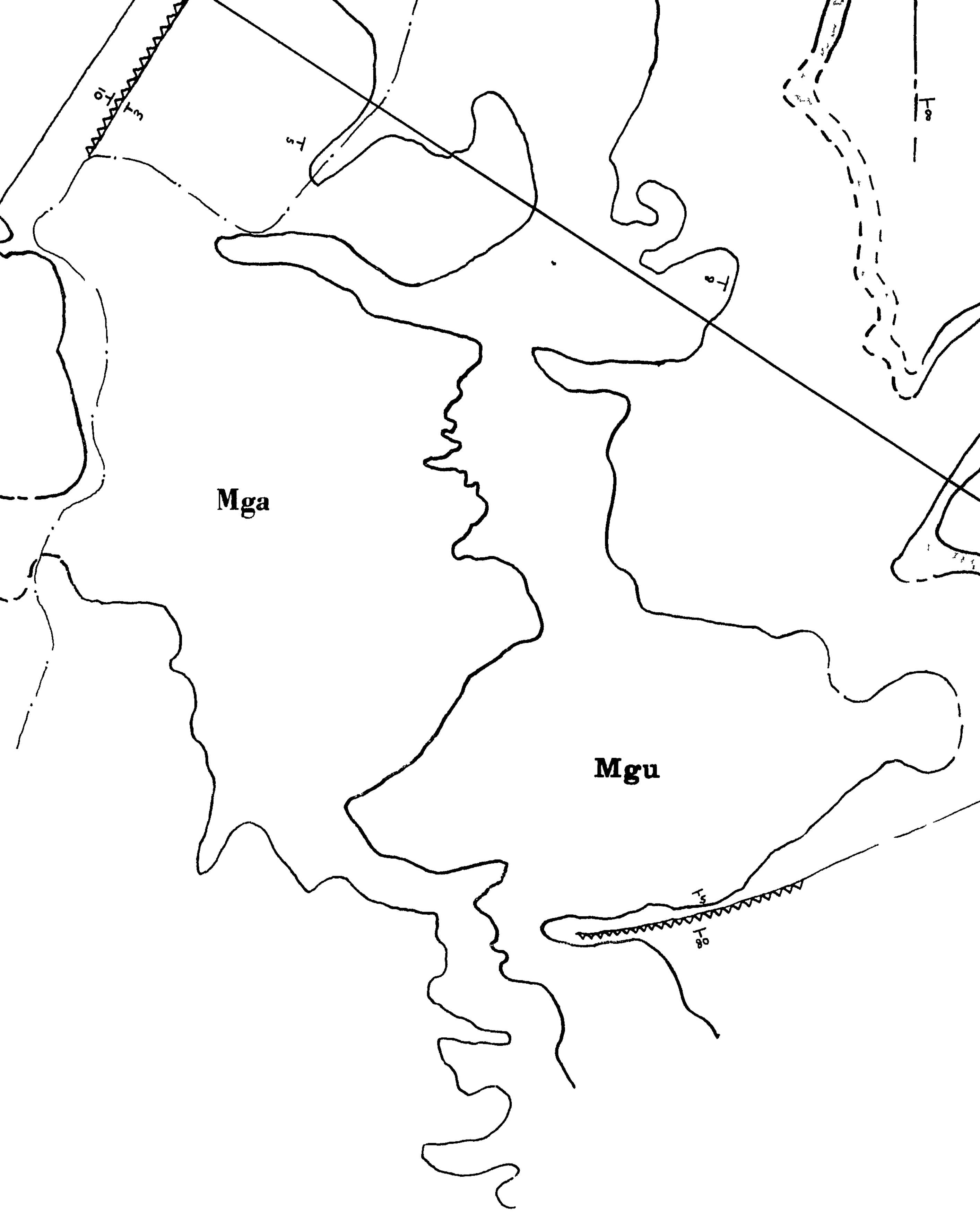

Mgu
Mm
Mgp
Mgs
M
Mgpt
Mgt

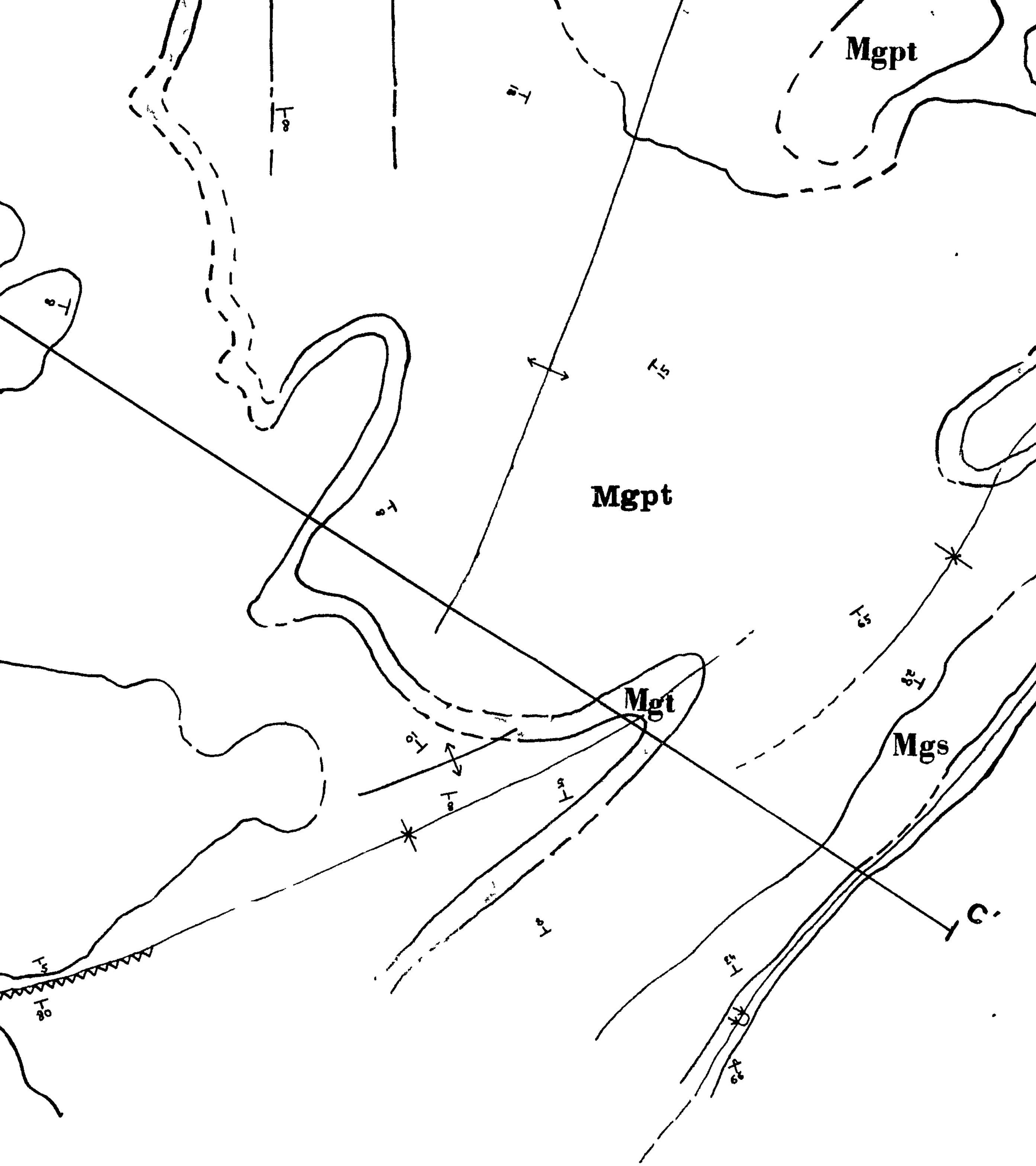

Mm
Mgh
23
12
12
Mgs
Mgpt
Mgt
23
18
Mgp
15
Mgpt
Mgh
65
Mm
Mgt

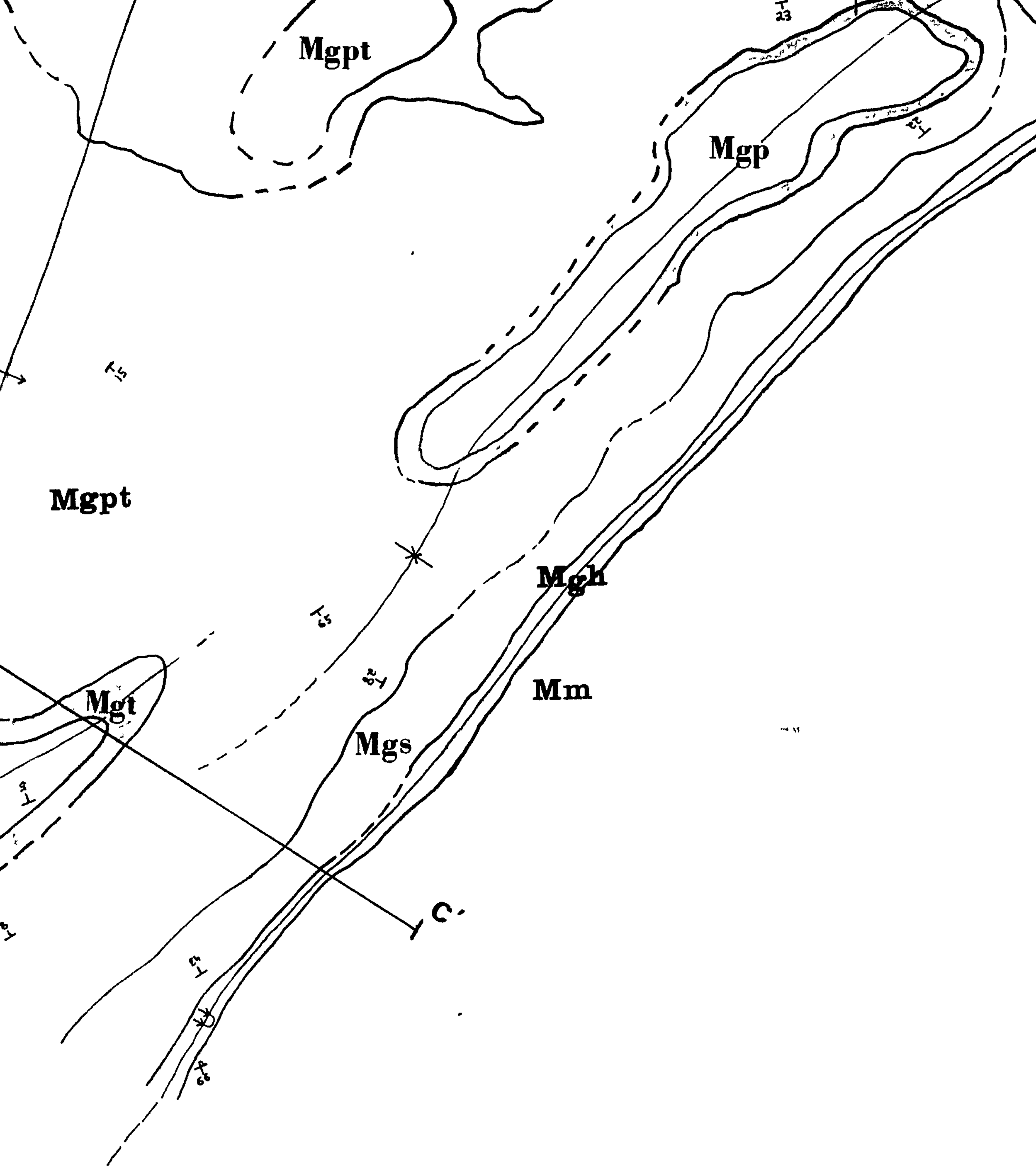

Mgh
Mm
M
Mgt
Mgp
B'
Mgh
Mm
12
28
33
9
87
23
27
87
22
LEGEND
0
0
1
Axial trace of syncline
Axial trace of anticline
Axial trace of overturned syncline

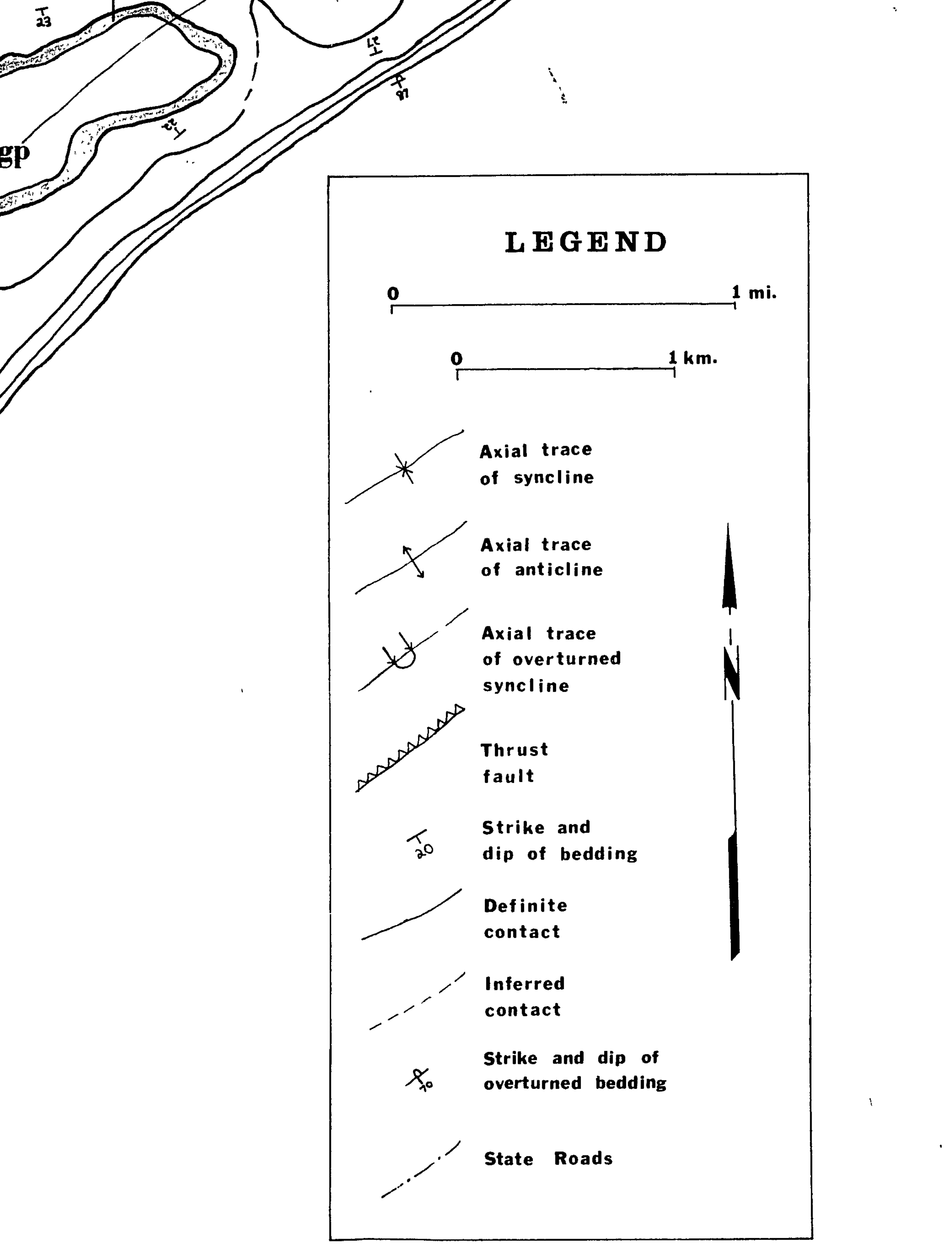

Mm
Mgs
33
87
87
B'
LEGEND
0
1 mi.
0
1 km.
Axial trace of syncline
Axial trace of anticline
Axial trace of overturned syncline

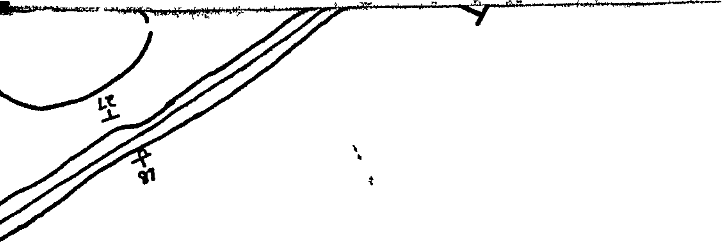

10
3
Mmc
Mg

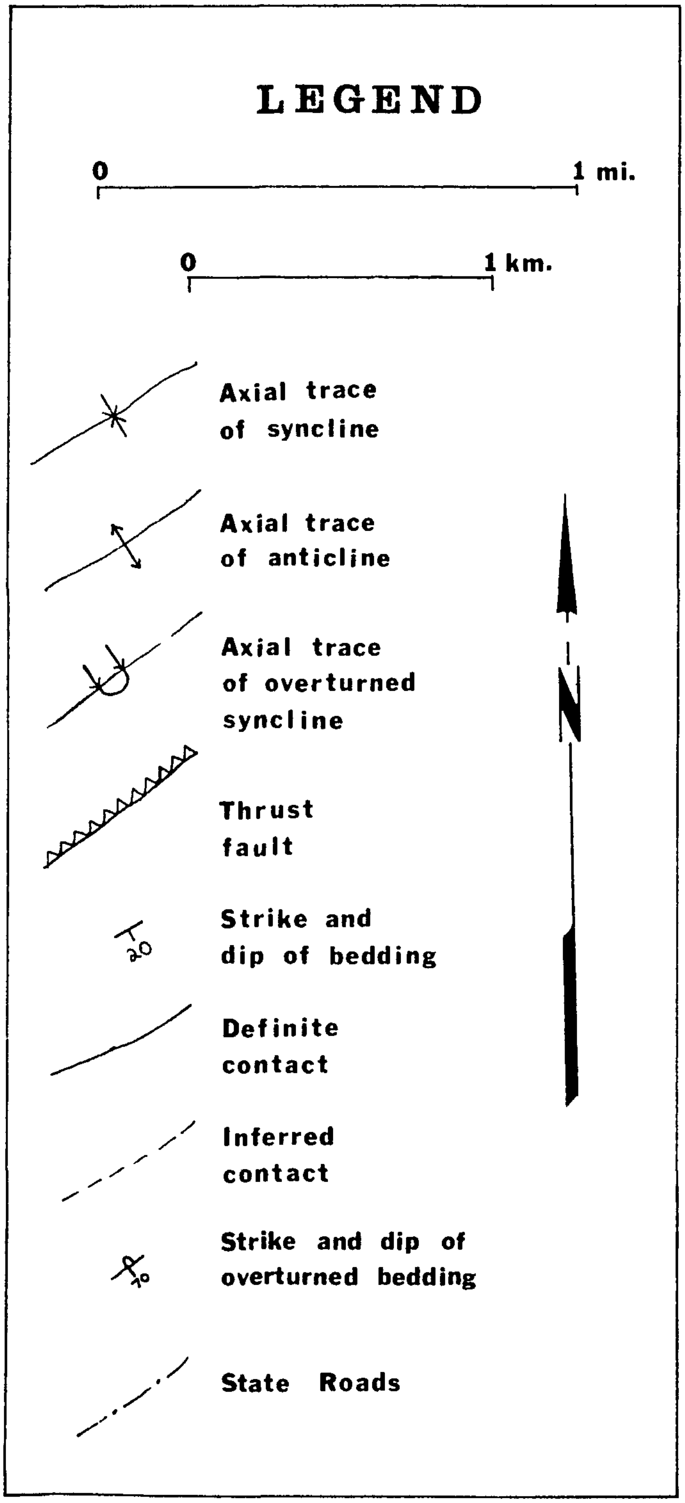

10
3
5
8
9
Mga
Mgu
5
80


Mgpt
8
18
8
15
Mgpt
8
Mgt
10
8
5
65
28
Mgs
C'
8
43
66
5
80

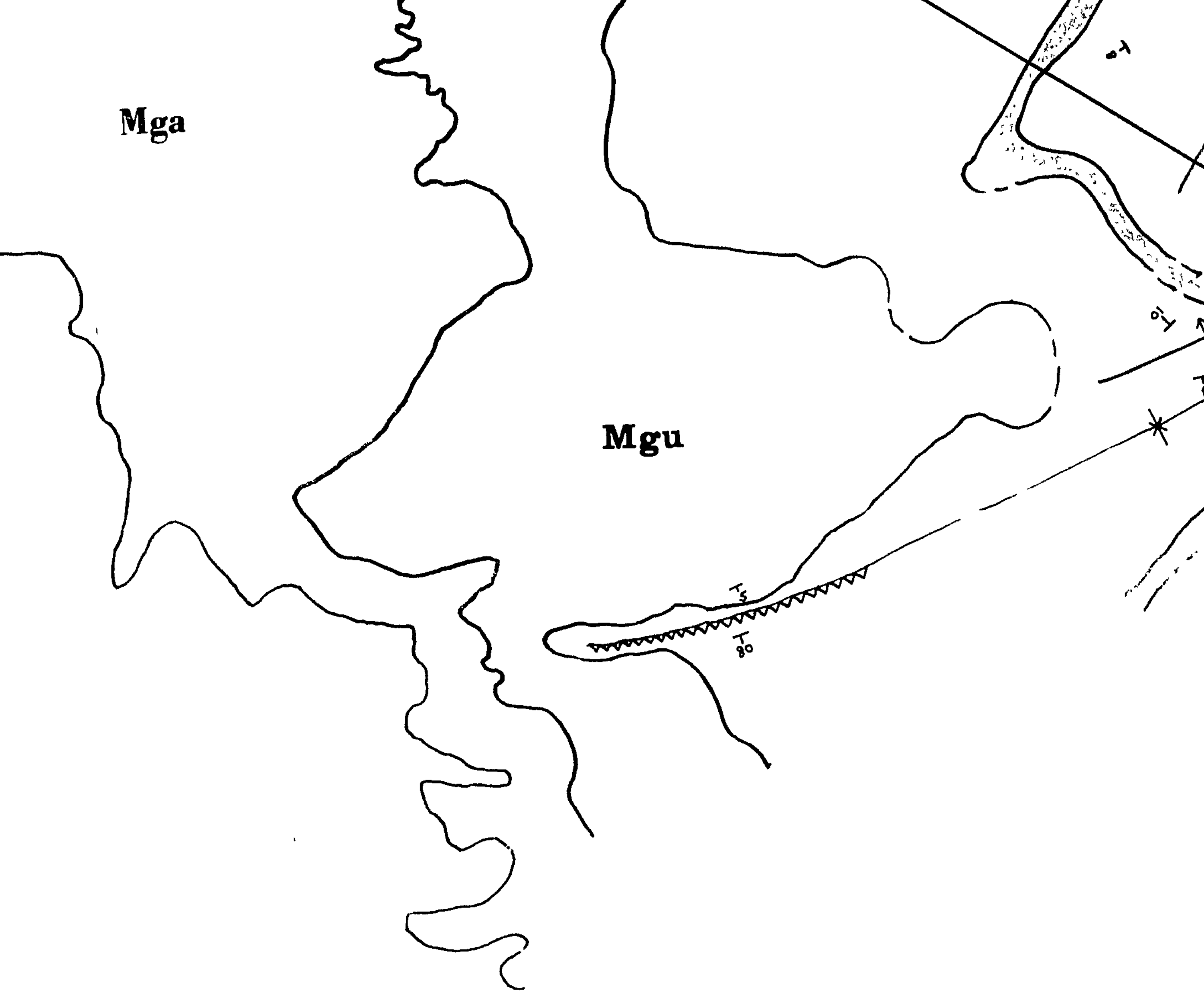

Mgpt
23
Mgp
15
Mgpt
Mgh
65
28
Mgt
Mm
Mgs
5
C'
47
66

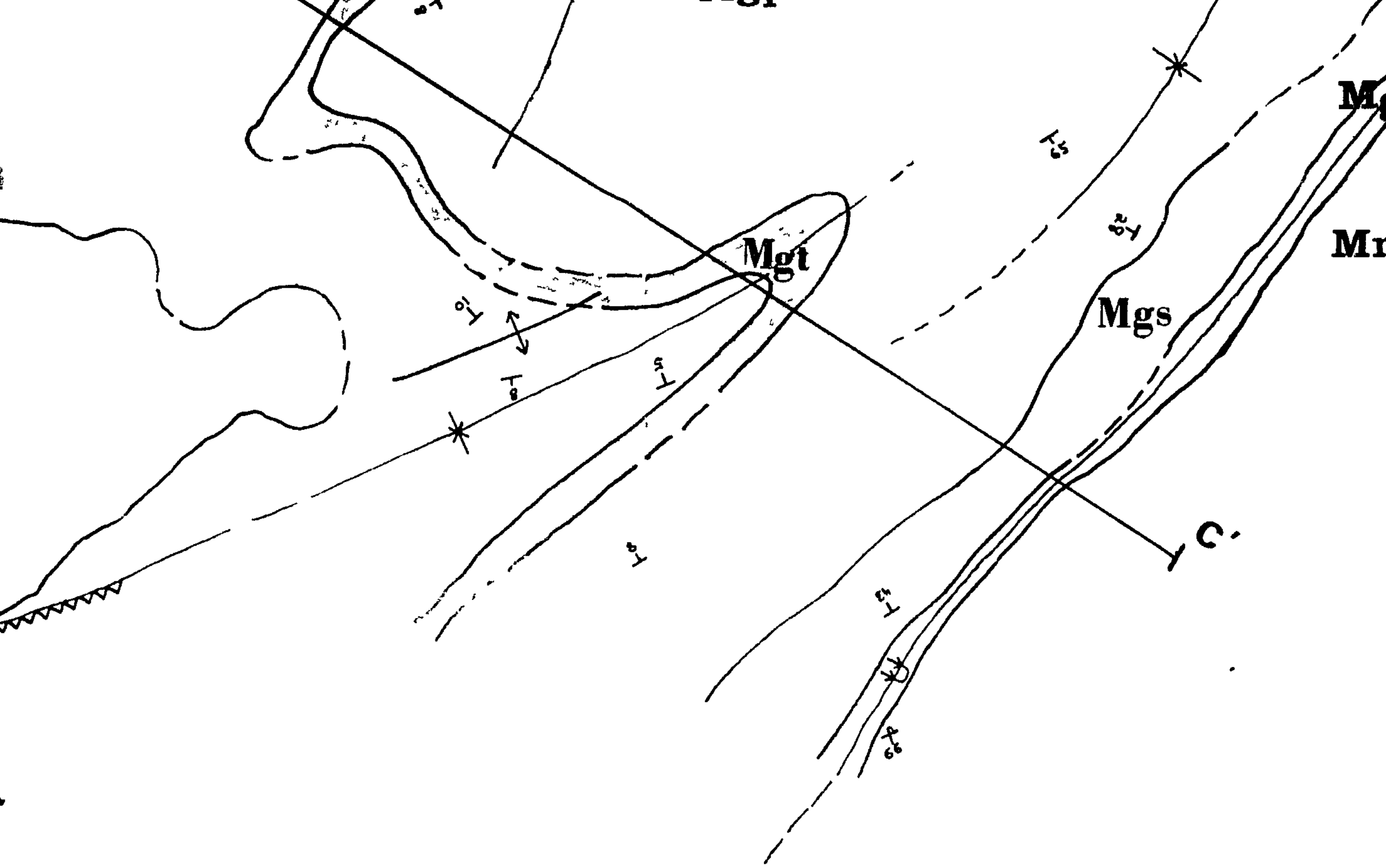

gp
23
27
18
23
LEGEND
0
1 mi.
0
1 km.
Axial trace of syncline
Axial trace of anticline
Axial trace of overturned syncline
Thrust fault
20
Strike and dip of bedding
Definite contact
Inferred contact
70
Strike and dip of overturned bedding
State Roads
N

