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The geology of the Thayer area emphasizing the stratigraphy of the Cotter and the Jefferson City formations

William Jesse Hedden

THE GEOLOGY OF THE THAYER AREA
EMPHASIZING THE STRATIGRAPHY OF
THE COTTER AND THE JEFFERSON CITY FORMATIONS

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ABSTRACT

Detailed geologic mapping of the Cotter-Jefferson City formational contact in the Thayer, Missouri area demonstrates the feasibility of using this contact. This mapping also delineates significant faulting in the area.

The stratigraphy of the Cotter and Jefferson City formations in the Thayer area has been studied to find a mappable contact between the two formations. The contact was mapped in this area by using marker beds, the stratigraphic positions of which were determined by applying insoluble residue techniques to outcrop sections. Because the insoluble residue zones of the Cotter and Jefferson City formations are recognizable throughout the state of Missouri in the subsurface, mapping the contact between the formations should be possible anywhere within their outcrop area by applying the method described in this report.

Mapping has revealed three distinct zones of block faulting with vertical displacements as great as 350 feet. The faults were mapped using a combination of structural control and airphoto lineations, because the fault traces cannot usually be seen in the field. The faulting may be a southeastward extension of the Graydon Springs fault zone, or it may be part of a suspected east-west trending fault zone of regional extent. Mammoth Spring, the second largest spring in the Ozarks, rises along a fault surface and near the intersection of two fault zones.

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I. INTRODUCTION

A. Description of Problem and Objectives

The geology of the region surrounding Thayer, Missouri has received little attention in the past. Although the brown iron ores, Grand Gulf, and Mammoth Spring have been studied and described, little has been known about the stratigraphy of the region and even less has been known about its structure. The Jefferson City and the Cotter formations have been mapped together in previous reconnaissance work in the area. The failure to separate the two formations and the lack of detailed mapping has resulted in failure to detect significant faulting.

The basic objectives of the research were to find a method by which the contact between the Cotter and the Jefferson City formations could be mapped, and to demonstrate the existence of significant faulting in the Thayer area. The thesis is designed to provide a basis for future work on the contact between the Cotter and the Jefferson City formations, and to serve as a foundation for extended mapping in the region of south-central Missouri. A secondary objective was to provide information on the general geology, geography, and physiography of the Thayer area.

The research was divided into six parts to accomplish the objectives. They are:

1) To study and to describe the stratigraphy of the Cotter Formation and the Jefferson City Formation. This was done primarily to find and to describe reliable marker units which could be used for mapping, and to ascertain whether local correlations could be made between measured sections.

2) To continue the stratigraphic study of the Cotter Formation and the Jefferson City Formation from the mapped area southward to Ash Flat, Arkansas. This was done to ascertain whether, as indicated by McCracken (1968, personal communication), any significant facies changes occur toward the sedimentary basin of northern Arkansas.

3) To prepare a geologic map of part of the Thayer quadrangle. The purpose of this was to apply the results of the stratigraphic study to field mapping, and to show the existence, trend, distribution, and magnitude of displacement of the faults in the area.

4) To ascertain the possible relationship of the faults in this area to other known faults in the southern Ozarks.

5) To study and describe the stratigraphy of the Roubidoux Formation with available surface and subsurface data, and to briefly describe the subsurface geology of the sub-Roubidoux formations.

6) To study and briefly describe other aspects of the geology, geography, and physiography of the Thayer area.

B. Location and General Description of Area

The thesis area is in south-central Missouri and north-central Arkansas. It includes mainly parts of the Thayer and Mammoth Spring quadrangles.

The area for which a geologic map has been completed is primarily in the southeast part of the Thayer quadrangle, and it also includes a small area in the vicinity of Mammoth Spring, Arkansas, in the Mammoth Spring quadrangle. The main body of the map is bounded as follows:

North boundary--------latitude 36°38' N.

South boundary--------the Arkansas-Missouri border

East boundary---------longitude 91°30' W.

West boundary---------longitude 91°35' W.

The smaller area in the Mammoth Spring quadrangle includes the N½, Sec. 8, and the NE¼, Sec. 7, T. 21 N., R. 5 W., with the east and west boundaries extended north to the Arkansas-Missouri border to join the main geologic map. Together these areas include about 44 square miles.

In addition to the geologic mapping a stratigraphic study of the Cotter Formation and the Jefferson City Formation has been continued southward from the mapped area to Ash Flat, Arkansas. Also, certain solution features which are near to but outside of the mapped area have been studied and are discussed in this report.