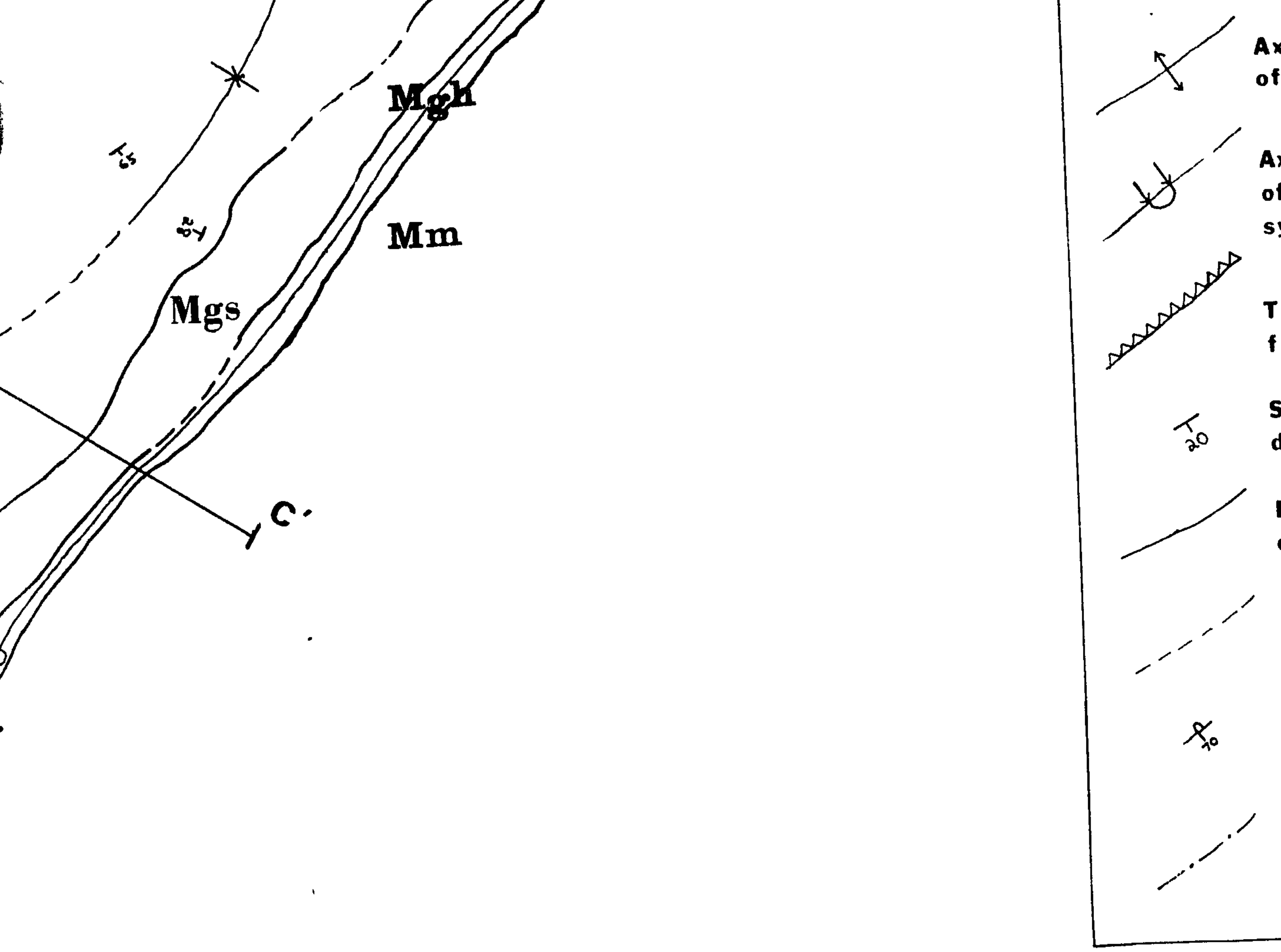


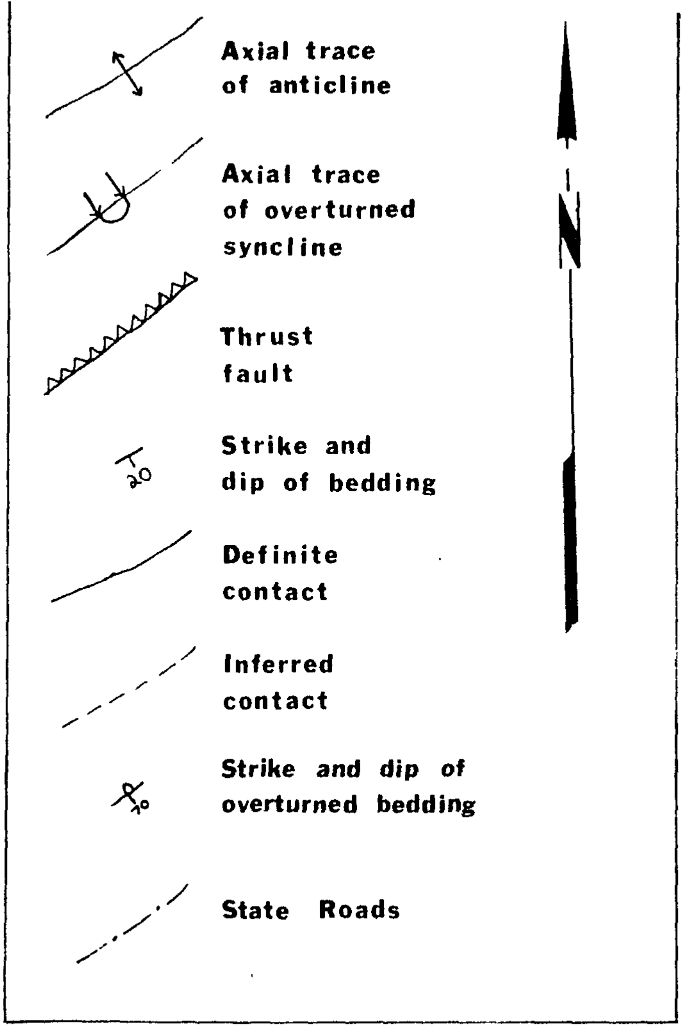

LEGEND
0
1 mi.
0
1 km.
Axial trace of syncline
Axial trace of anticline
Axial trace of overturned syncline
Thrust fault
20
Strike and dip of bedding
Definite contact
Inferred contact
70
Strike and dip of overturned bedding
State Roads
N

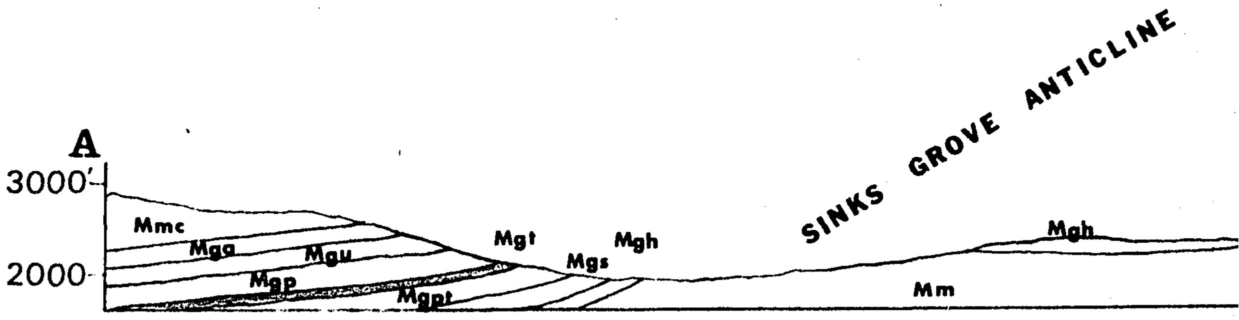

Mmc
Mga


Mga
Mgu
5
80
10
8

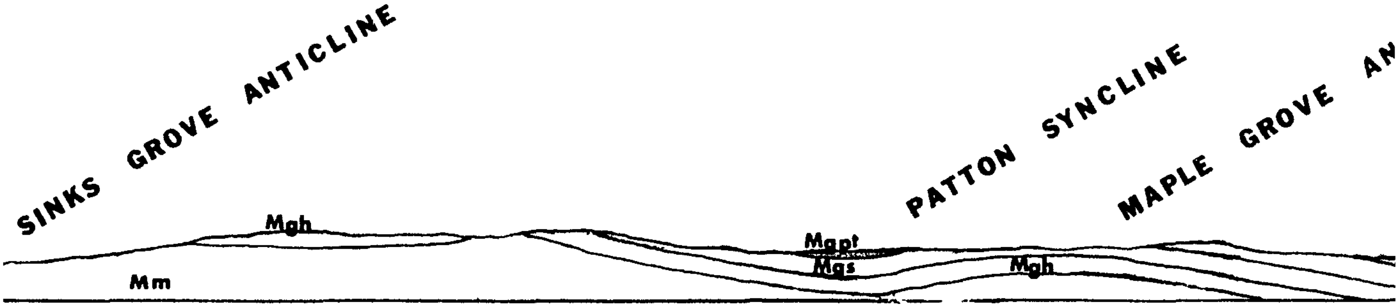

Mgt
Mgs
C'
66


Mgh
Mm
Mgs
C'
65
28
20
70
Ax
of
Ax
of
sy
T
f
S
d


Axial trace of anticline
Axial trace of overturned syncline
Thrust fault
20
Strike and dip of bedding
Definite contact
Inferred contact
70
Strike and dip of overturned bedding
State Roads
N



Mauch Chunk	Mmc
Alderson Ls. with thin Greenville Shale at base when present	Mga
Union Ls.	Mgu
Pickaway Ls.	Mgp

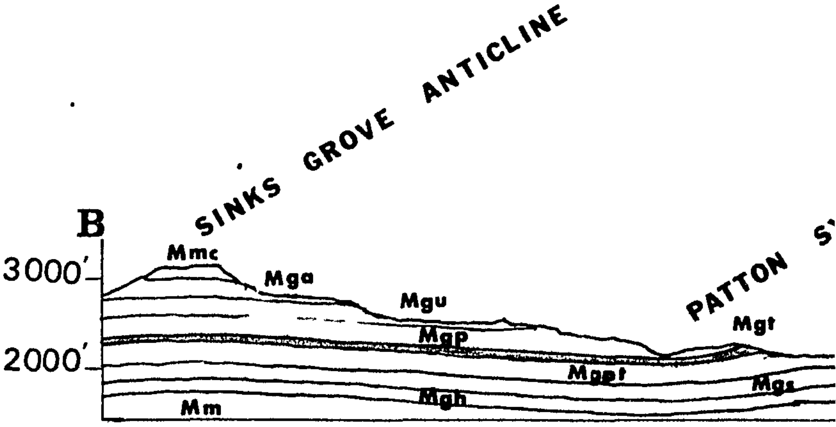


hunk Mmc

nville
nt Mga

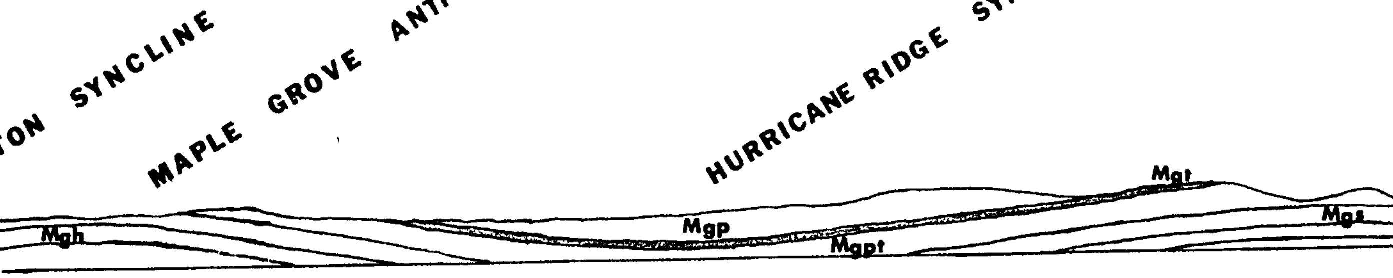
Ls. Mgu

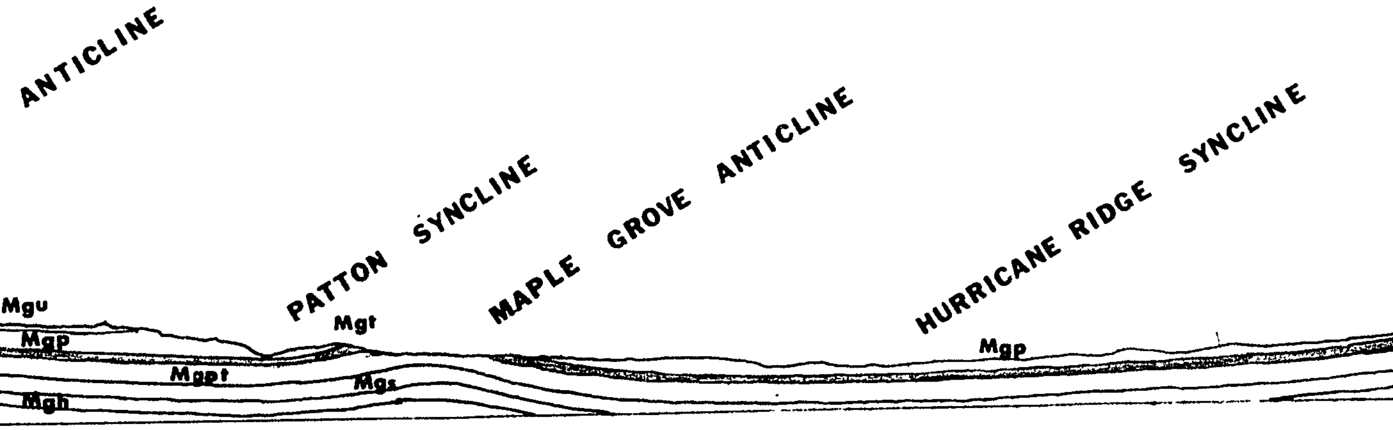
Ls. Mgp



CROSS-SECTIONS

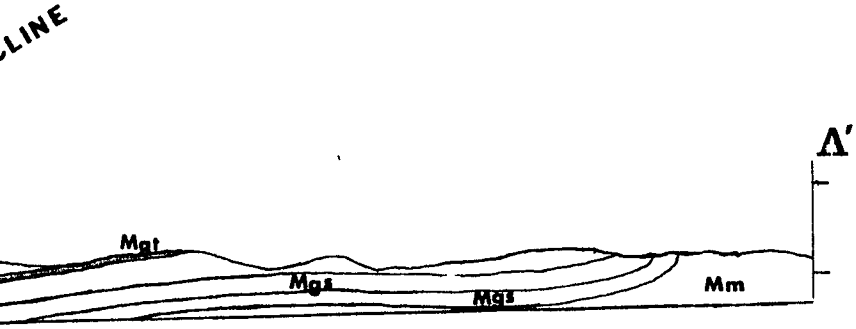
CENTRAL MONROE COUNTY

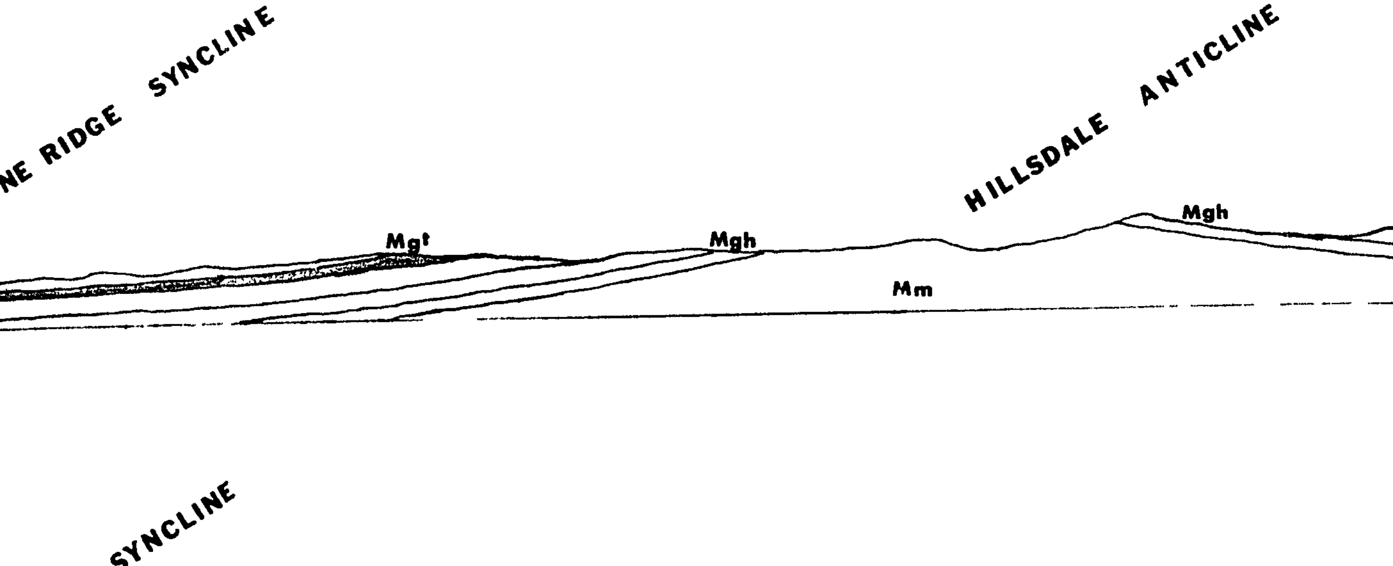




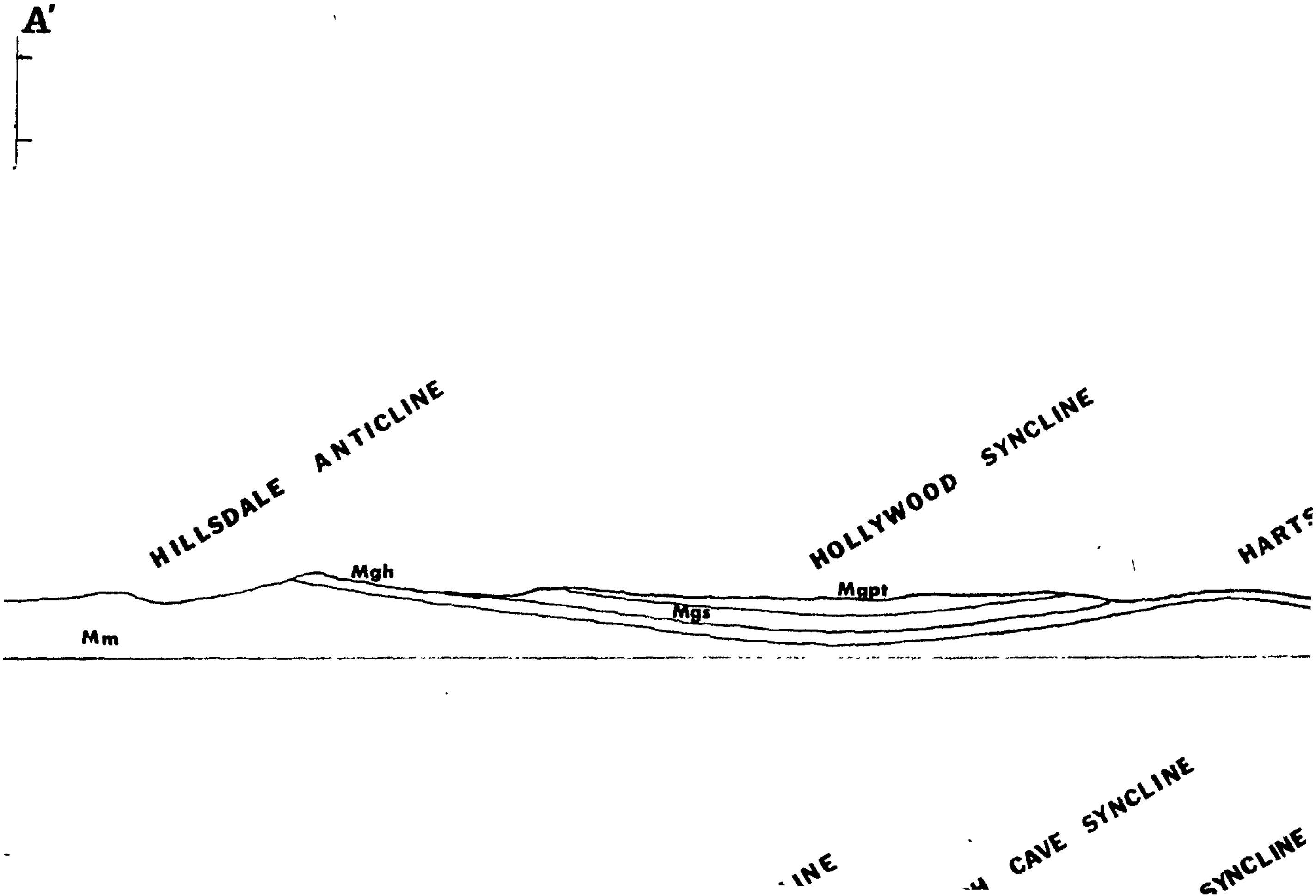
CTIONS
OE COUNTY

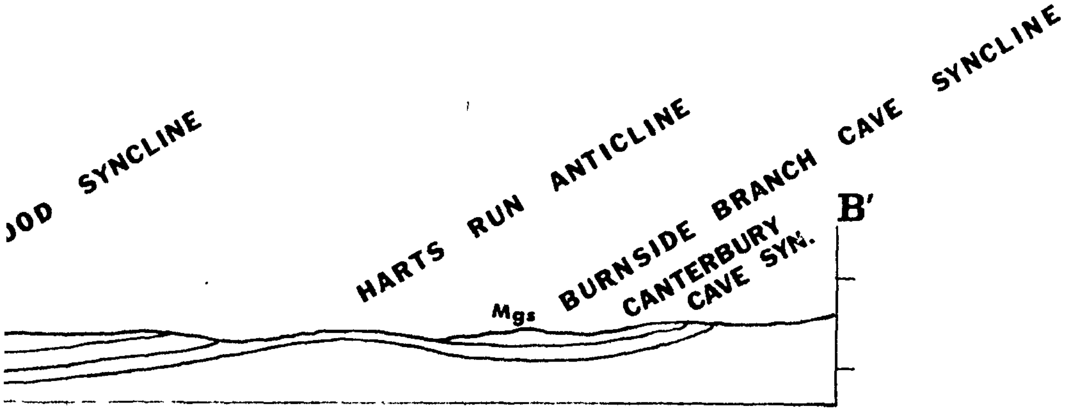
PLATE 2

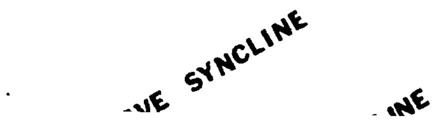


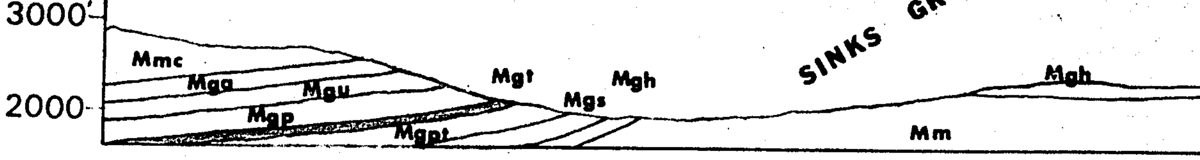


2

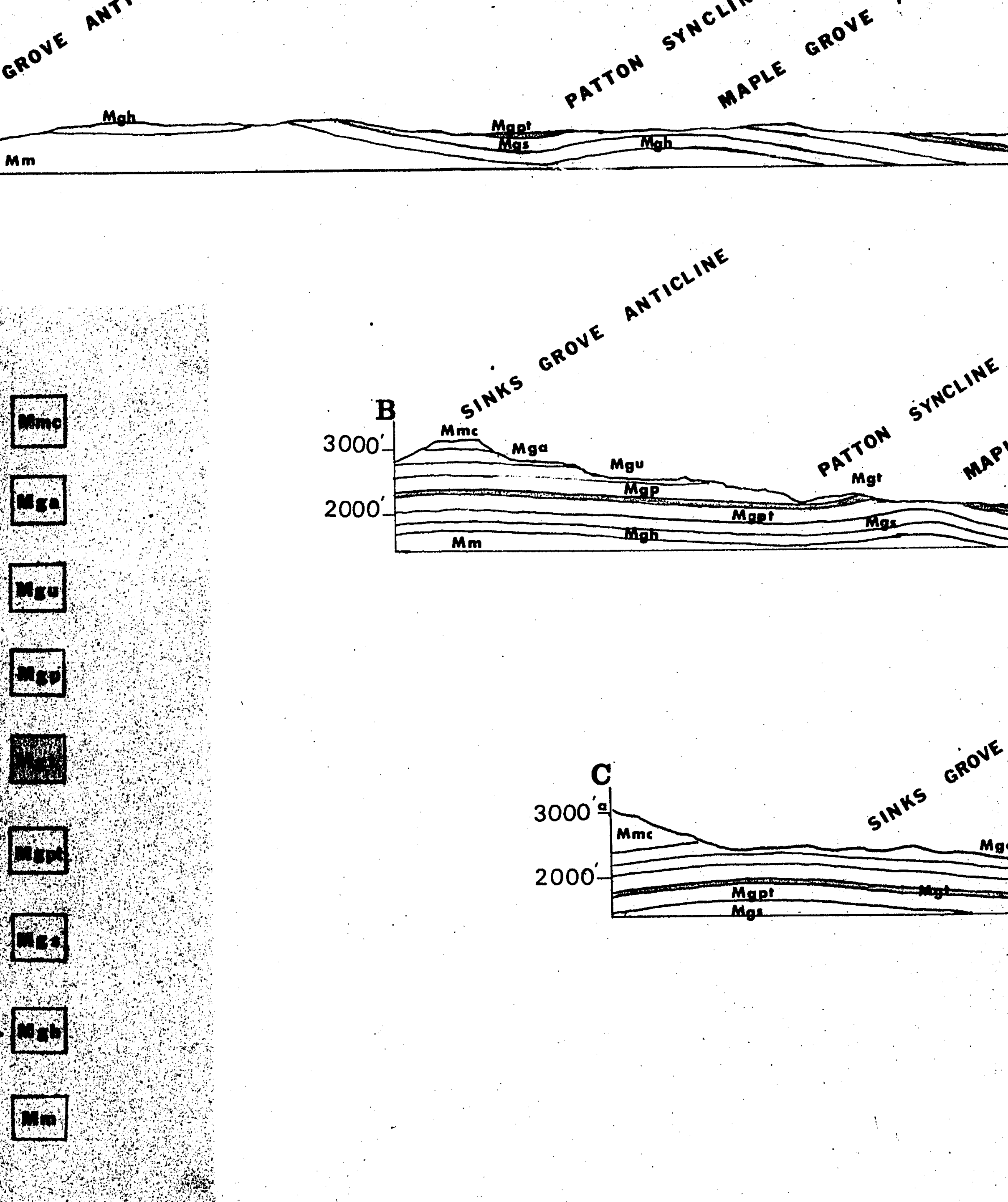

A'
HILLSDALE ANTICLINE
HOLLYWOOD SYNCLINE
HARTS
Mgh
Mgpt
Mgs
Mm
INE
H CAVE SYNCLINE
SYNCLINE

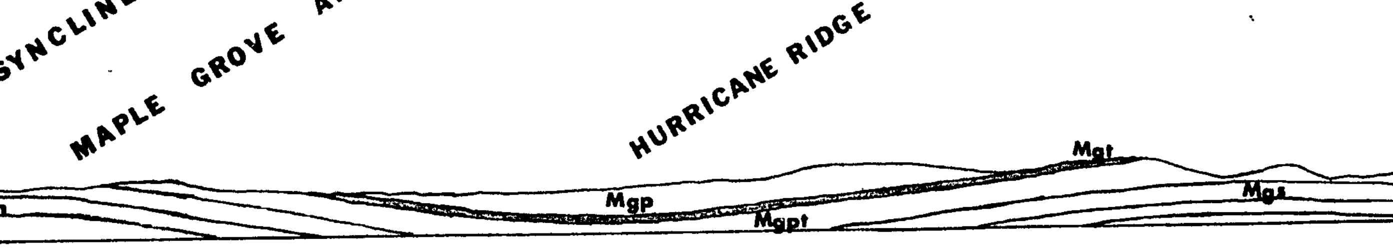

OOD SYNCLINE
HARTS RUN ANTICLINE
BURNSIDE BRANCH CAVE SYNCLINE
CANTERBURY CAVE SYN.
Mgs
B'

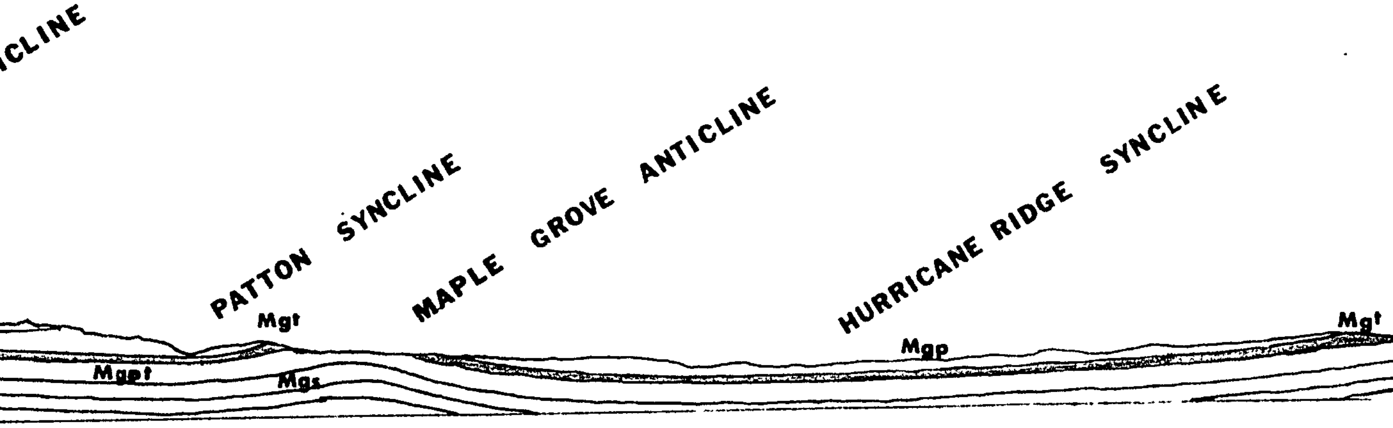

VE SYNCLINE
INE

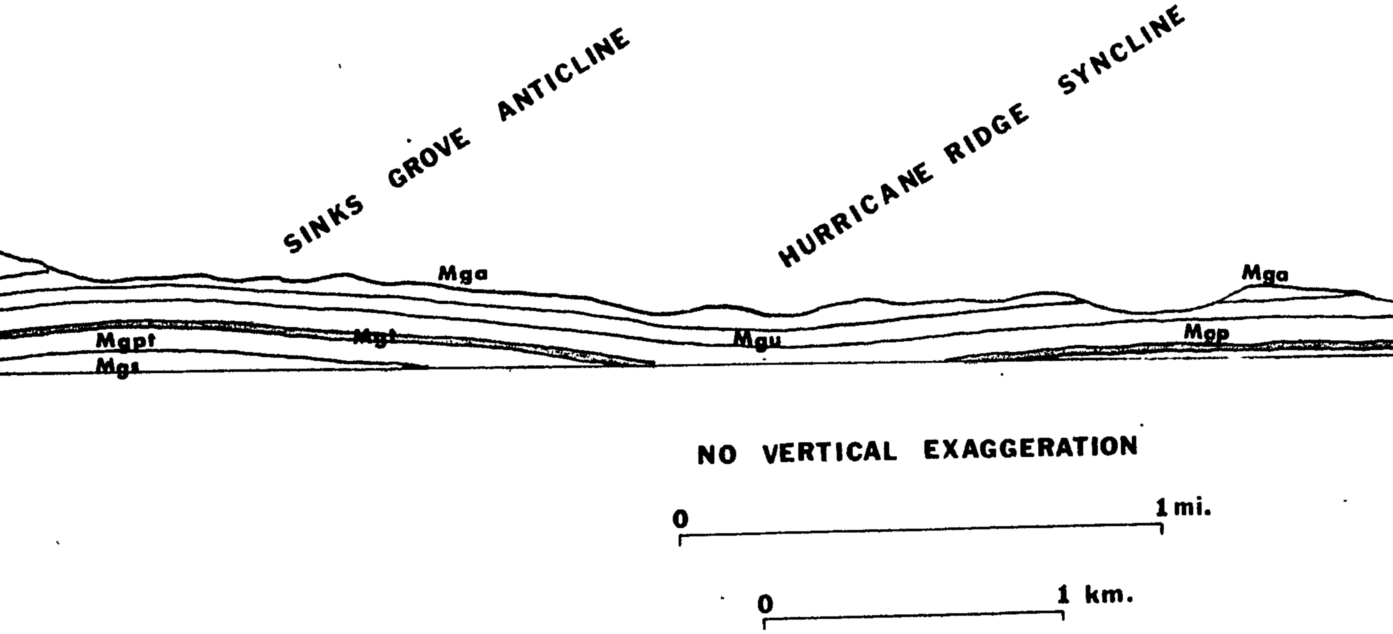


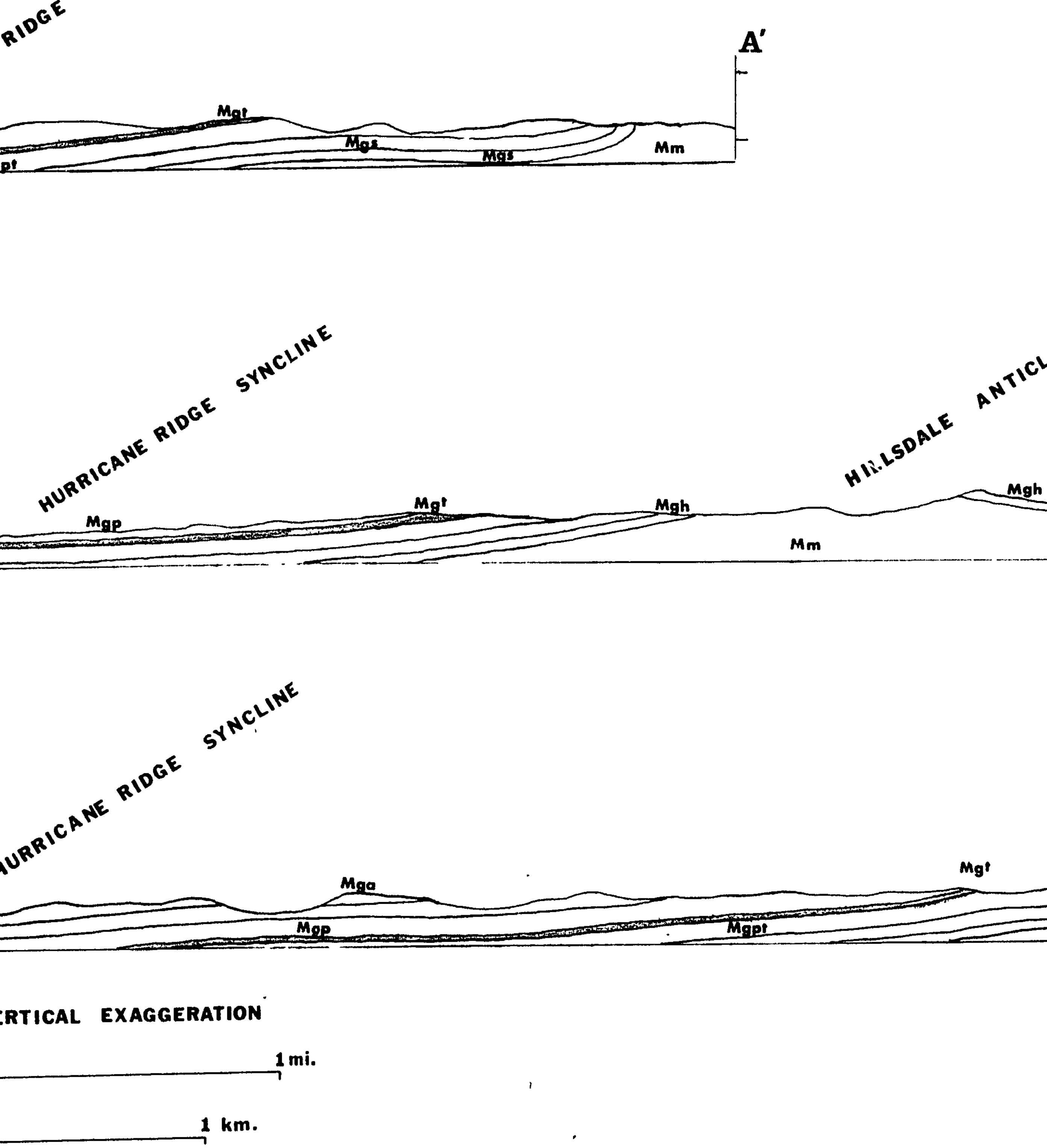
Mauch Chunk	Mmc
Alderson Ls. with thin Greenville Shale at base when present	Mga
Union Ls.	Mgu
Pickaway Ls.	Mgp
Taggard Ls. and Sh.	Mgt
Patton Ls.	Mgpt
Sinks Grove Ls. with overlying Patton Sh. when present	Mgs
Hillsdale Ls.	Mgh
Maccrady and older formations	Mm

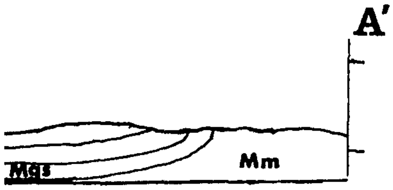

GROVE ANT
PATTON SYNCLI
MAPLE GROVE
Mgh
Mm
Mgpt
Mgs
Mgh
B
SINKS GROVE ANTICLINE
PATTON SYNCLINE
MAP
3000′
2000′
Mmc
Mga
Mgu
Mgp
Mgt
Mgpt
Mgs
Mgh
Mm
C
SINKS GROVE
3000′
a
2000′
Mmc
Mg
Mgpt
Mgt
Mgs
Mmc
Mga
Mgu
Mgp
Mgt
Mgpt
Mgs
Mgh
Mm

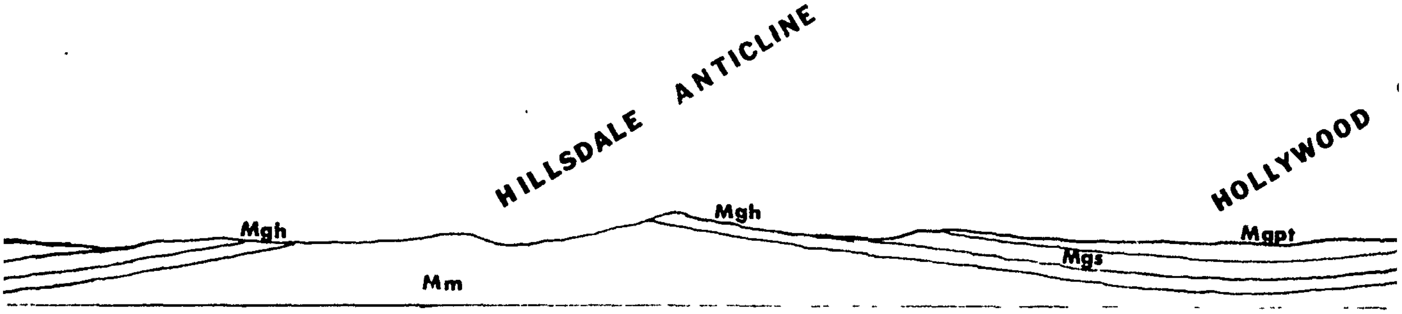

SYNCLIN
MAPLE GROVE A
HURRICANE RIDGE
Mgt
Mgp
Mgpt
Mgs

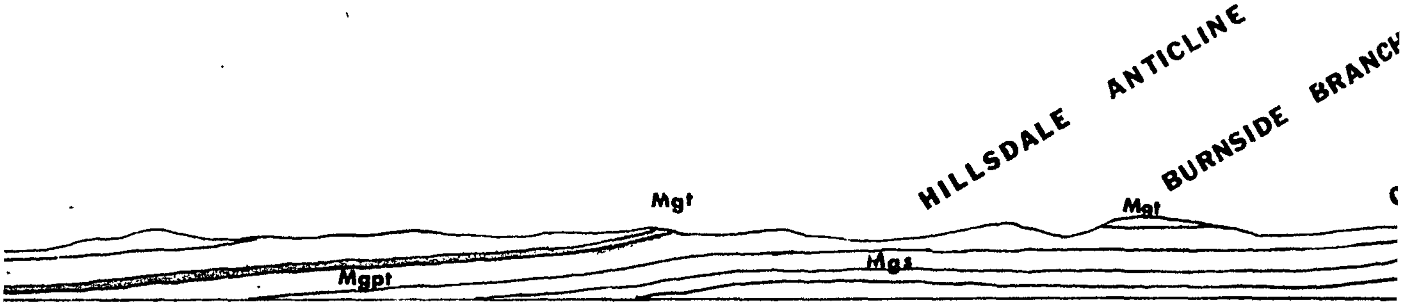

CLINE
PATTON SYNCLINE
MAPLE GROVE ANTICLINE
HURRICANE RIDGE SYNCLINE
Mgt
Mgpt
Mgs
Mgp
Mgt

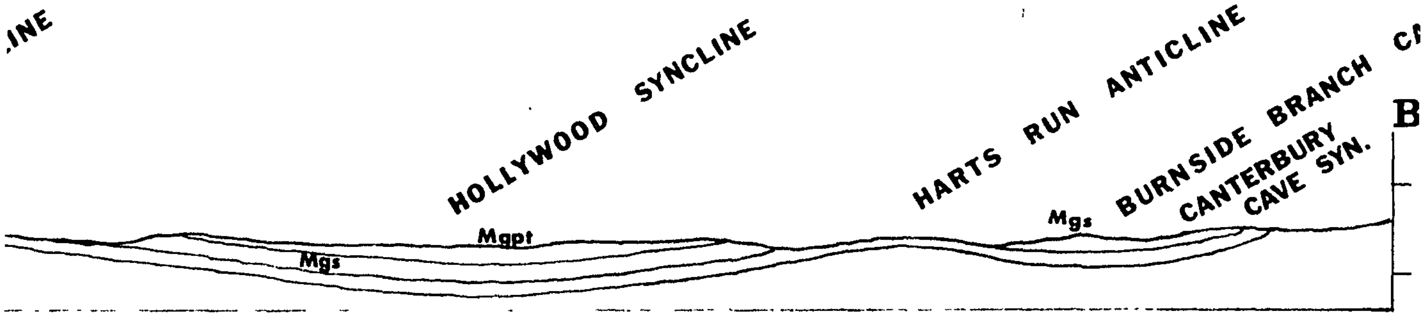

SINKS GROVE ANTICLINE
HURRICANE RIDGE SYNCLINE
Mga
Mgpt
Mgs
Mgt
Mgu
Mga
Mgp
NO VERTICAL EXAGGERATION
0
1 mi.
0
1 km.

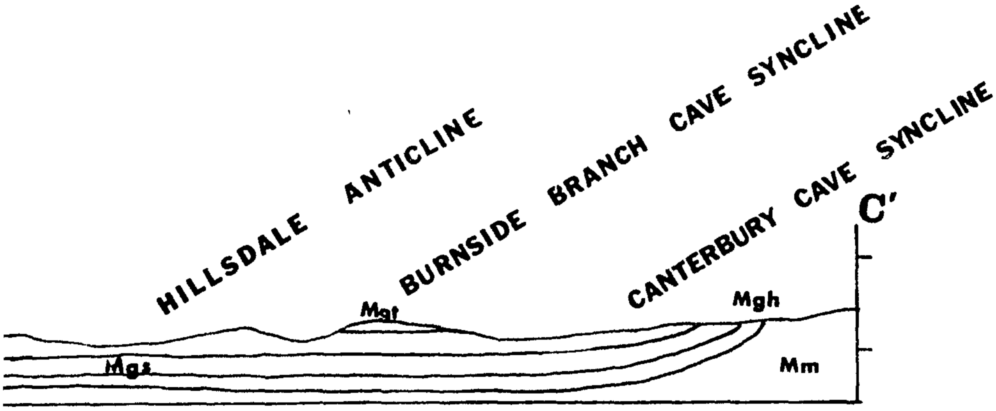

RIDGE
A'
Mgt
Mgs
Mgs
Mm
pt
HURRICANE RIDGE SYNCLINE
HILLSDALE ANTICL
Mgp
Mgt
Mgh
Mgh
Mm
HURRICANE RIDGE SYNCLINE
Mga
Mgt
Mgp
Mgpt
RTICAL EXAGGERATION
1 mi.
1 km.