C. Method of Investigation

Initially a field reconnaissance was made of the area to find mappable units distinctive enough to serve as marker horizons. The first unit found was a thin oolitic chert bed, seldom exceeding 0.5 foot in thickness, but very distinctive and always accompanied by a banded nodular chert. This easily recognized and persistent combination is the most useful marker horizon in the area.

After finding a reliable marker unit, it was necessary to determine the exact stratigraphic position of the unit with respect to the Cotter-Jefferson City formational contact. This was done by carefully measuring several stratigraphic sections including beds above and below the unit, giving particular attention to the types and percentages of insoluble material (chert, sand, silt, crystalline quartz, and shale). Comparison of the measured sections with water well logs from the area and with McCracken's insoluble residue zones* (McCracken, 1952, p. 61-70 and McCracken, undated, unpublished chart) led to the conclusion that the oolitic chert is at the top of McCracken's low-residue Zone 8 and 27 feet above the contact between the Cotter and the Jefferson City formations.

Along most of the major streams the contact between the

*See p. 93 for a detailed description of this method.

Cotter and the Jefferson City formations could be placed directly at the top of the highest chert bed in Zone 7 (ibid.), the high percentage chert zone at the top of the Jefferson City. However, the chert in Zone 7 varies considerably in thickness and appearance, and could easily be confused with some of the cherts of the Cotter or the Roubidoux formations. For this reason establishing the contact at a given locality on the basis of the Zone 7 cherts required the presence of the oolitic chert above them to confirm their identity.

Where the contact between the Cotter and the Jefferson City formations is not exposed, the oolitic chert was used to determine the elevation of the contact. This unit is especially useful for detecting and mapping faults in residuum-blanketed areas.

As mapping progressed into areas where only the strata above the oolitic chert are exposed, it was necessary to find other marker units or zones*. These units, which are described on p. 84 of this report, were used primarily for structural control. None of these units are as widespread as the oolitic chert.

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*The term "zone" is used in this thesis in the informal sense as indicated in Article 4g of the Code of Stratigraphic Nomenclature (American Commission on Stratigraphic Nomenclature, 1961, reprinted in Krumbein and Sloss, 1963, p. 625), and it does not indicate a biostratigraphic zone unless specifically stated.

Because of the lack of extensive outcrops, it was necessary to map much of the area away from major streams by using residual cherts for control. Although this is not a highly accurate method, these cherts were quite valuable for detecting significant faults which could not have been found otherwise.

Water well logs were used for structural and stratigraphic control wherever available; and where possible, residual control was supplemented by well log data. Well logs not showing good formational contacts were not used for control unless the well log data in question were supported by reliable field evidence.

Fault traces could not usually be recognized in the field because of the residual cover, and the rectangular stream pattern of the area failed to provide any proof of the faults. For these reasons most of the faults were mapped by using aerial photographs. The procedure was to establish and plot as many structural control points as possible, and then to find a pattern of airphoto lineations which would best account for the structural displacements between the control points. (For a description of airphoto lineations see El Etr, 1967, p. 10-13, 62-81, 94-96, 200-202, 209-210.) The airphotos used were Agricultural Stabilization and Conservation Service (ASCS) photos with a scale of approximately 1:20,000 and a size of approximately 9" X 9". No attempt was made to plot all the lineations which could be seen on the photographs, but only those needed to account for structural displacement were used.

To avoid cluttering the map with unnecessary detail, and thus to place emphasis on the more significant faulting, many faults and monoclines having displacements of less than ten feet were not portrayed.

Field elevations were established with a hand level, taking as a reference the elevation of some nearby landmark which could be recognized on the topographic map.

Stratigraphic sections were measured with a hand level and a five-foot rod calibrated in tenths of a foot. Most of the sections were described in the field. Samples from each unit of two of the measured sections, however, were examined with a binocular microscope at 20X magnification.

D. Previous Work

No detailed geologic mapping has previously been done in the thesis area. Some reconnaissance work has been done in the area, however, and a chronological summary of this work is included herein.

The first known geological reconnaissance of the area was made by Owen (1858, p. 60-62, pl. 5) while working on a reconnaissance of the northern counties of Arkansas during 1857 and

1858. Owen had been appointed as the first State Geologist of Arkansas in January of 1857, and his reconnaissance of the northern counties of Arkansas was the first official geologic work of the Arkansas Geological Survey. In his report he gave a description of Mammoth Spring, which is quite interesting because of its historical content. He suggested that the source of water for Mammoth Spring was probably "Howel's valley" (presumably what is now known as Bussell Branch), which was recognized even at that time as having no surface drainage outlet. He also mentioned the occurrence of brown iron ore in the area.