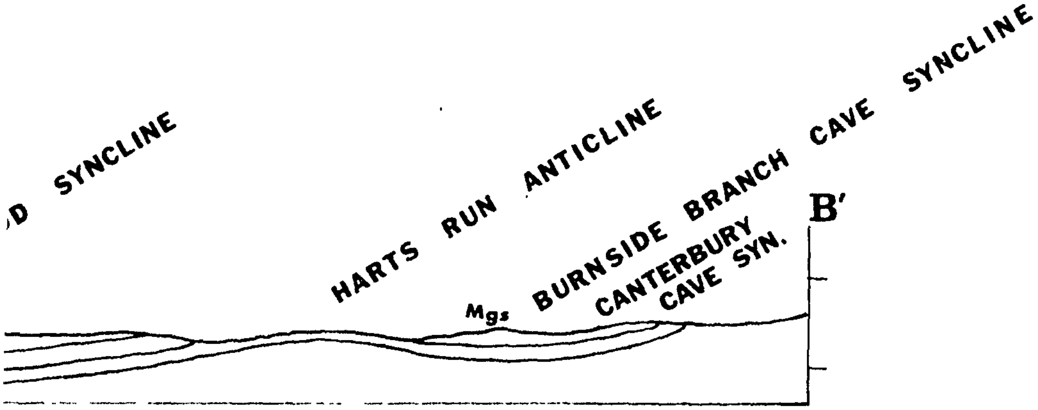

A'
Mgs
Mm

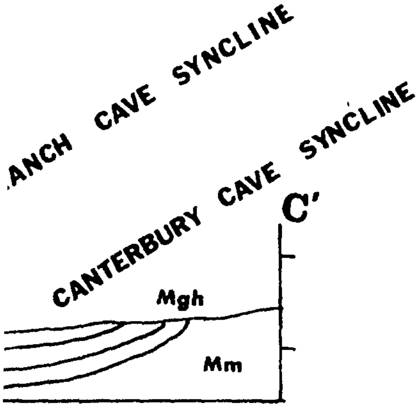

HILLSDALE ANTICLINE
HOLLYWOOD
Mgh
Mgh
Mgpt
Mgs
Mm

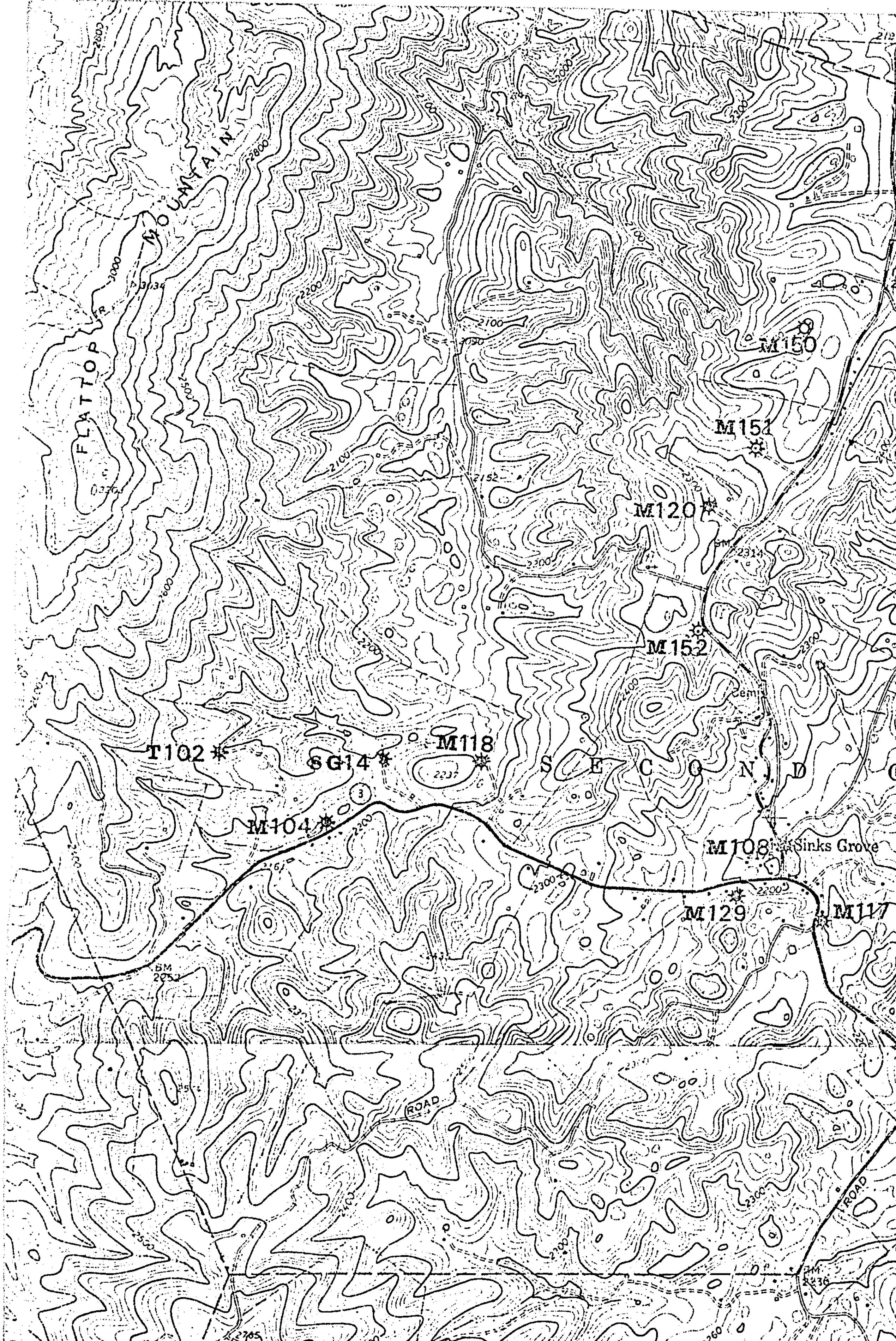

HILLSDALE ANTICLINE
BURNSIDE BRANC
Mgt
Mgt
Mgs
Mgpt

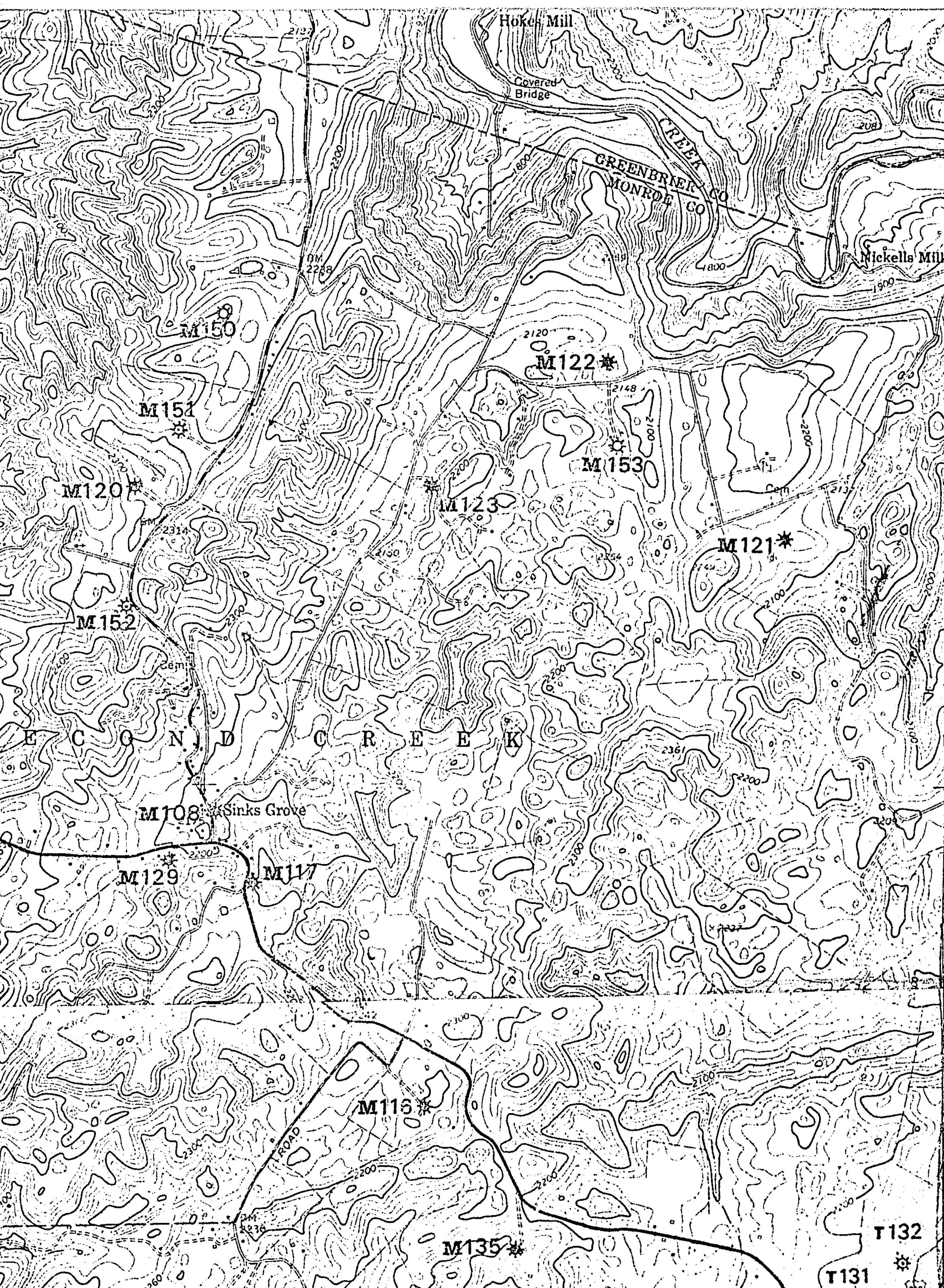

INE
HOLLYWOOD SYNCLINE
HARTS RUN ANTICLINE
BURNSIDE BRANCH C
CANTERBURY CAVE SYN.
B
Mgpt
Mgs
Mgs

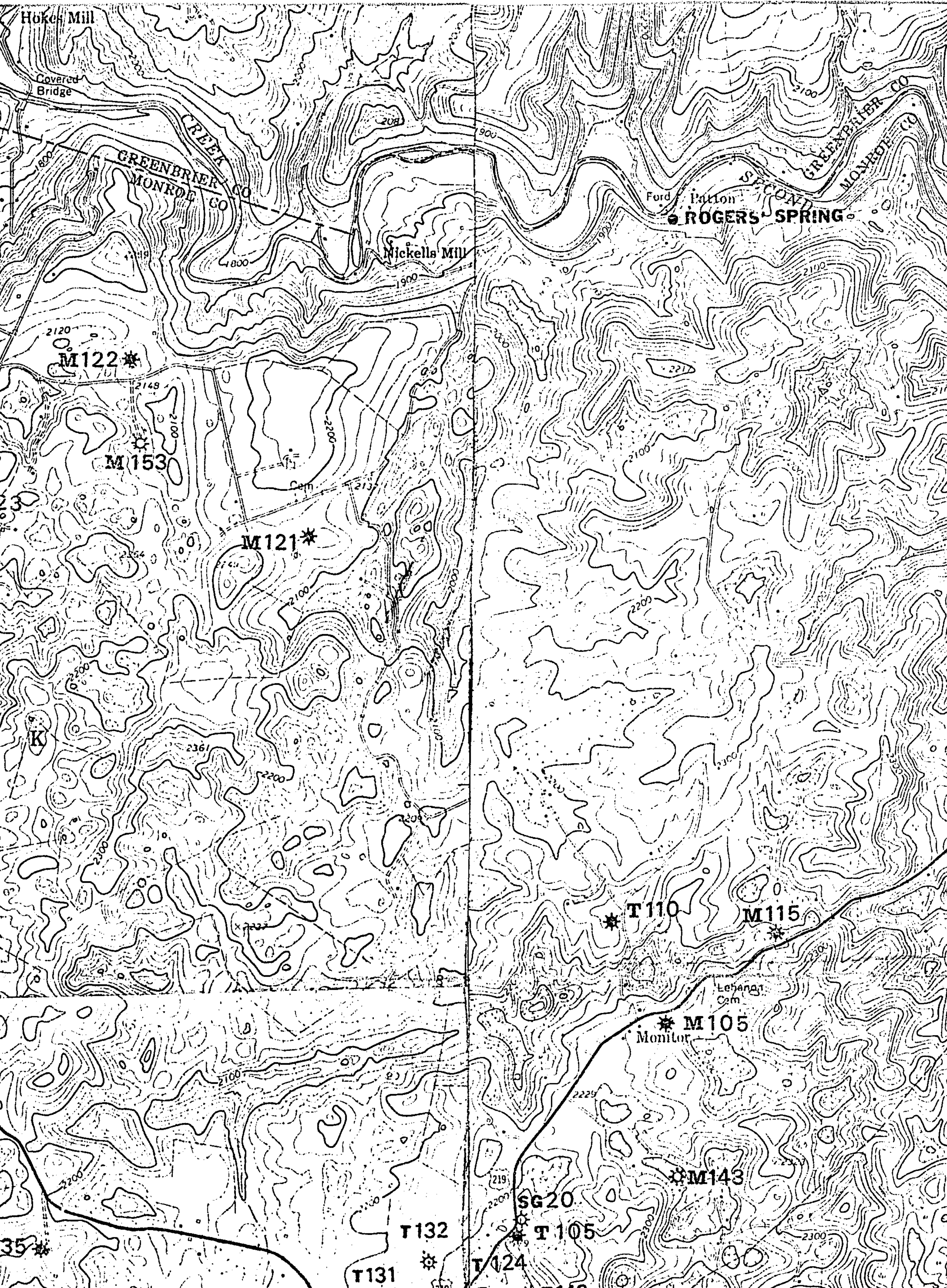

HILLSDALE ANTICLINE
BURNSIDE BRANCH CAVE SYNCLINE
CANTERBURY CAVE SYNCLINE
C′
Mgt
Mgh
Mgs
Mm


D SYNCLINE
HARTS RUN ANTICLINE
BURNSIDE BRANCH CAVE SYNCLINE
CANTERBURY CAVE SYN.
Mgs
B'

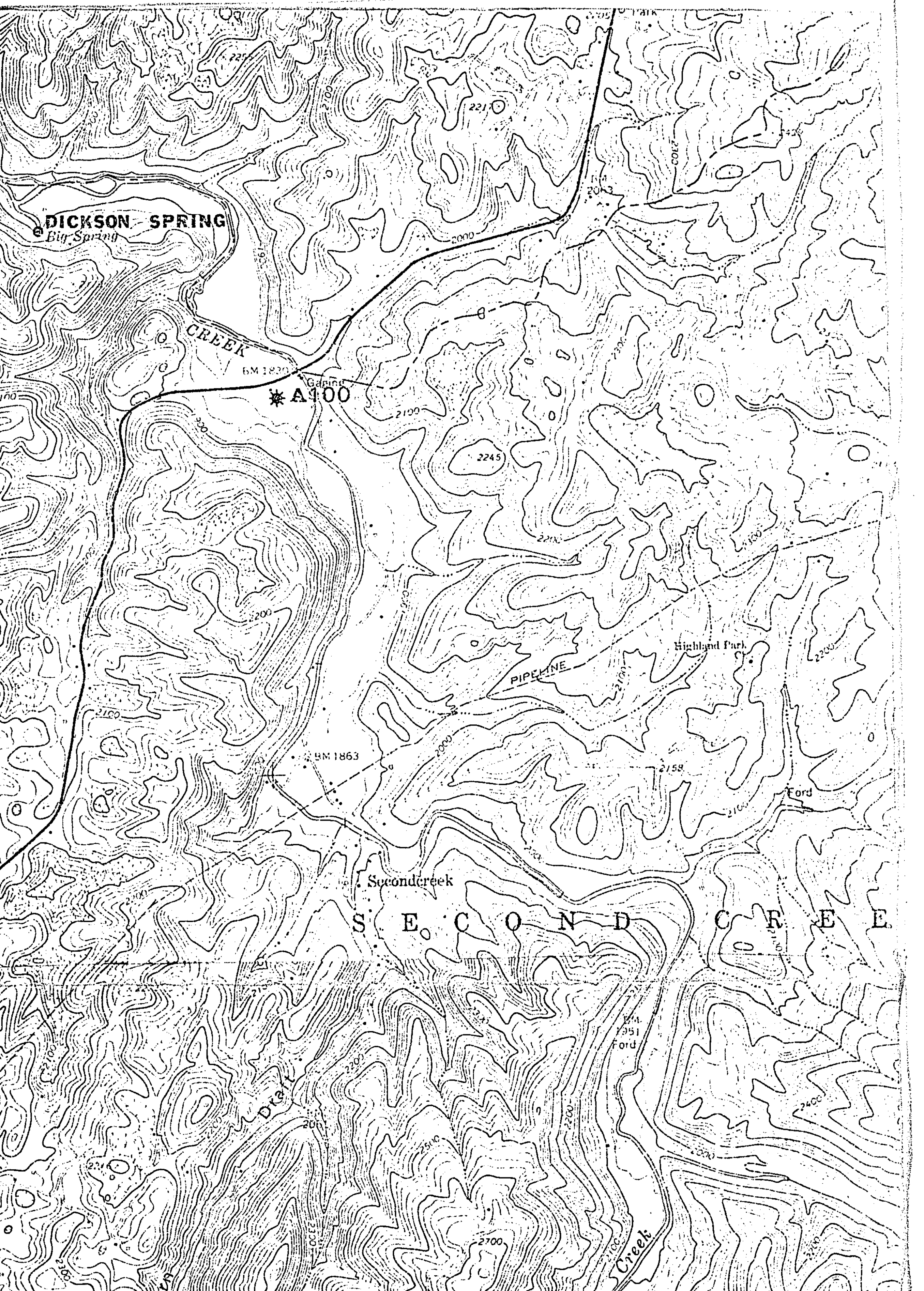

ANCH CAVE SYNCLINE
CANTERBURY CAVE SYNCLINE
C'
Mgh
Mm

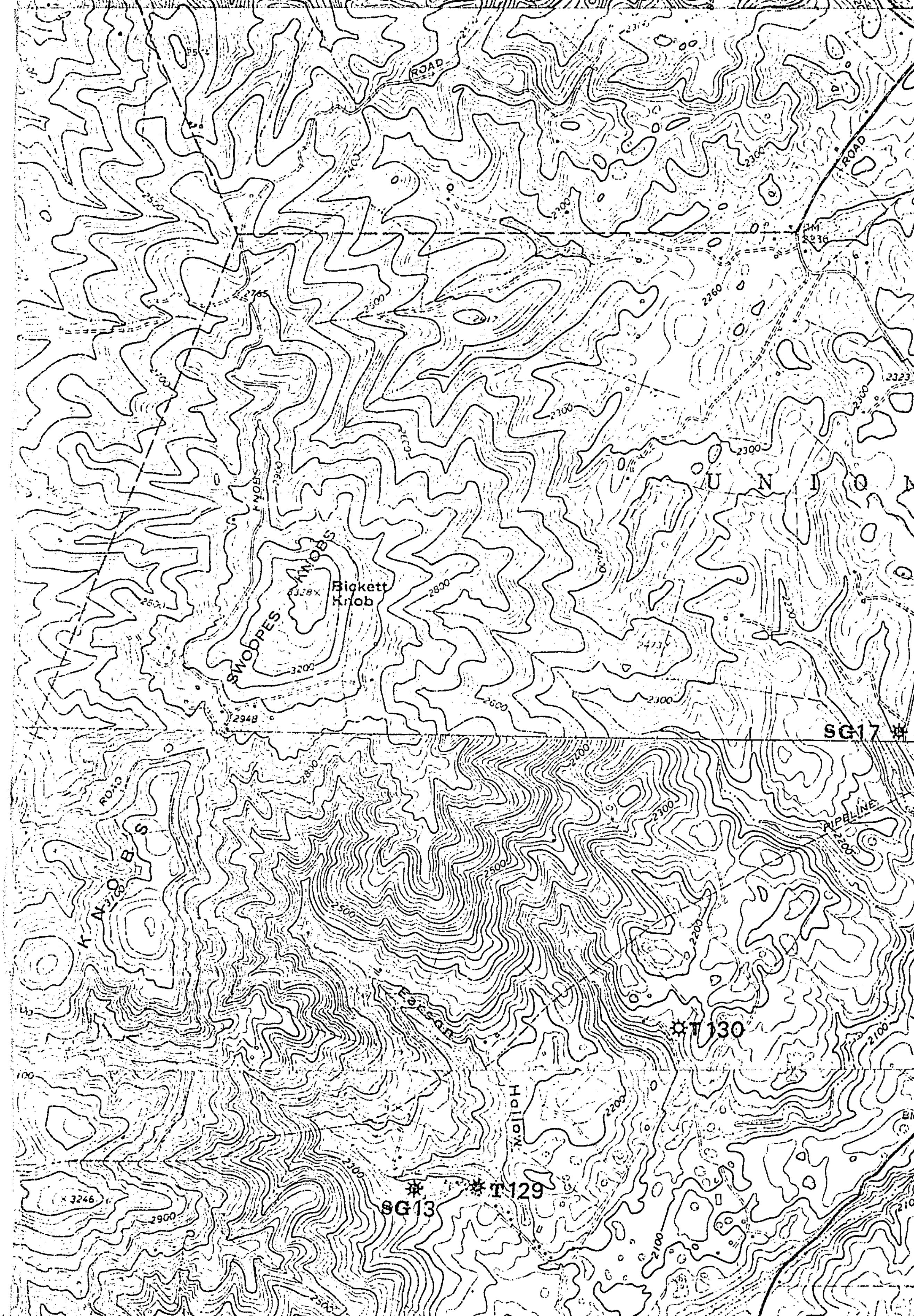

FLATTOP MOUNTAIN
M150
M151
M120
BM 2314
M152
Cem
T102
SG14
M118
2237
SECOND
M104
M108
Sinks Grove
M129
M117
BM 2253
ROAD
ROAD
BM 2236
2100
2200
2300
2400
2500
2800
3000
3134
2152

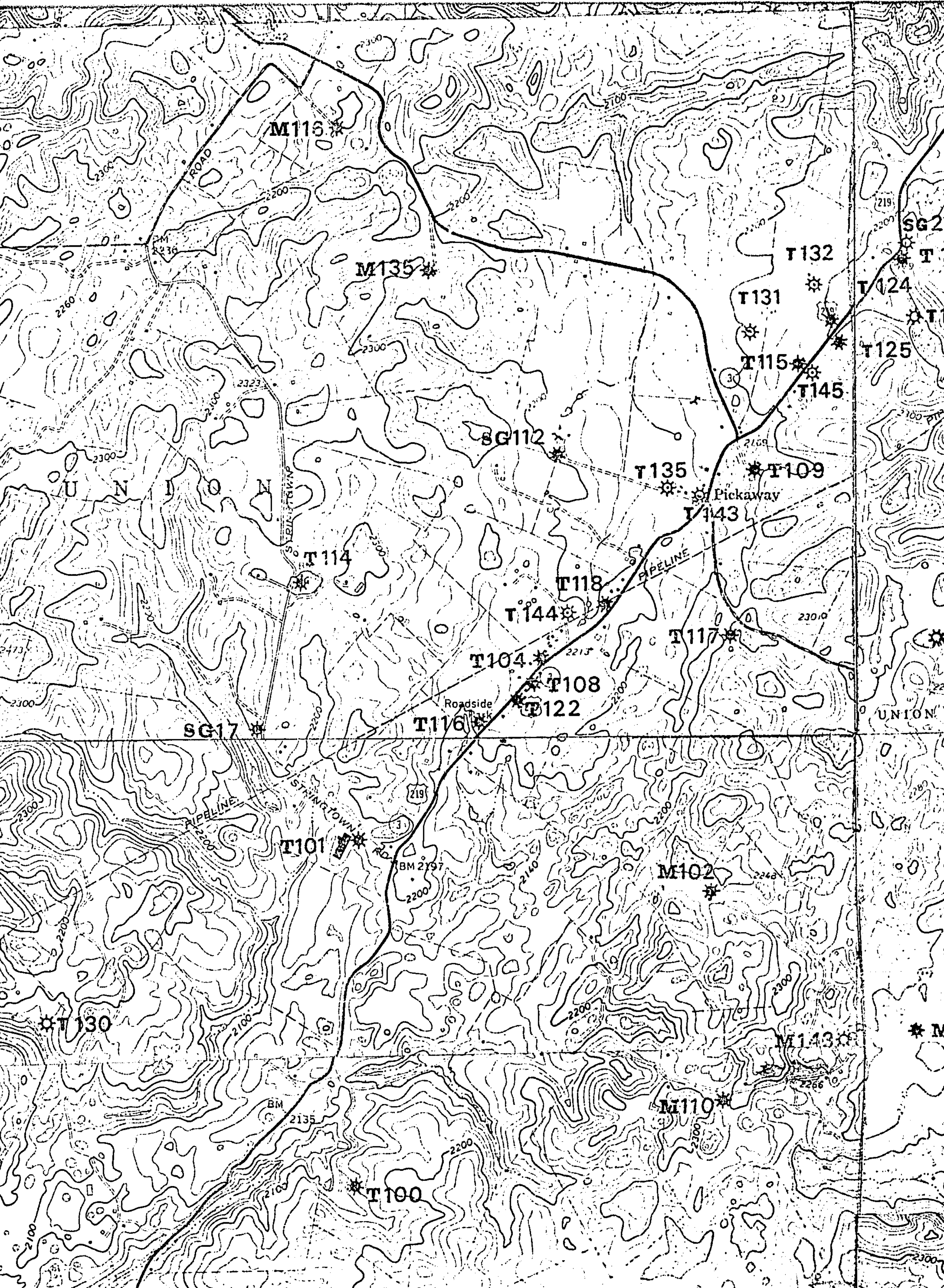

Hokes Mill
Covered Bridge
CREEK
GREENBRIER CO
MONROE CO
Nickells Mill
1800
1900
2300
2127
BM 2238
M150
M151
M120
BM 2314
M152
Cem
M122
2120
2148
2100
2200
M153
M123
Cem
M121
2254
2361
ECOND CREEK
M108
Sinks Grove
M129
M117
2227
M116
ROAD
2200
2100
BM 2236
M135
T132
T131

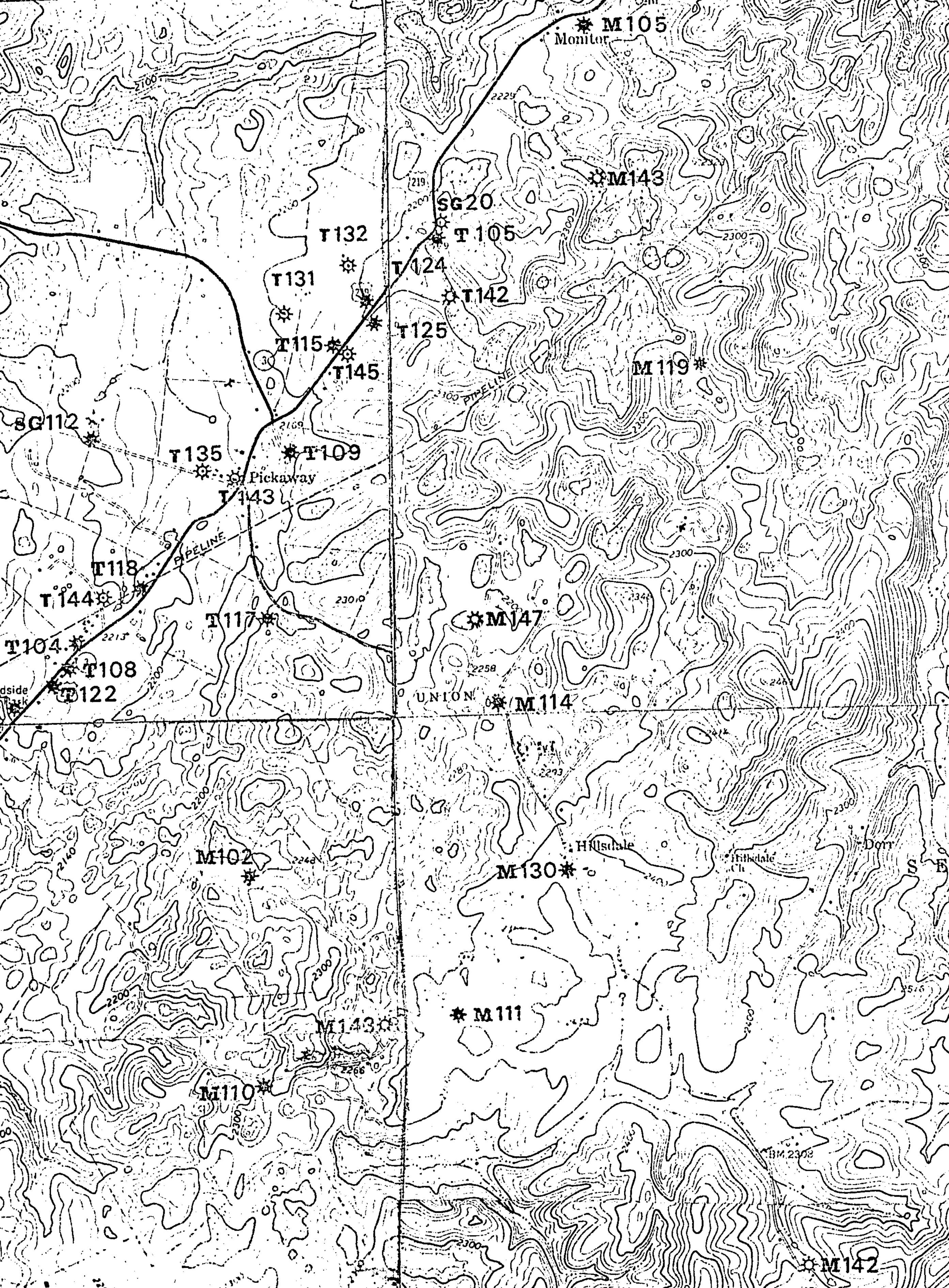

Hokes Mill
Covered Bridge
CREEK
GREENBRIER CO
MONROE CO
Nickells Mill
Ford
Patton
SECOND
GREENBRIER CO
MONROE CO
ROGERS SPRING
M122
M153
23
Cem
M121
K
T110
M115
Lebanon Cem
M105
Monitor
M143
SG20
T105
T132
T131
T124
35
1800
1900
2100
2120
2148
2200
2300
2361
2229

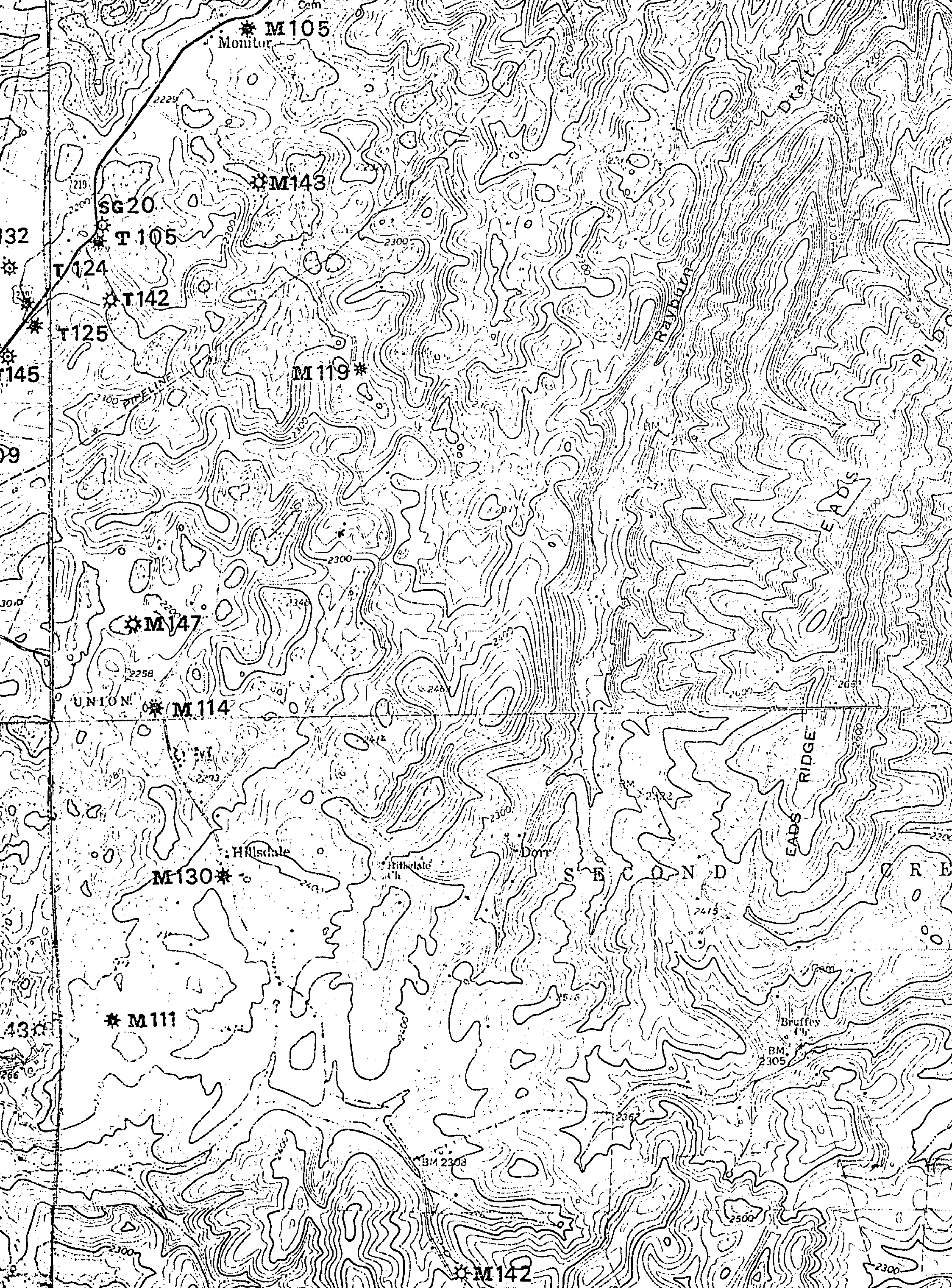

GREENBRIER CO
MONROE CO
SECOND
CREEK
Ford
Patton
ROGERS' SPRING
DICKSON SPRING
Big Spring
Mill
BM 1830
Gaping
A100
BM 1863
Secondcreek
S E
T110
M115
Lebanon Cem
M105
Monitor
M143
SG20
T105
T124
32
219
2100
2200
2300
2229
2211
2000
1900

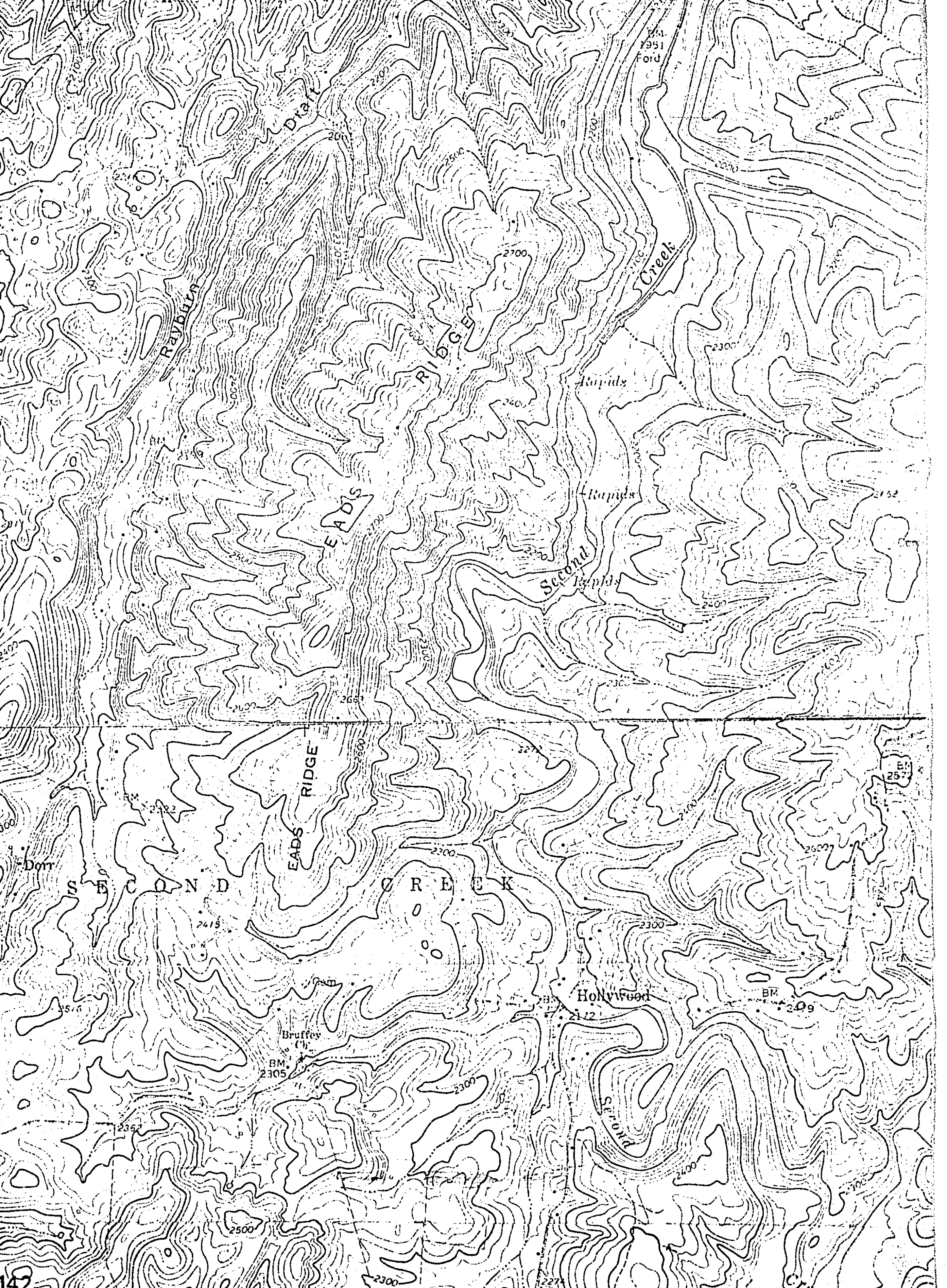

DICKSON SPRING
Big Spring
CREEK
BM 1830
Gaging
A100
2063
2000
2100
2200
2210
2245
2300
PIPELINE
Highland Park
BM 1863
2158
Ford
Secondcreek
SECOND CREE
BM 1951
Ford
2400
2700
Creek

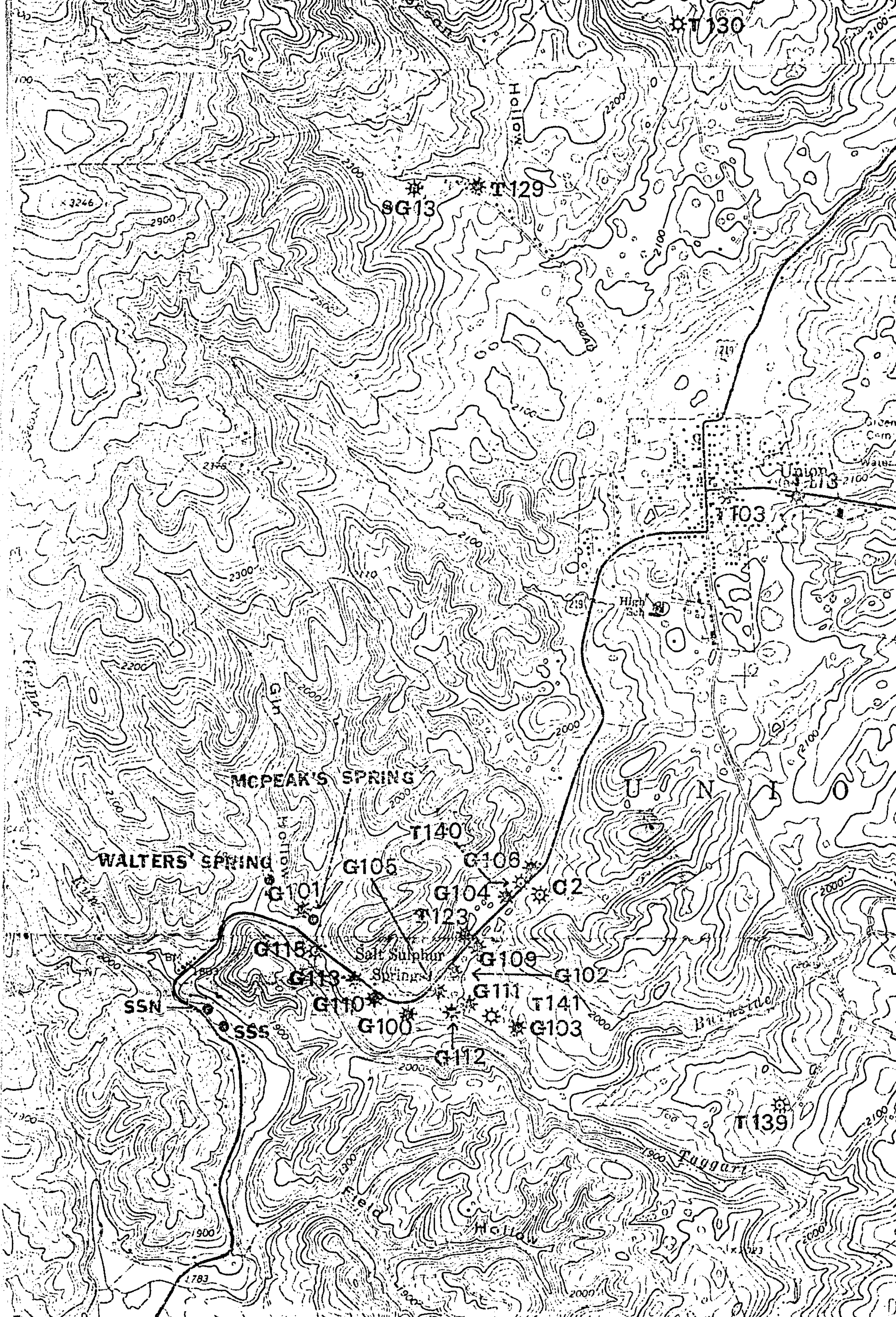

ROAD
ROAD
2400
2500
2300
2200
BM 2436
2765
2500
2417
2260
2700
2300
2323
2300
U N I O N
KNOBS
2900
SWOOPES KNOBS
Bickett Knob
3328 X
2800
3200
2473
2600
2300
2948
SG17
2810
ROAD
K N O B S
2200
2300
PIPELINE
2200
2500
2500
Falcon
Hollow
T130
2200
2100
2300
SG13
T129
× 3246
2900
2100
2500

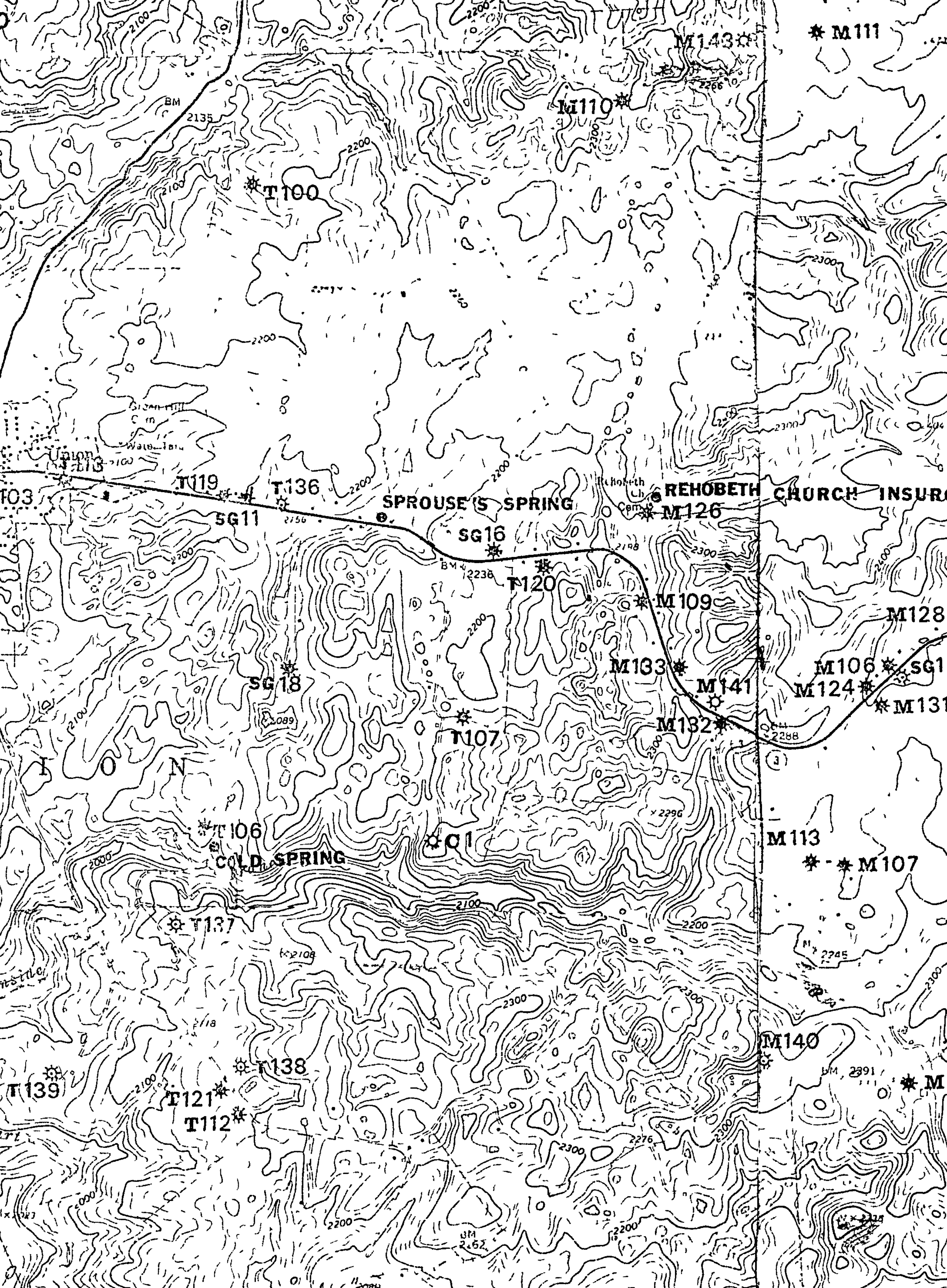

M116
ROAD
BM 2336
2300
2200
2260
M135
2323
U N I O N
SPIRIT TWP
T114
SG112
T135
Pickaway
T143
T109
T132
T131
T124
T125
T115
T145
219
30
PIPELINE
T118
T144
T104
2213
T108
T122
Roadside Park
T116
T117
SG17
UNION
STRINGTOWN RD.
219
3
PIPELINE
T101
BM 2197
2140
M102
2248
2280
T130
2100
M143
2266
M110
BM 2135
T100
2473

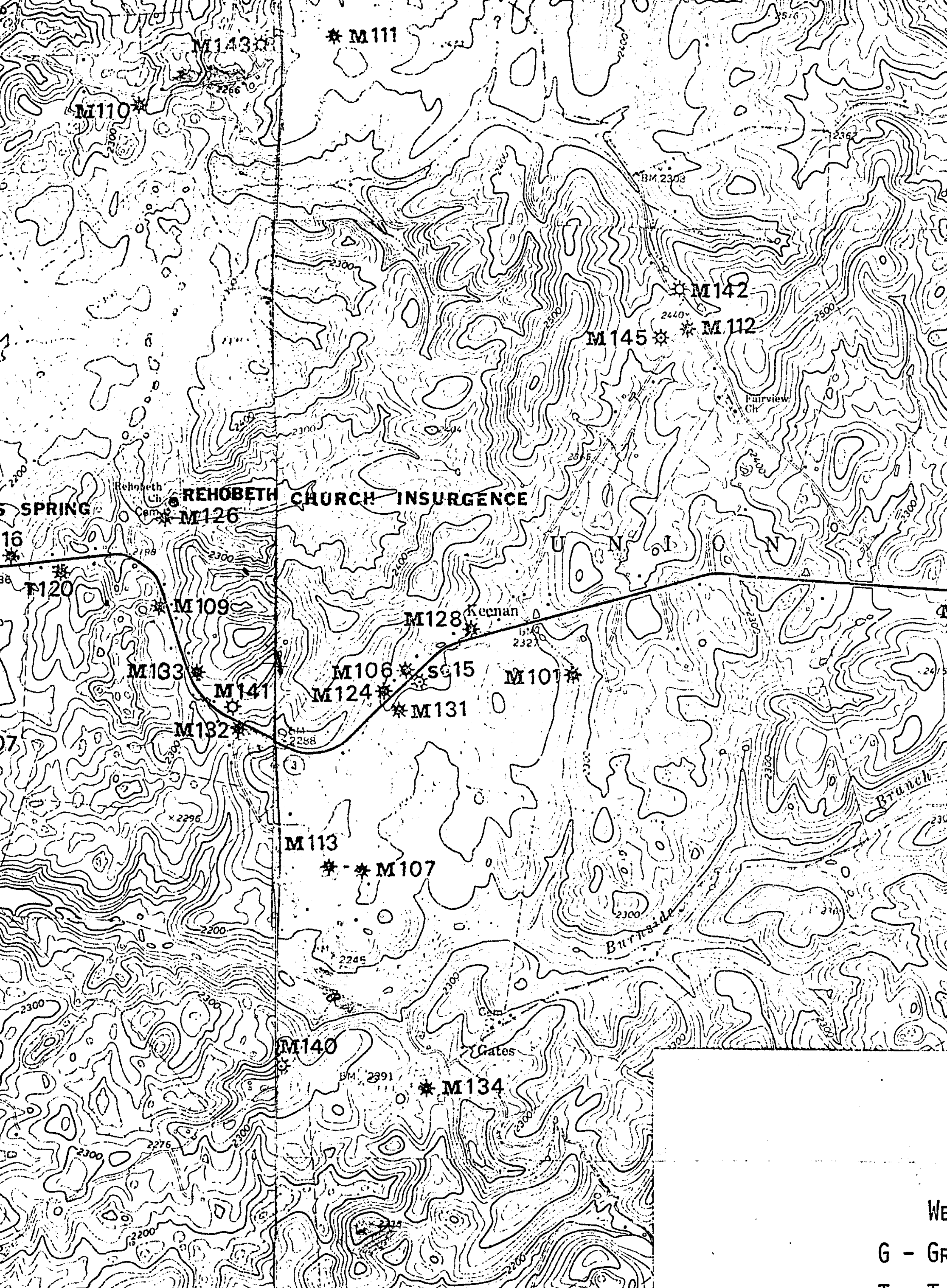

M105
Monitor
2229
M143
219
SG20
T105
T132
T124
T131
T142
T125
T115
T145
M119
PIPELINE
2300
2100
2200
SG112
T135
T109
Pickaway
T143
PIPELINE
T118
T144
2213
T117
2301
M147
T104
T108
T122
dside
UNION
M114
2258
M102
Hillsdale
Hillsdale Ch
Dorr
M130
S E
M111
M143
2266
M110
BM 2303
M142

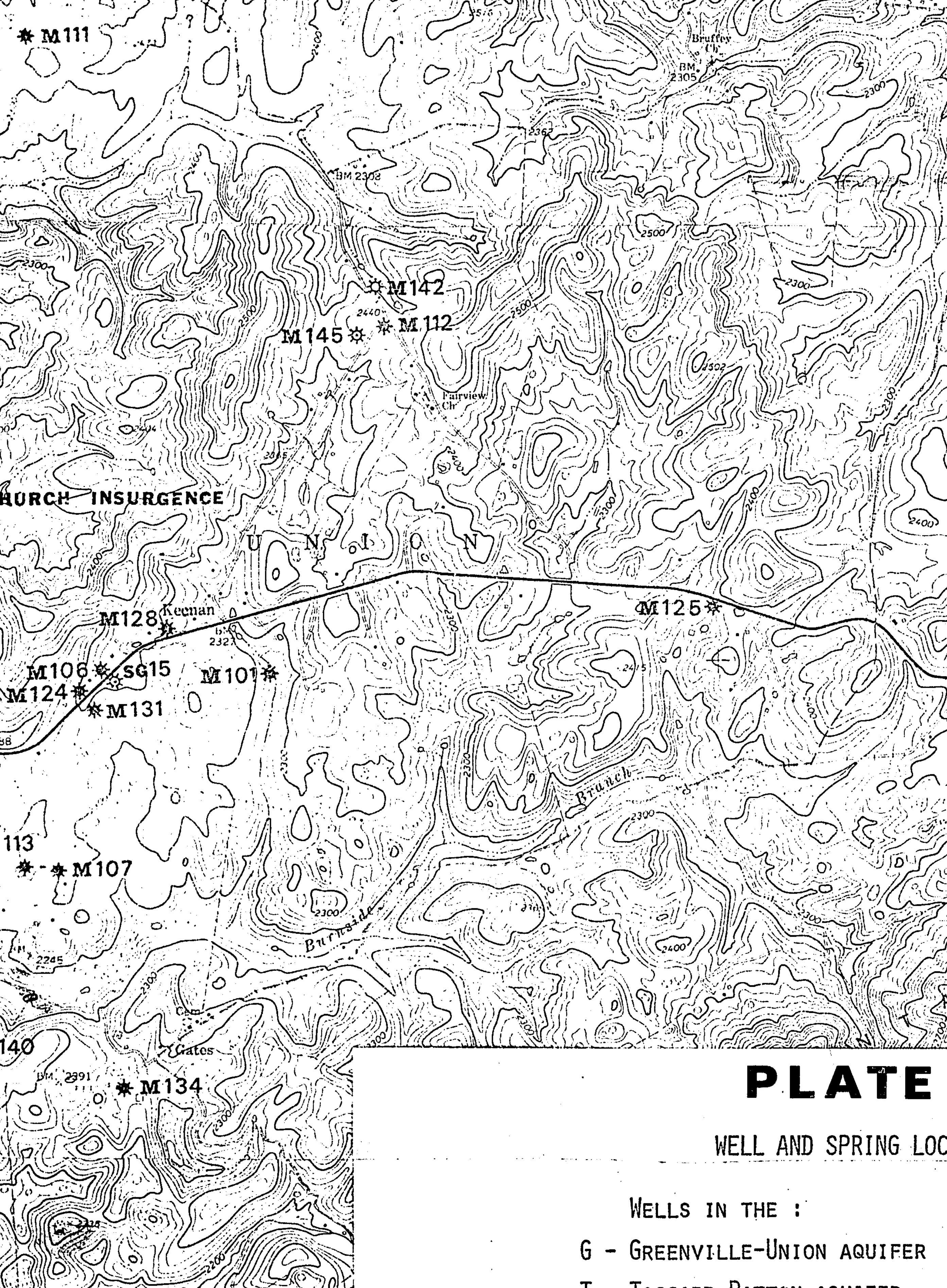

Cam
M105
Monitor
2229
M143
219
2200
SG20
132
T105
T124
T142
T125
T145
M119
PIPELINE
2300
09
Rayburn
EADS
RIDGE
M147
2258
UNION
M114
2280
2293
2461
2300
2400
BM 2322
EADS RIDGE
Hillsdale
Hillsdale Ch
M130
Dorr
S E C O N D   C R E
2415
Cam
Bruffey Ch
BM 2305
M111
43
2266
2362
BM 2308
2500
2300
M142


BM
1951
Ford
Draft
Rayburn
EADS RIDGE
Creek
Rapids
Rapids
Second
Rapids
Cem
EADS RIDGE
BM
2577
BM 2322
Dorr
SECOND CREEK
2415
Cem
Hollywood
BM
2112
BM
2209
Bruffey
Ch.
BM
2305
Second
2362
2500
2300
2100
2200
2400
2600
2700
2650
2275


T130
Hollow
SG13
T129
×3246
2900
2300
2200
2100
2000
1900
219
Union
T103
High Sch
Gin
Hollow
U N I O
MCPEAK'S SPRING
WALTERS' SPRING
Run
T140
G106
G105
G101
G104
C2
T123
G115
Salt Sulphur Springs
G109
G102
G113
G111
T141
SSN
G110
G100
G103
SSS
G112
Burnside
T139
Taggart
Field
Hollow
1783


M111
M143
M110
BM
2135
2100
2200
2266
2300
T100
Union
T113
T119
T136
SG11
SPROUSE'S SPRING
Rehobeth Ch
Cem
REHOBETH CHURCH INSURC
M126
SG16
BM 2238
T120
M109
M128
M133
M141
M106
SG1
M124
M131
M132
2288
SG18
2089
T107
I
O
N
T106
C1
COLD SPRING
2296
M113
M107
T137
2108
2245
2118
M140
BM 2391
T138
T139
T121
T112
M
2276
2000
2400


M111
M143
M110
2266
2300
2400
BM 2302
2367
M142
2440
M112
M145
2500
Fairview Ch
2404
2300
Rehobeth Ch Cem
REHOBETH CHURCH INSURGENCE
S SPRING
M126
16
2198
2300
T120
M109
U N I O N
M128
Keenan
BM 2327
M106
SC15
M101
M133
M141
M124
M131
M132
2288
07
×2296
M113
M107
2200
2245
Burnside
Branch
2300
M140
Gates
BM 2391
M134
2276
2200
WE
G - GR
T - T



PLATE

WELL AND SPRING LOC

WELLS IN THE :