Nason (1892, p. 248-249, 297-298) described a few of the iron ore deposits in the Thayer area. In his report he also referred to Mammoth Spring and Grand Gulf, making note of their probable subsurface connection.

Marbut (1896, p. 90-91), in describing the development of the "canyon phase" of stream valleys in the Ozarks, referred to Grand Gulf as "...the first stage in the process". He stated that at Grand Gulf "a large underground stream is made visible for a short distance by the falling in of the [cave] roof." In the same paper he referred to the broad, shallow, trough-like valleys of Howell and Oregon counties as "valleys of solution" (p. 89).

Owen (1898) stated that she went more than 500 feet into the outlet cave of the Grand Gulf (per Bretz, 1956, p. 353).

Crane (1912, p. 273) described some of the iron ore deposits in the area and listed several additional reported occurrences of the ore.

Reconnaissance mapping of the Roubidoux Formation in this area for the 1926 Missouri geological map was done by Dake (Dake, undated, unpublished notes and maps).

The guidebook for the Second Annual Field Conference of the Kansas Geological Society (1928, p. 4a-5) pointed out a few outcrops in the Thayer-Mammoth Spring area and made mention of Mammoth Spring.

Five years later another field trip of the Kansas Geological Society (1933, p. 32-34) went through the area, and the guidebook for this conference gives more detail on the stratigraphy and structure of the area than did the 1928 guidebook. In reference to Mammoth Spring, the guidebook cites field work by the Missouri Geological Survey which suggests the association of the Mammoth Spring with faulting.

Doll (1938, unpublished thesis, p. 13, 17, 29-30, 55-57, 59, 90-93) gave a detailed description of Mammoth Spring, outlined what he believed to be the effective drainage area of the spring, and made some hydrologic calculations for the spring based upon his ideas. In the same thesis he quoted an unpublished letter by McQueen regarding field work which he (McQueen) had done on Mammoth Spring. McQueen's letter, which was very similar to the previously mentioned work by the Missouri Geological Survey cited in the Kansas Geological Society (1933) guidebook, suggested the association of Mammoth Spring with faulting.

Beckman and Hinchey (1944, p. 90-91) discussed Mammoth Spring and recorded flow data. They suggested that the source area of water for the spring is a large area with a poorly developed stream network to the north and northwest of the spring. The possible subterranean connection between Mammoth Spring and Grand Gulf was also discussed.

In 1953 the Missouri Geological Survey (1953, 7p.) compiled a list of known brown iron ore deposit locations in Oregon County.

Bretz (1956, p. 350-355) investigated Grand Gulf, described it in detail, and proposed a theory for its origin and for the survival of the natural bridge. In this same report he described the broad, flat upland divide between Koshkonong and Brandsville as being "...remnants of the old Ozark lowland...".

Hayes (1957, p. 16-18) reported on the brown iron ore deposits of what he referred to as the "West Plains District", which included the deposits of the Thayer-Koshkonong area.

Stenchcomb made a reconnaissance of parts of the area for the 1961 Geologic Map of Missouri, revising Dake's previous mapping (McCracken, 1968, personal communication) and mapping outcrops of the Roubidoux Formation on Warm Fork north of Thayer, as shown by the 1961 map.

Mehl investigated a deposit of vertebrate remains in 1964 which had been found in a collapsed cave exposed by a highway cut. He identified the remains as "Recent fish, lizards, and small snakes" (Mehl, 1964, written communication).

Bretz (1965, p. 79) correlated the prominent upland area in the southwest quarter of the Couch quadrangle, immediately to the east of the thesis area, with the "Springfield Peneplain".

Beveridge (1966, p. 12-13) described Grand Gulf and discussed its probable subsurface connection with Mammoth Spring in the Missouri Conservationist (October 1966).

In October of 1967 Toney Aid (1967, unpublished report), a student at West Plains High School, definitely established the subsurface connection between the Grand Gulf and the Mammoth Spring, using fluorescent dye for a tracer. His procedure and results are given on page 111 of this report.