G - GREENVILLE-UNION AQUIFER

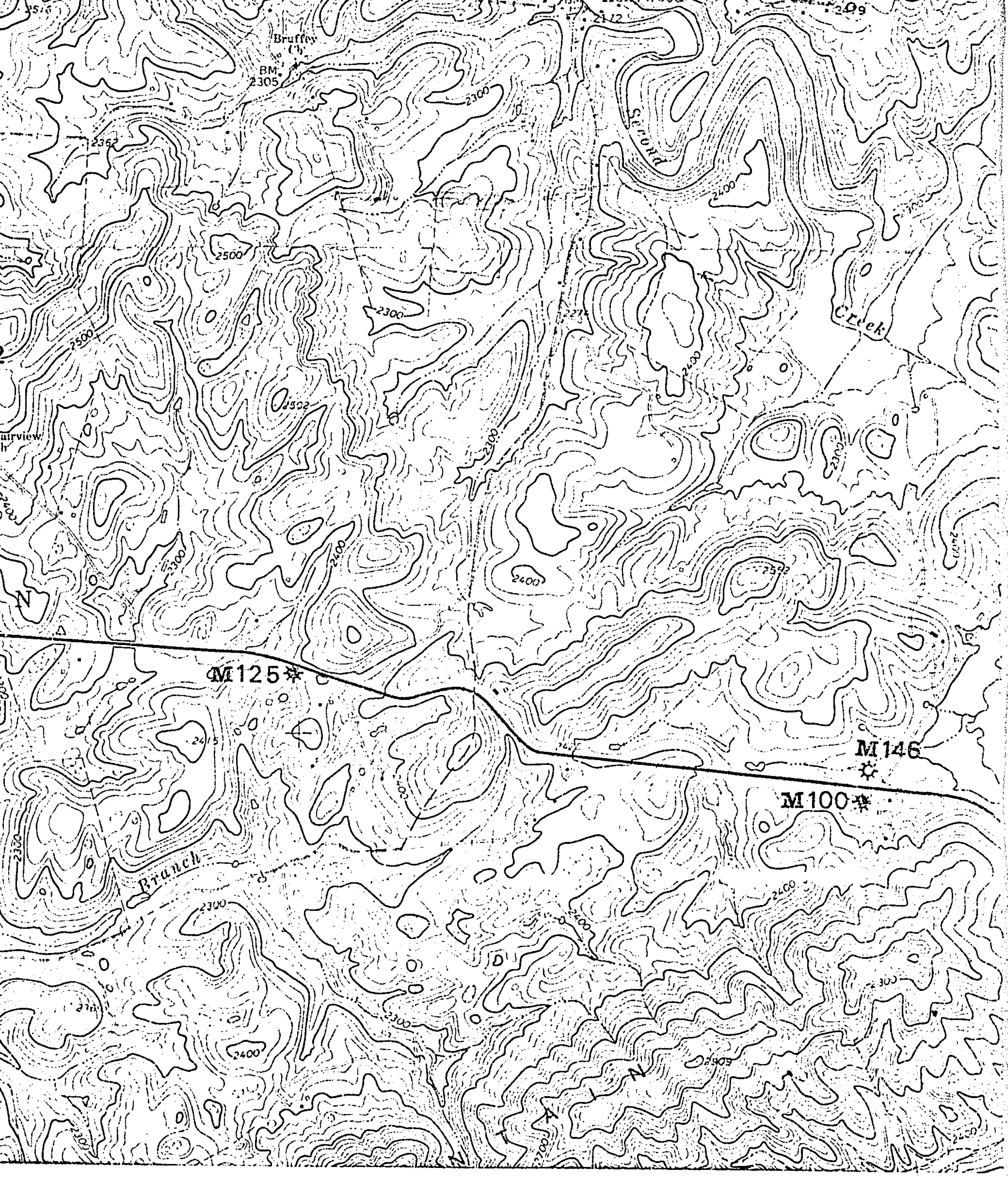


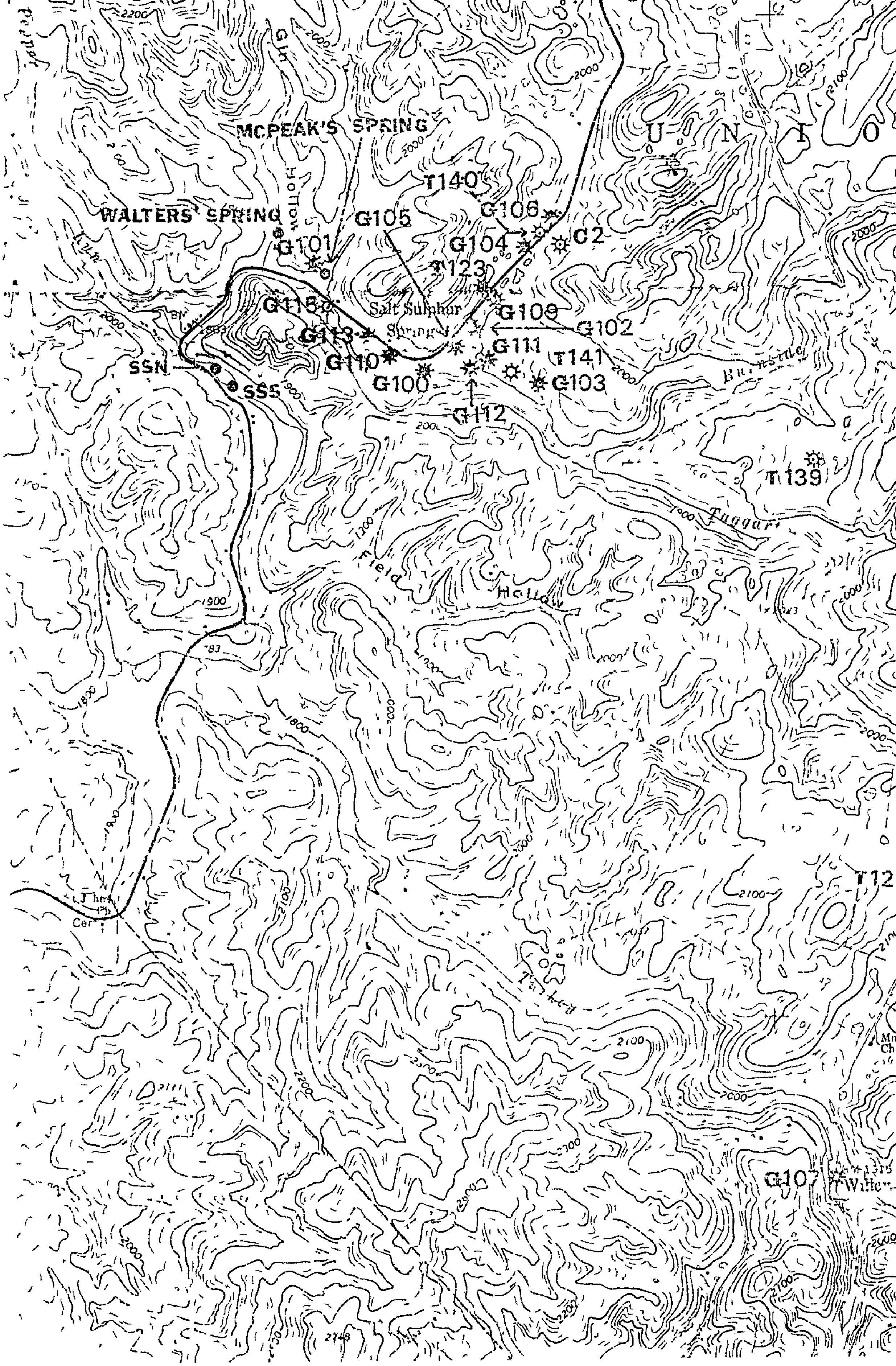
PLATE 3

WELL AND SPRING LOCATION MAP

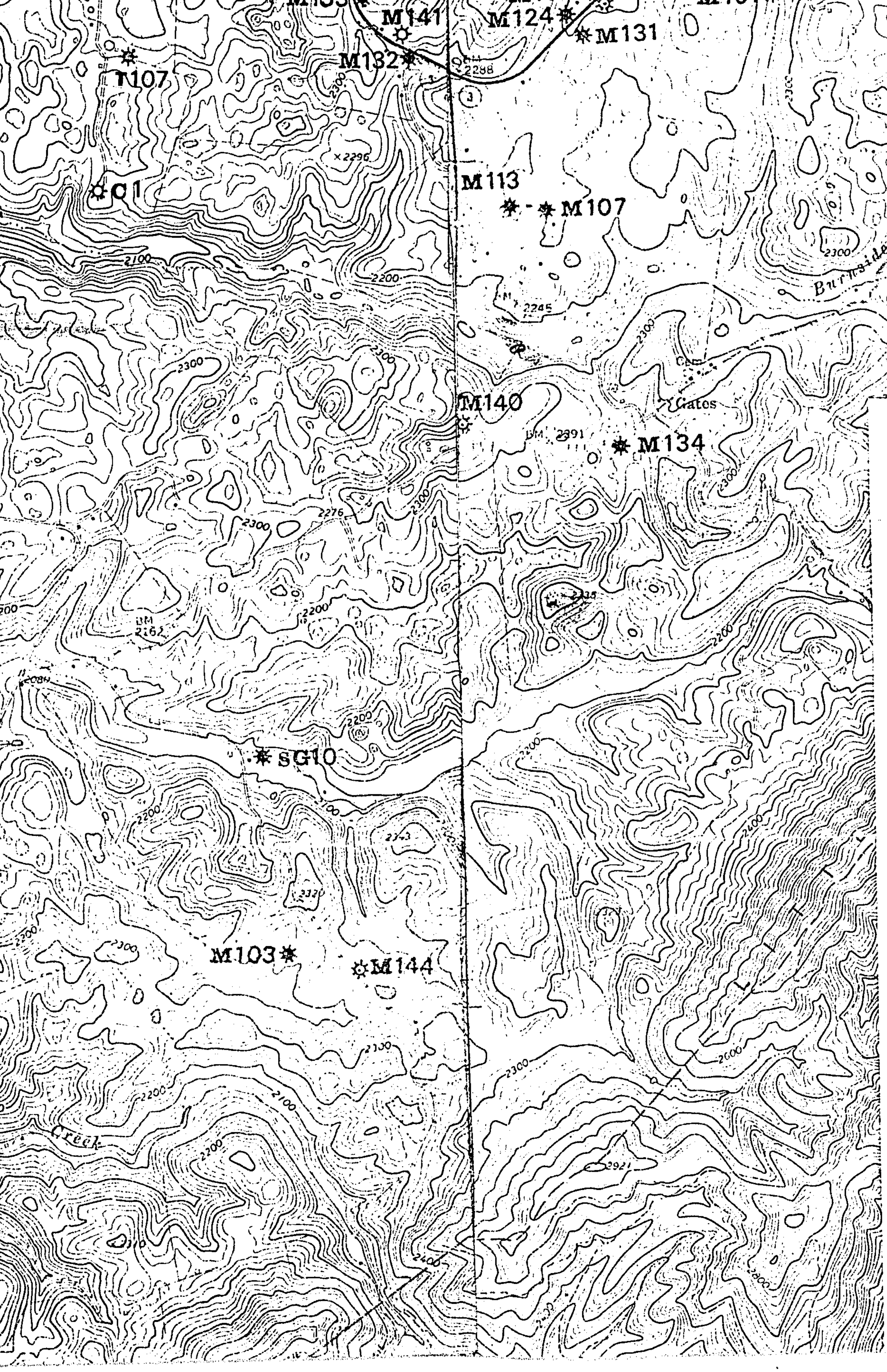
Wells in the :

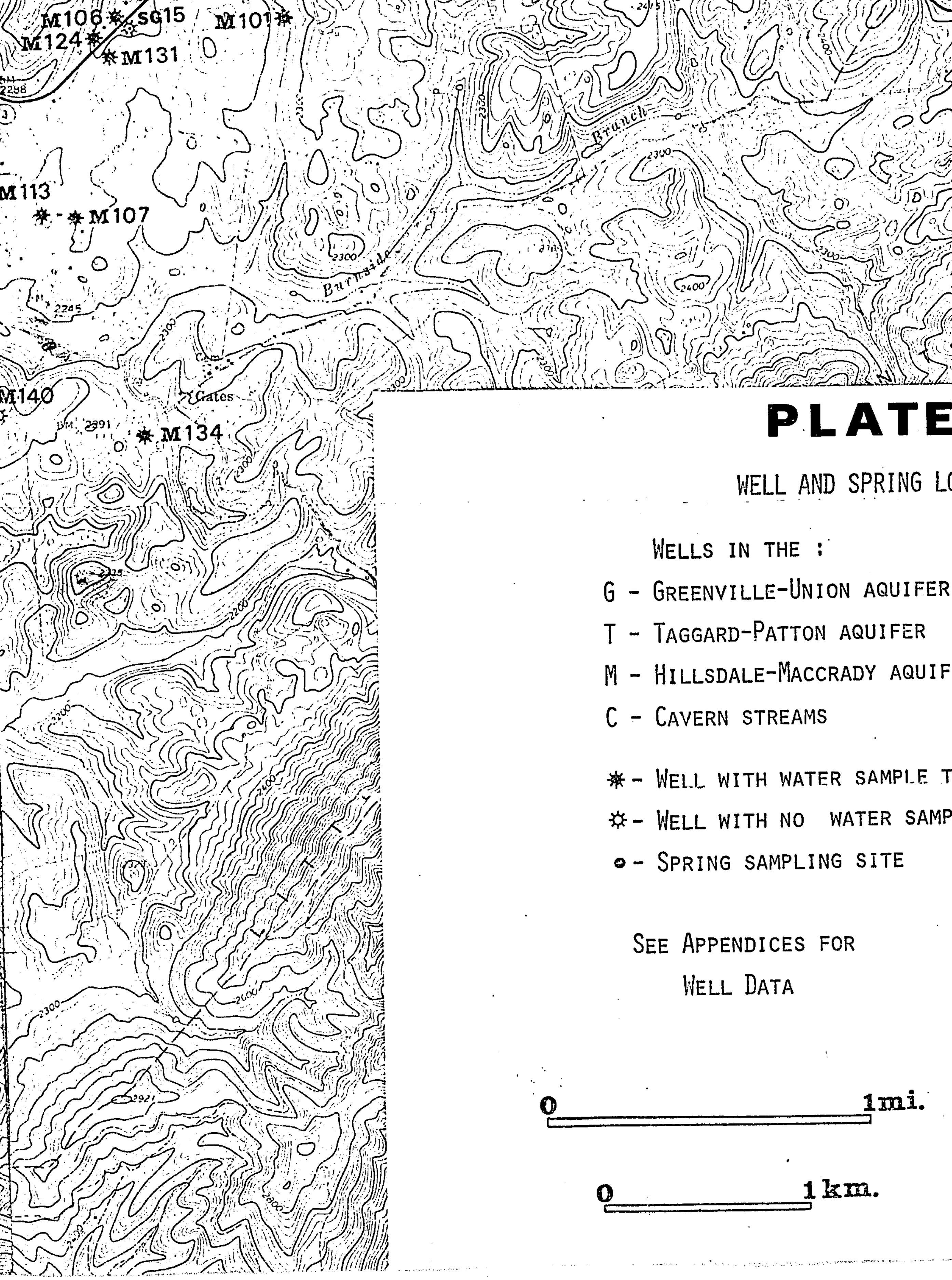
G - Greenville-Union aquifer

T - Taggard-Patton aquifer


MCPEAK'S SPRING
WALTERS' SPRING
T140
G106
G105
G101
G104
C2
T123
G115
Salt Sulphur
Springs
G109
G102
G113
G110
G111
T141
SSN
SSS
G100
G103
G112
U N I O
Burnside
T139
Taggart
Field
Hollow
T12
G107
2000
2100
2200
1900
1800
2748


SG18
M133
M141
M12
M132
T107
UNION
T106
COLD SPRING
C1
M113
T137
Burnside
T138
T139
T121
T112
Taggart
M140
BM 2262
SG10
T111
T128
T127
Branch
M103
M144
Marvin Chapel
Creek
G107
Willow Bend
2000
2100
2200
2300
2400
2089
2288
2296
2108
2276
2387


M141
M124
M131
M132
T107
BM 2298
2300
x 2296
C1
M113
M107
2100
2200
Burnside
2300
2245
Cem
Gates
M140
BM 2391
M134
2276
2300
2335
BM 2162
2200
2080
2200
sG10
2100
2200
2332
M103
M144
2300
2100
2200
Creek
2300
2600
2921
2400
2800
L I T T L



PLATE

WELL AND SPRING LO

Wells in the :

G - Greenville-Union aquifer

T - Taggard-Patton aquifer

M - Hillsdale-Maccrady aquif

C - Cavern streams

✷ - Well with water sample t

☼ - Well with no water samp

• - Spring sampling site

See Appendices for
Well Data

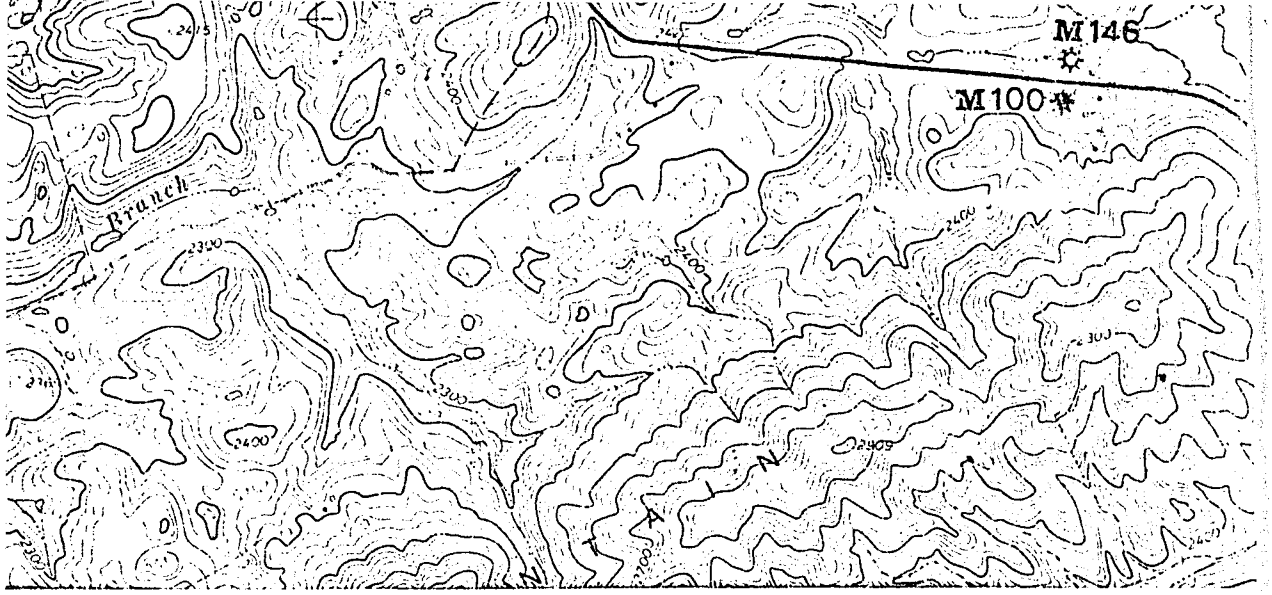


PLATE 3

WELL AND SPRING LOCATION MAP

WELLS IN THE :

G - GREENVILLE-UNION AQUIFER

T - TAGGARD-PATTON AQUIFER

M - HILLSDALE-MACCRADY AQUIFER

C - CAVERN STREAMS

✹ - WELL WITH WATER SAMPLE TAKEN

☼ - WELL WITH NO WATER SAMPLE TAKEN

○ - SPRING SAMPLING SITE

N

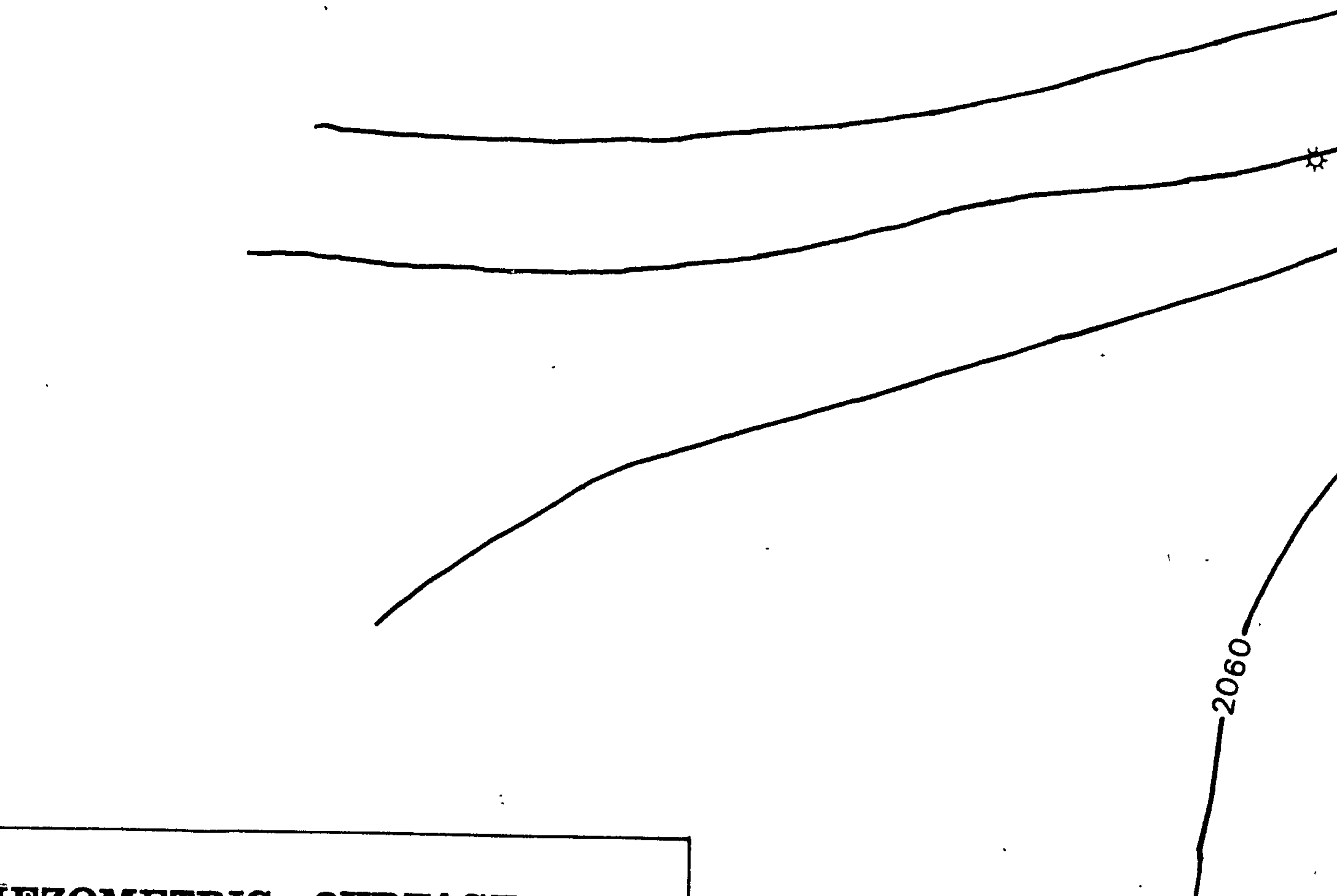
SEE APPENDICES FOR
WELL DATA

PORTIONS FROM THE
FOLLOWING 7½" QUADRANGLES:

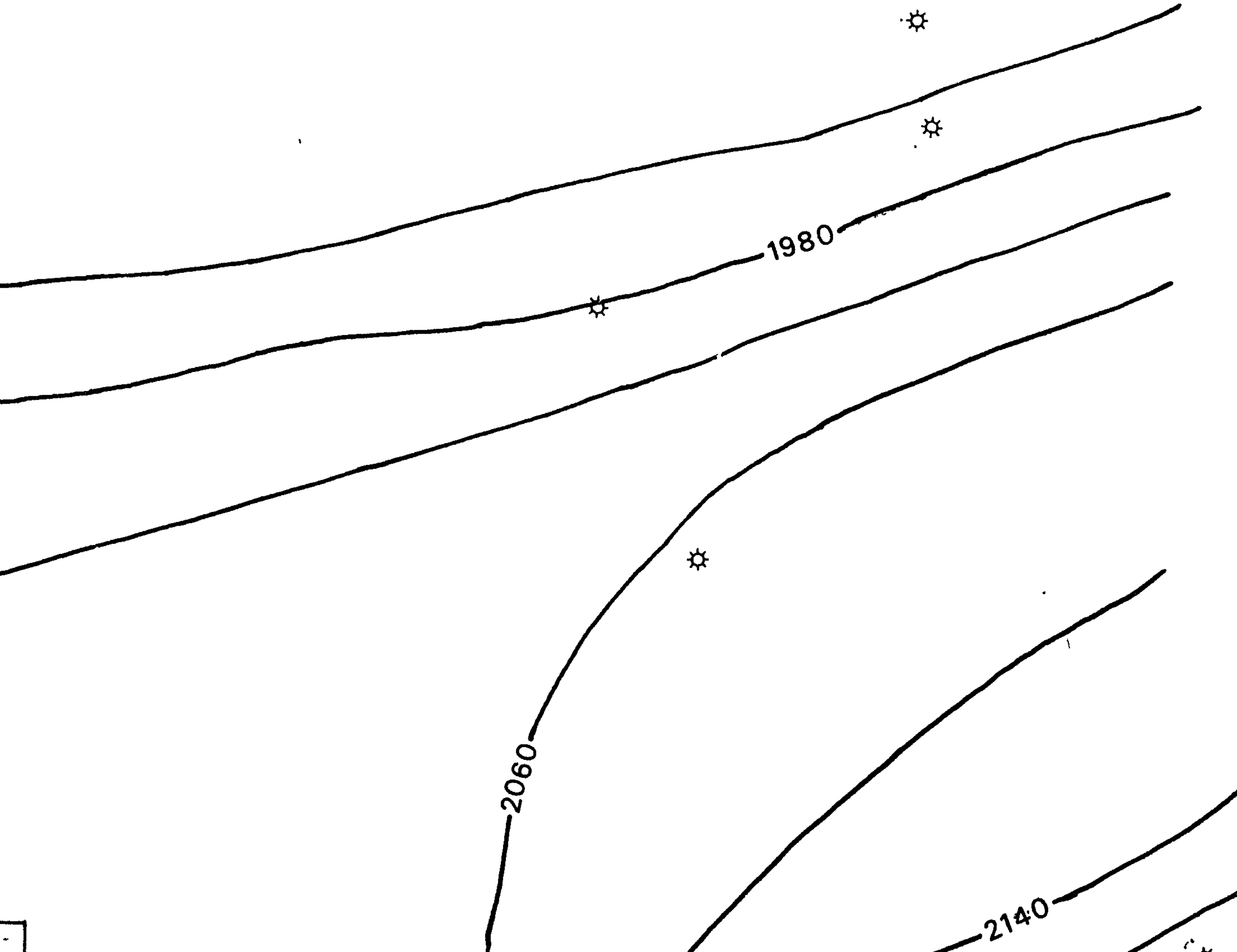
FORT SPRINGS T117	RONCEVERTE M147
M102 UNION	M130 GAP MILLS

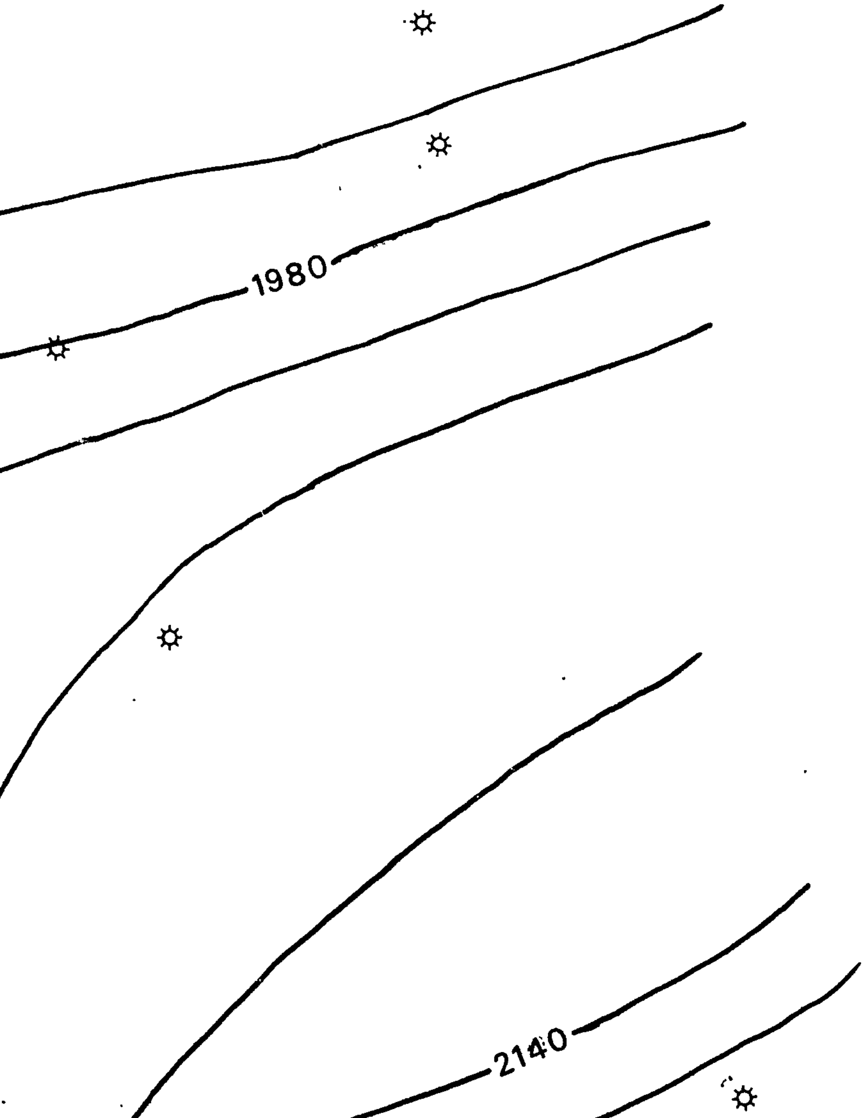
0 1mi.

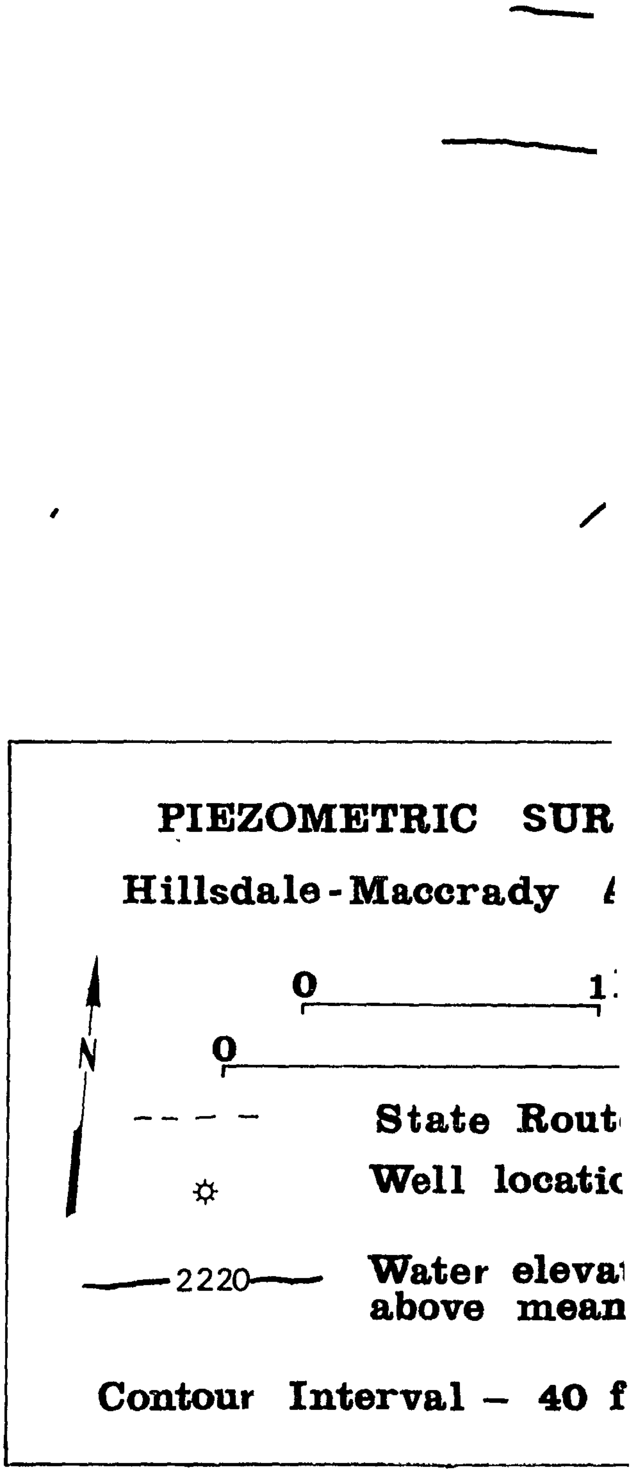
0 1km.



2060


1980
2060
2140

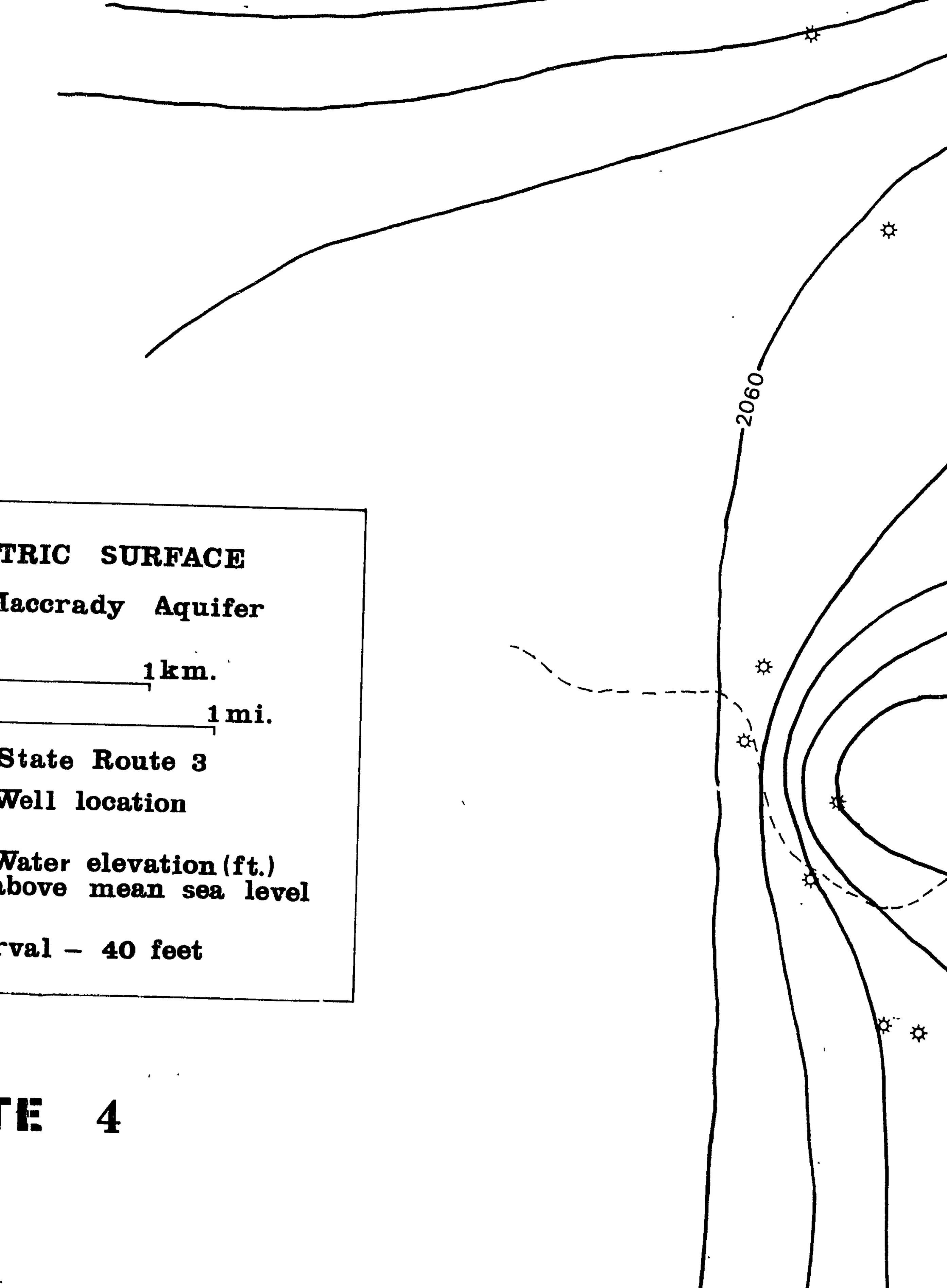

1980
2140



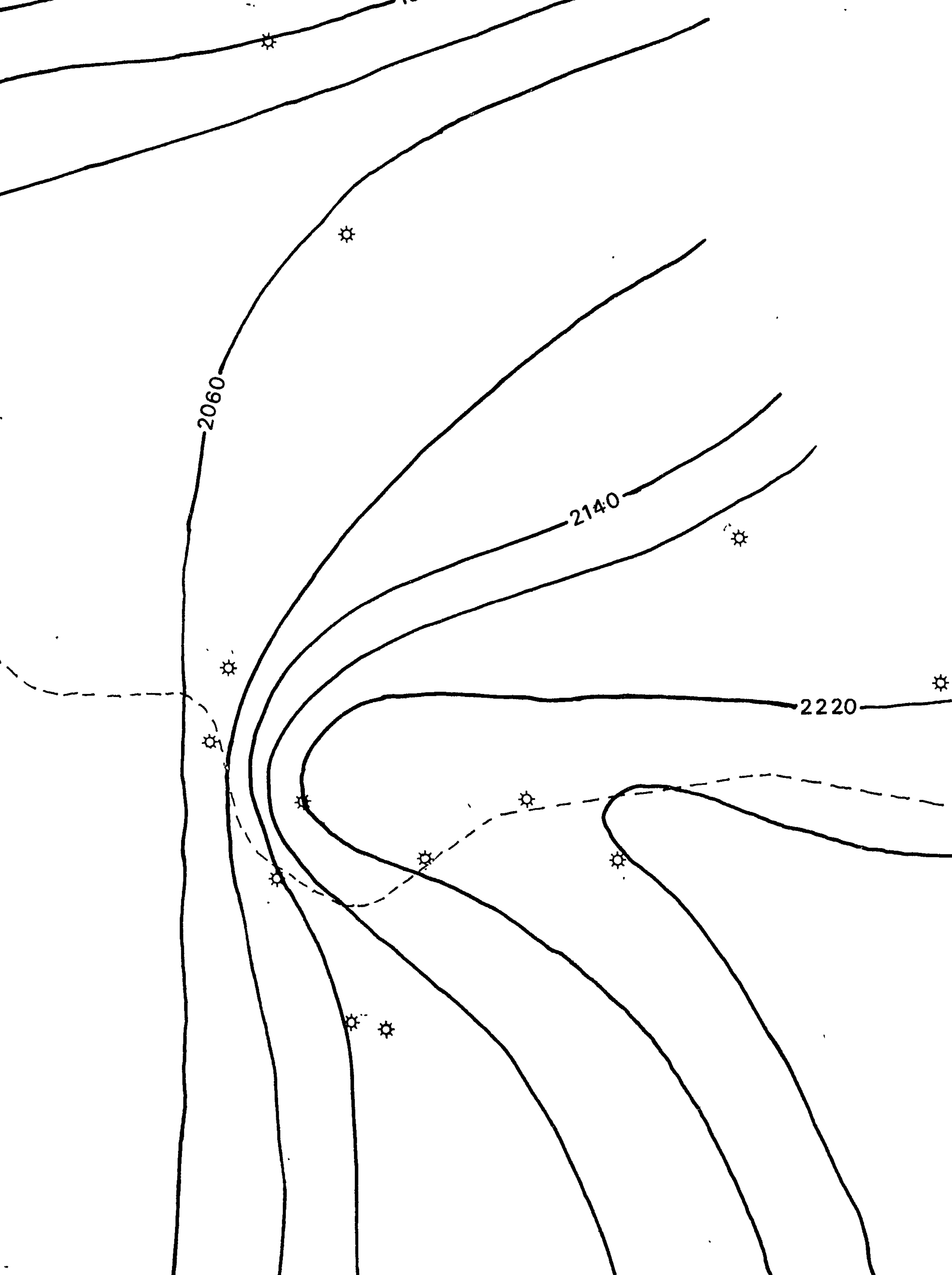
PIEZOMETRIC SUR

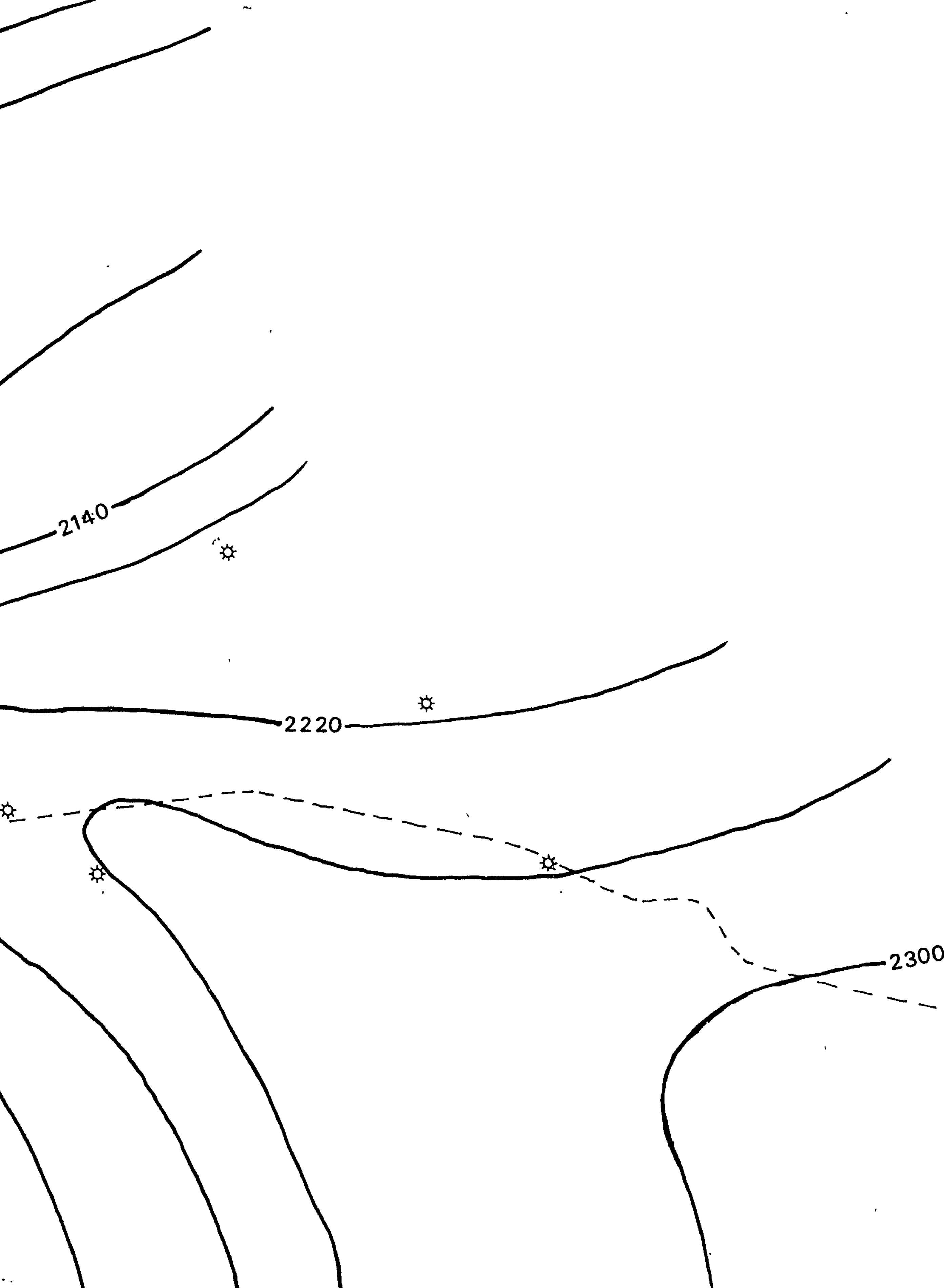
Hillsdale-Maccrady

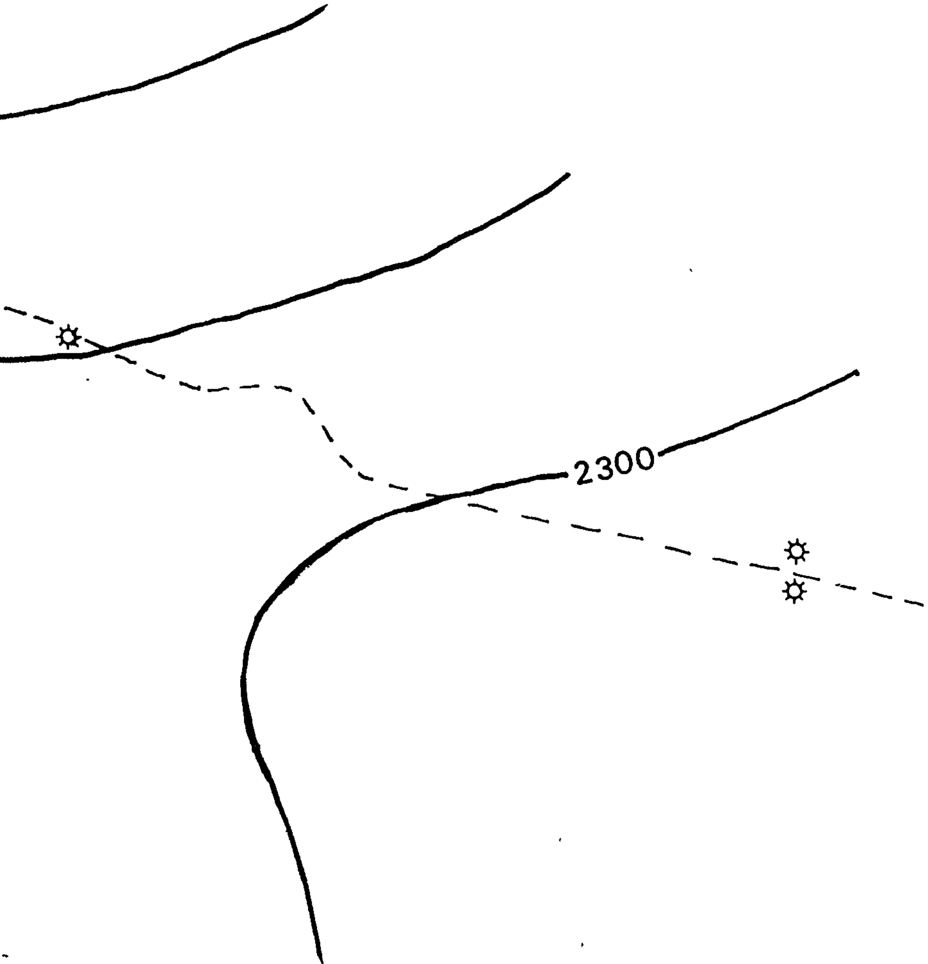
PLATE 4


TRIC SURFACE
laccrady Aquifer
1 km.
1 mi.
State Route 3
Well location
Water elevation (ft.)
bove mean sea level
rval – 40 feet
2060

TE 4


2060
2140
2220


2140
2220
2300


2300

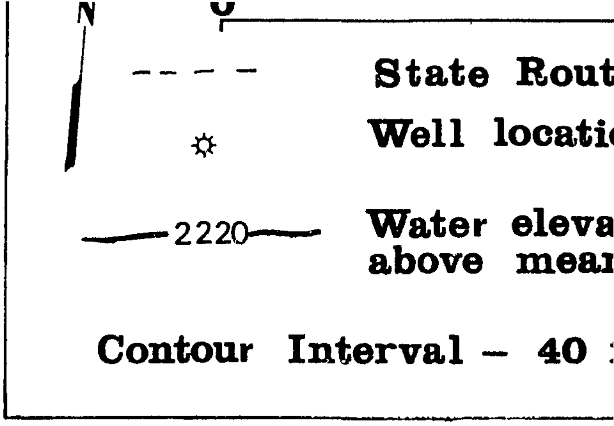
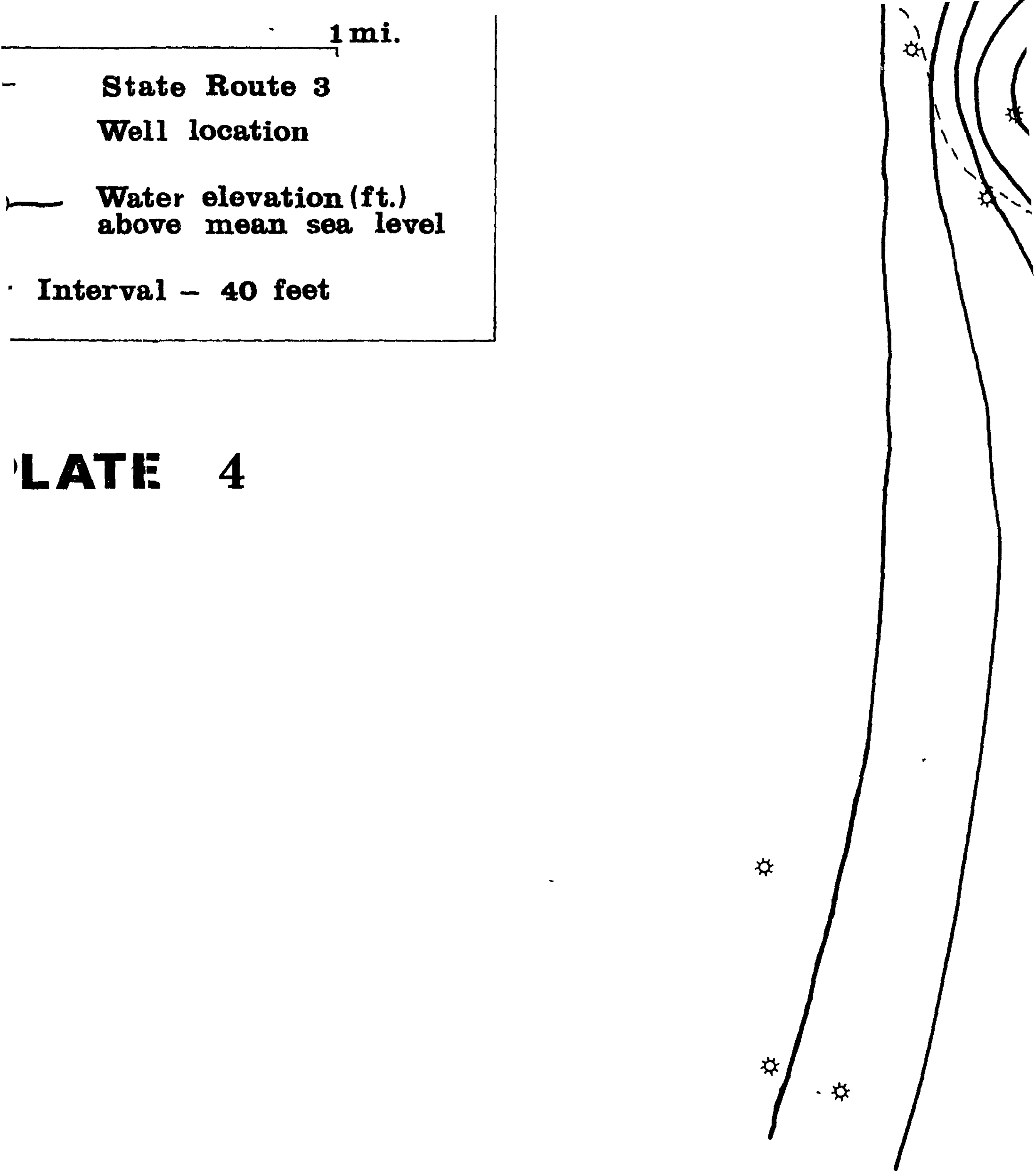
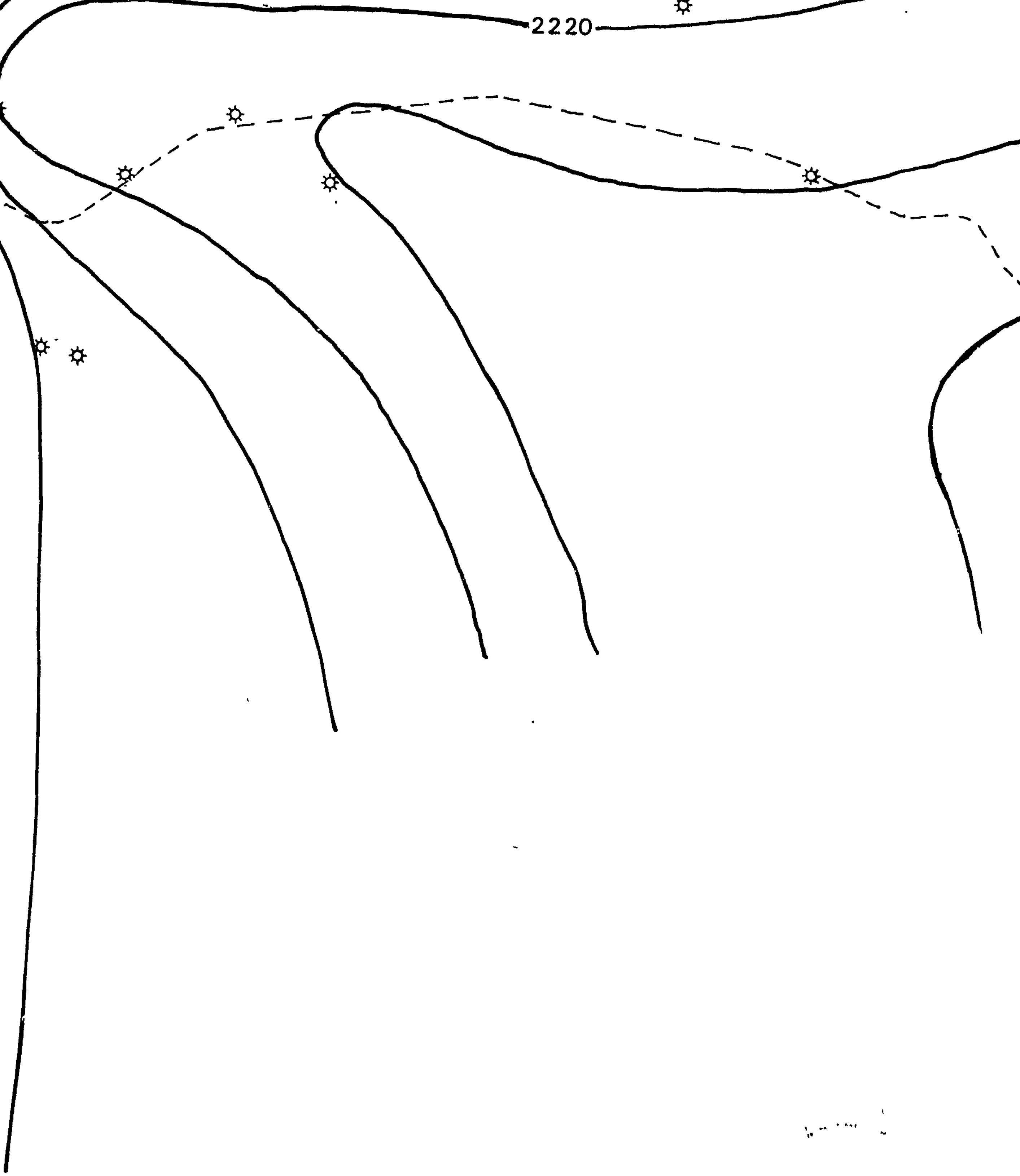