E. Acknowledgements

A number of persons have contributed immeasurably to the research and to the preparation of this thesis, and to these persons the writer is deeply indebted. Dr. Thomas R. Beveridge, Chairman of the Department of Geology, suggested the problem; provided a graduate assistantship; offered many helpful suggestions; visited the area; and supervised the final writing of the thesis. Mrs. Mary H. McCracken of the Missouri Geological Survey provided much valuable information on the Jefferson City and Cotter formations; assisted in correlating measured sections; and provided unpublished information on faulting in southern Missouri. Mr. Kenneth H. Anderson and the staff of the Subsurface Geology Section of the Missouri Geological Survey provided ready access to well logs and cuttings on file; promptly processed and logged water well cuttings which the writer brought in from the research area; prepared residues of samples from measured sections; and prepared copies of many well logs for the writer's personal use. The V. H. McNutt Memorial Foundation provided a generous grant to defray field and research expenses for the summer of 1968. The Department of Geology provided aerial photographs of the research area.

Mr. Gene Blankenship of Thayer directed the writer to a number of outcrops in unexpected places which have provided much needed structural control. Mr. Jim Hedden, brother of the writer, assisted in measuring and describing outcrop sections and in other field work. The Dillard Well Drilling Company of Mammoth Spring, Arkansas saved many excellent sets of samples from wells.

An especially warm note of thanks is extended to my wife, Mrs. Fay Hedden, for her patience and encouragement during the course of the field work, and for her careful typing of this thesis.

II. PHYSIOGRAPHY AND GEOGRAPHY

A. Regional Physiography

The Salem Plateau consists of relatively flat upland divides of varying width, but of more or less accordant summit elevations; these uplands are separated by the major streams and tributaries of the plateau. Many of the divides are quite broad, and they usually have a rolling topography in which the relief is seldom over 100 feet. On the other hand, the topography near the major streams is usually very rugged, and the relief may be as much as 500 feet.

The geomorphic development of the Ozark Province is a subject of controversy, and a discussion of the conflicting points of view is beyond the scope of this report. The interested reader is referred to Bretz (1965) and Hack (1960) for a discussion of the problem.

B. Drainage

The area studied in Missouri drains, for the most part, into the Warm Fork of Spring River*; and the area studied in Arkansas drains into Spring River. Warm Fork** begins its first

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*Not to be confused with the Spring River of southwestern Missouri.

**Since cartographers are not consistent in the use of the names "Warm Fork" and Spring River", this report follows the long-established local usage of the names: Warm Fork is considered to be a tributary of Spring River, and Spring River is considered to originate at the Mammoth Spring.

permanent flow at Warm Fork Spring (NE¼, SE¼, NE¼, Sec. 25, T. 23 N., R. 6 W.), above which the stream is intermittent. The flow of Warm Fork is permanent but small between Warm Fork Spring and the point where it joins the flow of Mammoth Spring (discharge 279,000,000 g. p. d.) immediately south of the Arkansas-Missouri border. From its point of origin at Mammoth Spring, Spring River flows southeasterly toward the Mississippi alluvial plain, to join Black River immediately outside the Ozark Province.

The drainage pattern is rectangular. Northeast and northwest trends predominate, but secondary trends of north and east are also present. Although the area is extensively faulted, no evidence of faulting can be found in most of the stream valleys; on the contrary, the inferred fault traces show no relationship to the drainage pattern. Evidently the rectangular drainage pattern is controlled by a joint system rather than by the fault system.

Although the areas adjacent to the major streams and their tributaries have a well developed surface drainage, many of the broad, flat, upland divides have a very poorly developed surface drainage. Much of the rain that falls upon these areas goes underground either through the permeable residuum or through sinkholes, and for this reason an extensive system of underground drainage has developed in the dolomite bedrock. Some of the outstanding subsurface drainage features in the area include the sinkhole plain west of Koshkonong, Missouri; Grand Gulf, a collapsed cavern which receives drainage from approximately 22 square miles; and Mammoth Spring, the second largest spring in the Ozarks.

C. Topography and Relief

The topography ranges from gently rolling on the upland divides to rugged along the major streams. Local relief within a given square mile on the upland areas is usually less than 100 feet, whereas sections along Spring River commonly have a local relief as great as 350 feet. The difference in elevation between stream valleys and adjacent major divides ranges from about 380 feet in the north part of the mapped area to about 510 feet near Hardy, Arkansas. The topography along Spring River is generally more rugged than that along Warm Fork.

Altitudes in the thesis area range from a high of approximately 1,000 feet near Koshkonong, Missouri, which is on a broad major divide, to a low of approximately 370 feet along Spring River at Hardy, Arkansas. Regionally the general altitude decreases in a southeasterly direction toward the Mississippi alluvial plain; and within the area the general altitude decreases southward along Warm Fork and Spring River.