N
0
State Rout
Well locati
2220
Water eleva
above mea
Contour Interval – 40

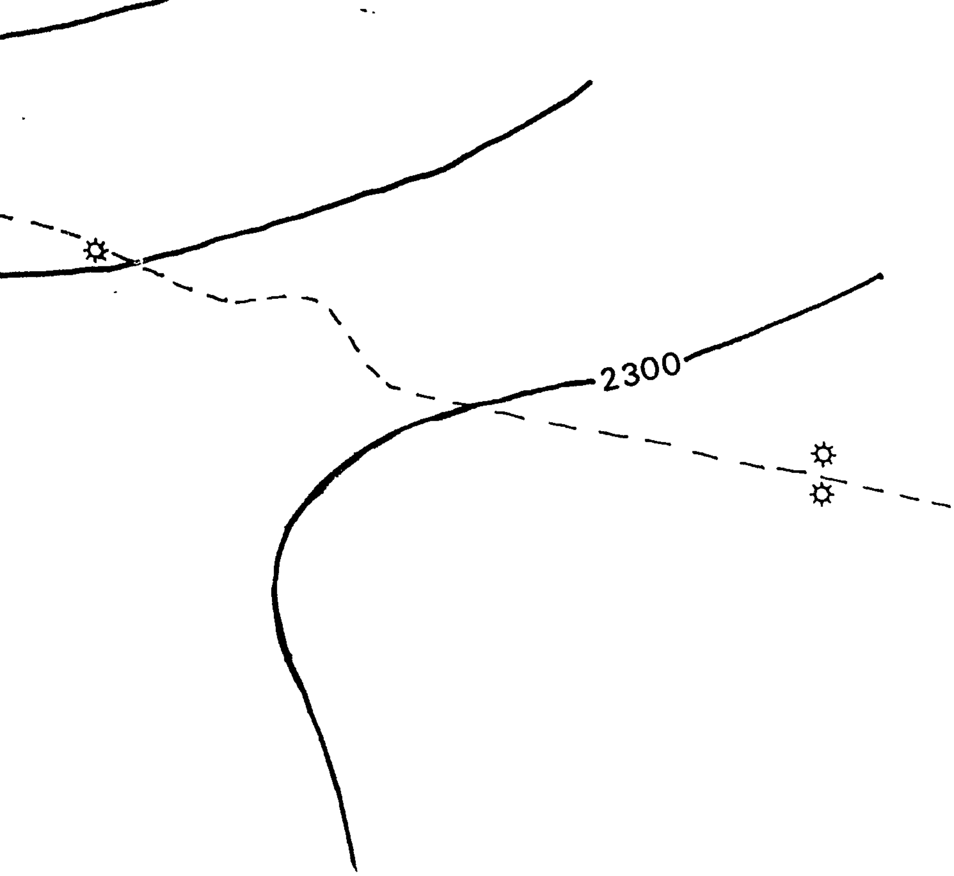
PLATE 4

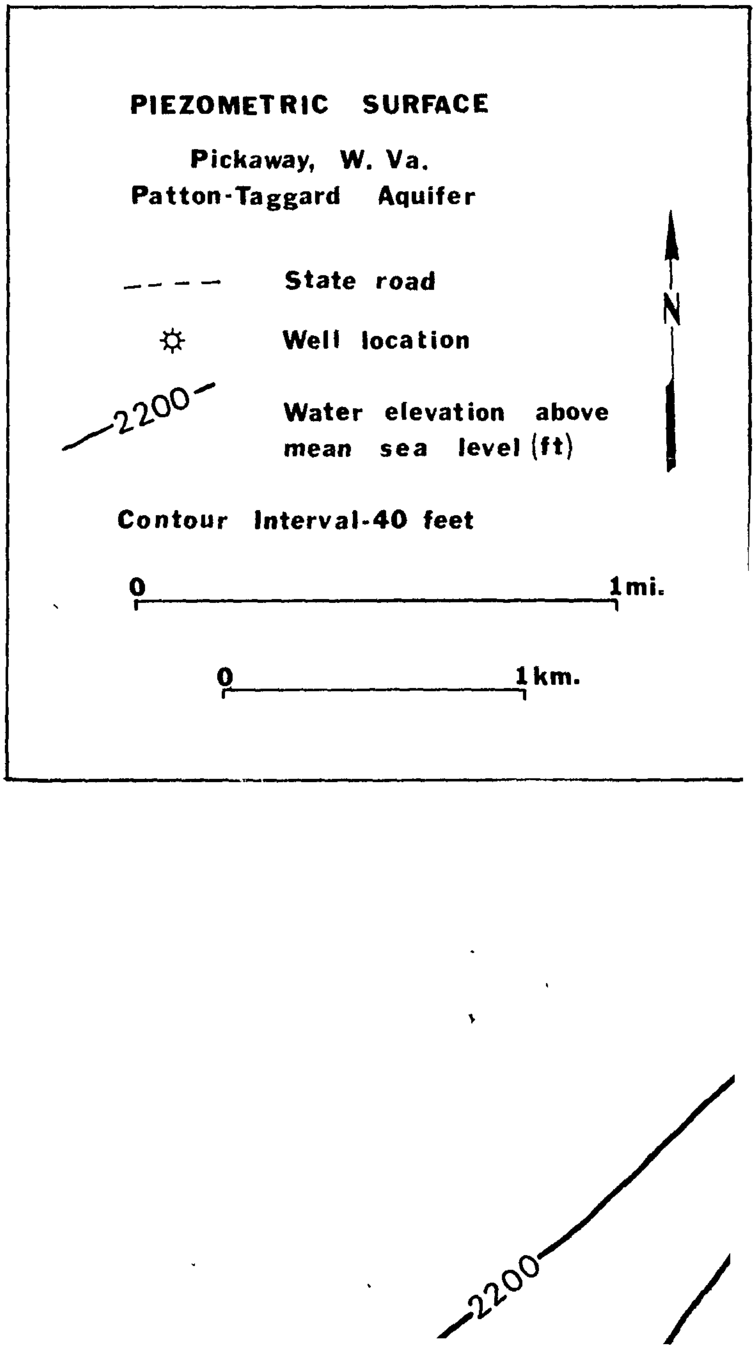

1 mi.
State Route 3
Well location
Water elevation (ft.) above mean sea level
Interval – 40 feet

LATE 4

2


2220


2300



PIEZOMETRIC SURFACE

Pickaway, W. Va.
Patton-Taggard Aquifer

PLATE 5

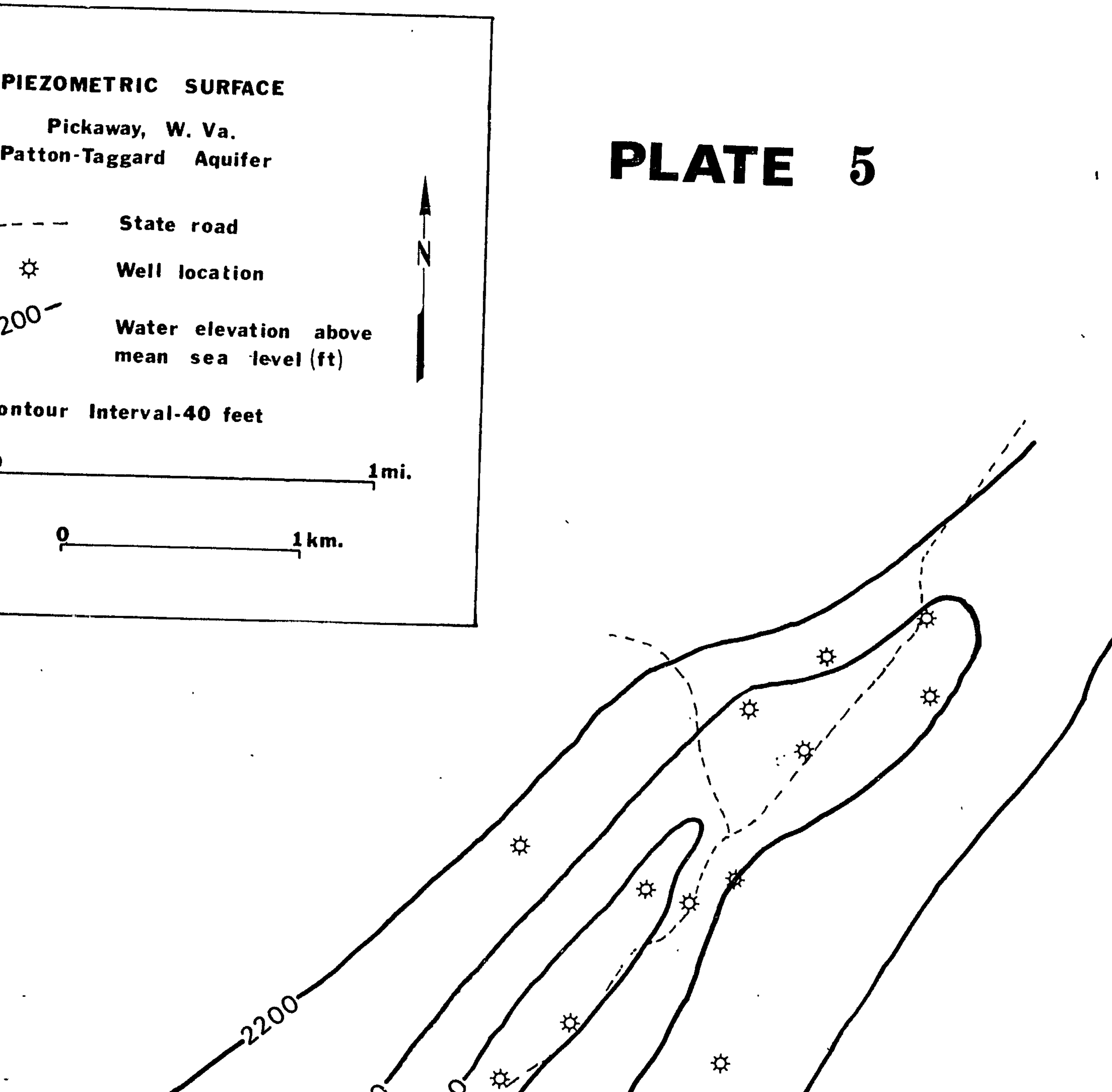
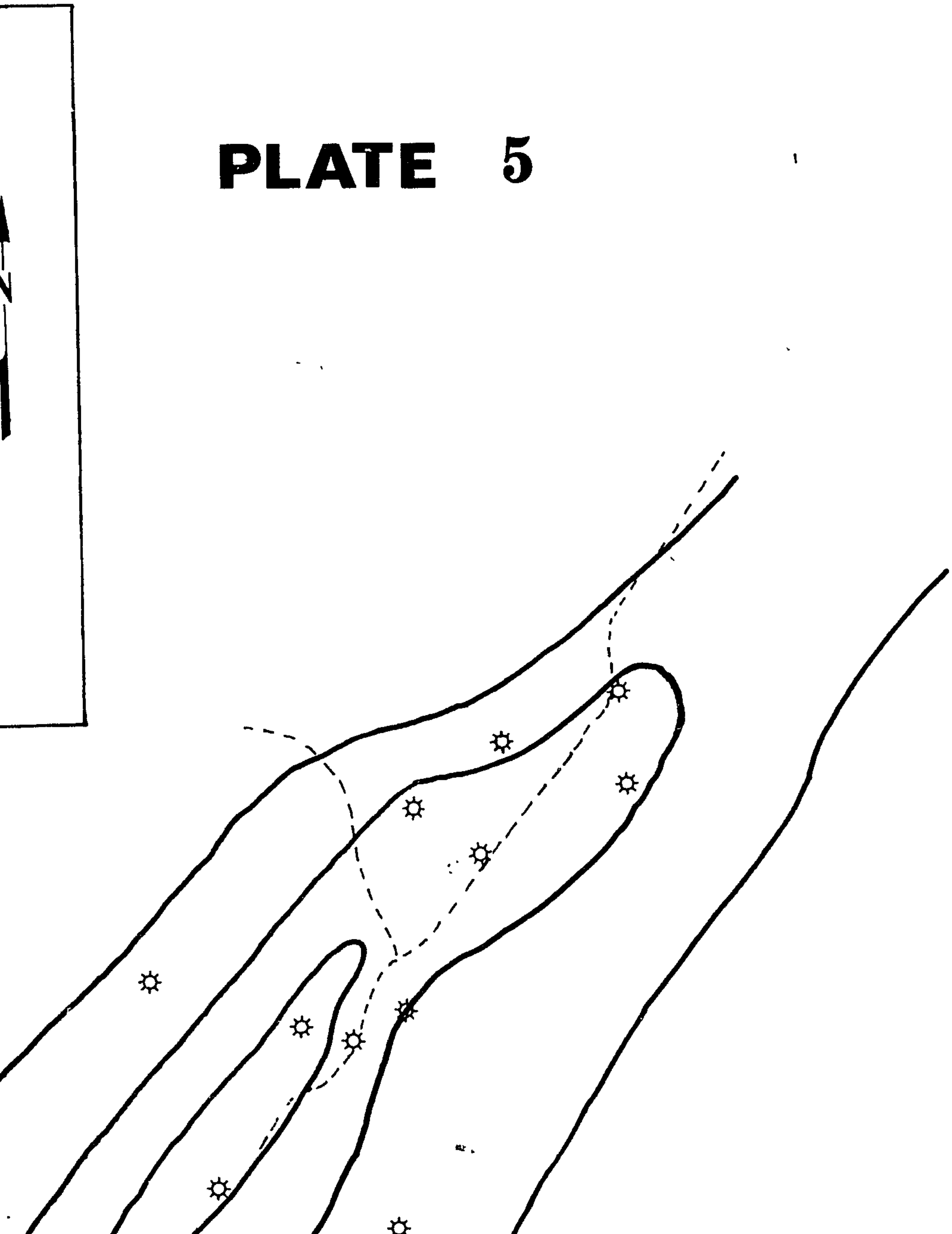
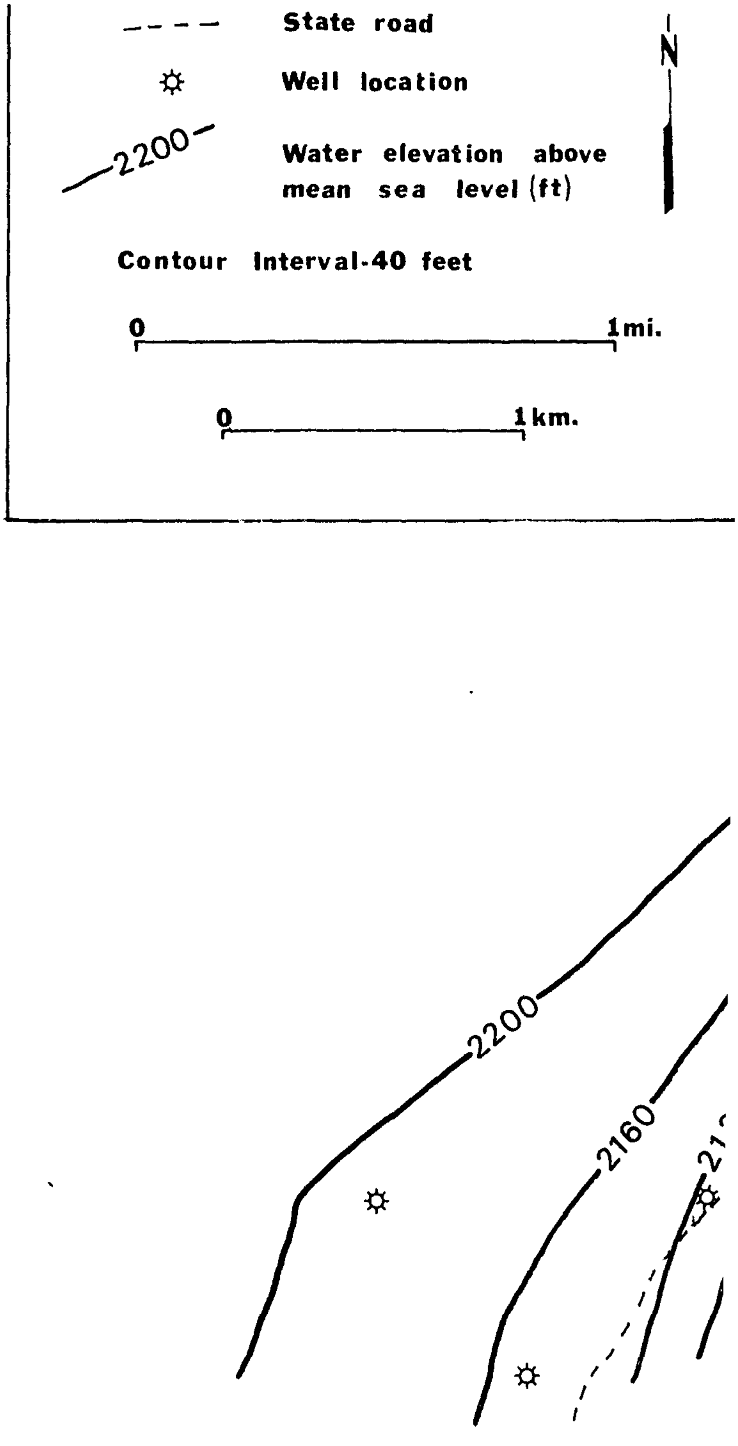
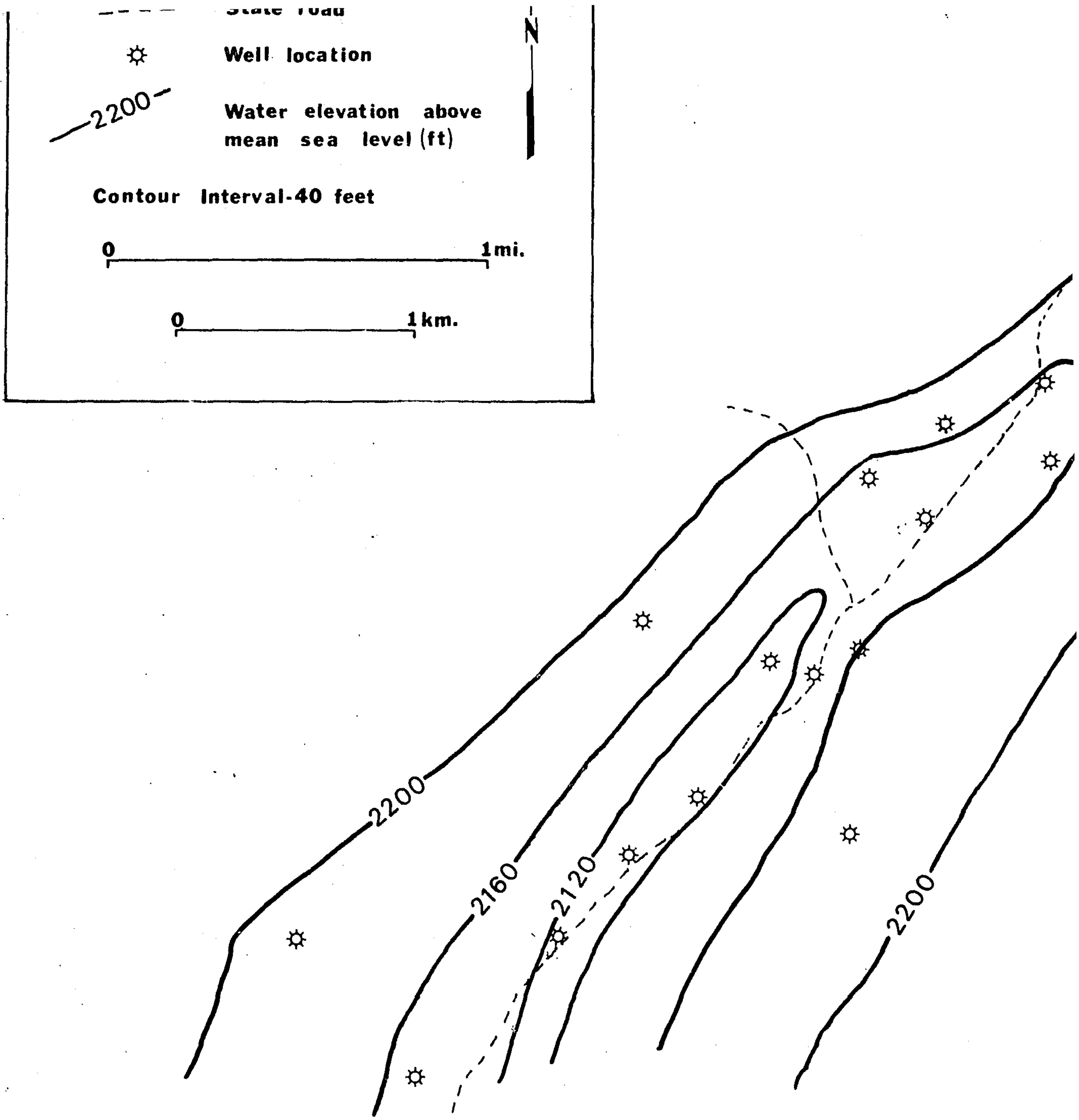
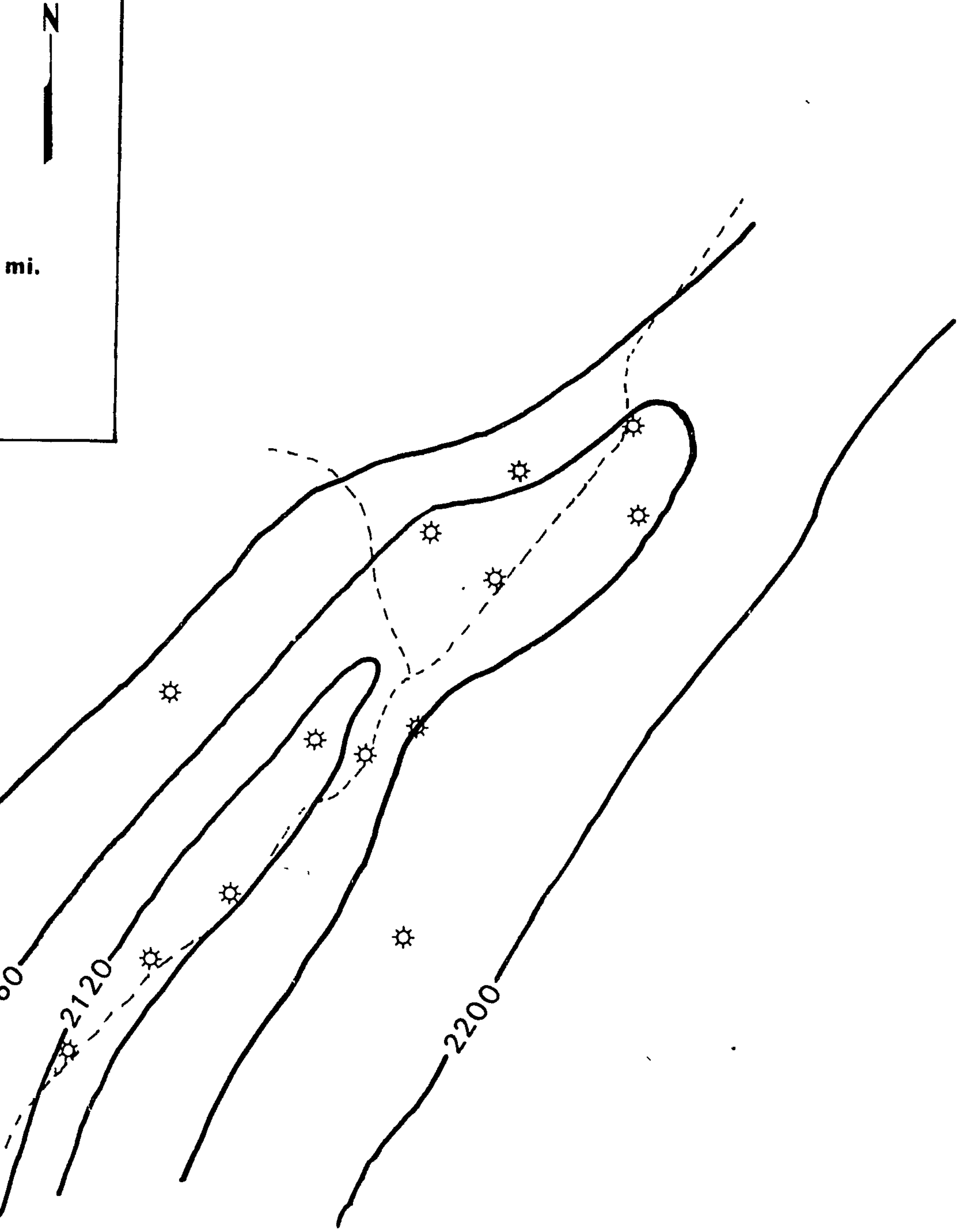

PIEZOMETRIC SURFACE
Pickaway, W. Va.
Patton-Taggard Aquifer
State road
Well location
200
Water elevation above mean sea level (ft)
ontour Interval-40 feet
1 mi.
0
1 km.
N
2200

PLATE 5




State road
Well location
2200
Water elevation above mean sea level (ft)
Contour Interval-40 feet
0
1mi.
0
1km.
N
2200
2160


State road
Well location
2200
Water elevation above mean sea level (ft)
N
Contour Interval-40 feet
0
1mi.
0
1km.
2200
2160
2120
2200


N
mi.
2120
2200