With the exception of a sinkhole plain west of Koshkonong, Missouri, karst topography is not as well expressed on the surface as might be expected for this area of carbonate bedrock, despite the apparently well-developed underground drainage network. Sinkholes are scattered throughout the area, but are not an important part of the overall topography.

D. General Description of Bedrock and Soil

Indurated rocks exposed in the area all belong to the Canadian Series of the Ordovician System, with the exception of one known Mississippian or Cretaceous outlier. Most of the bedrock is dolomite, but much chert and some sandstone are also present.

The bedrock weathers to a residual soil of cherty and sometimes sandy, plastic but permeable red clay. This residual material blankets practically the entire area, and it commonly reaches thicknesses of over 100 feet. The contact between the bedrock and the residual soil is very irregular, and the depth to bedrock is unpredictable. Both large and small cutters and pinnacles exist throughout the area, and it is not uncommon for excavation to unearth a very large pinnacle covered by many smaller pinnacles.

E. Climate

Hunt (1967, p. 205) describes the climate of the Ozark Province as "continental". The average annual rainfall is approximately 40 inches, and the annual snowfall is usually less than 10 inches. During the coldest winter months the daytime temperatures commonly range from 20° F. to 30° F., and in the warmest summer months the most frequent daytime temperatures range from 85° F. to 95° F.

F. Vegetation

Most of the forested areas are covered predominantly with second-growth oak (red oak, white oak, post oak), intermixed with lesser quantities of hickory, redcedar (juniper), and black walnut. In the larger outcrop areas of the Roubidoux Formation, shortleaf pine is conspicuous.

Thick underbrush and dense foliage cover most of the area during the summer, and this makes outcrops very difficult to find. Underbrush and briar entanglements are especially dense along river bluffs, where most of the outcrops are found, and for this reason field work is best done in the winter.

G. Communities and Industry

The largest towns in the area are Thayer, Mo. (pop. 1,713), Mammoth Spring, Ark. (pop. 825), Hardy, Ark., (pop. 555), and Koshkonong, Mo. (pop. 478). All of these towns are served both by U. S. Highway 63 and the Frisco Railroad, and all but Koshkonong are along the Warm Fork-Spring River system. Thayer and Mammoth Spring are "twin cities", being only one mile apart.

Beef and dairy cattle, pigs, poultry and eggs, and lumbering are the most important sources of income to the area. Income from tourism is significant but is not as important as the other sources. Most of the land is not suited for cultivation because of the rugged terrain and the cherty soil, and crops are mostly limited to forage and grain for the winter feeding of livestock.

H. Transportation

U. S. Highway 63 runs in a general north-south direction across the area, and in addition several well-paved state highways serve the area. Coverage by farm-to-market roads, which are usually passable to ordinary vehicles, is good; although one who is unfamiliar with the roads may experience some difficulty since most of the backroads are winding and unmarked. It should be noted that the Thayer quadrangle, which was used as a base for the geologic map, is out of date for the location of highways, roads, and buildings.

The Frisco Railroad closely parallels U. S. Highway 63, and connects the area with Kansas City, Missouri; Springfield, Missouri; and Memphis, Tennessee.

An electrically lighted, sod airstrip suitable for landing of small aircraft is located about a mile west of Thayer.

III. STRATIGRAPHY

A. Introduction

The sedimentary rocks in this area, both surface and subsurface, are primarily dolomite, with lesser amounts of chert and sandstone. The deepest well in the Thayer area, the Thayer Municipal Well no. 4, bottoms in the Potosi Formation. The stratigraphic data for older formations were taken from deep wells at West Plains, Missouri and Pomona, Missouri, which are respectively about 20 miles and 30 miles northwest of Thayer. Although these wells are not in the area of study, they should give some indication of the subsurface geology of the older formations underlying the thesis area.

Only a few samples were saved from the deepest well at West Plains (West Plains Municipal Well no. 4, Mo. Geol. Surv. #3014), thus this well provides little information except the approximate depth to the Precambrian basement rock and the lithology of the basement rock. The well indicates the thickness of sedimentary rocks to be between 2,437 and 2,665 feet (see p. 21).

The well at Pomona (Pomona Oil and Gas, Mo. Geol. Surv. #3011) was used for description of the deepest subsurface units, because it is the only completely logged well close to the area which penetrates the entire sequence of sedimentary rocks. In this well 2,500 feet of sediments were penetrated before reaching

Precambrian basement rock.

The formations cropping out in this area are the Roubidoux, the Jefferson City, and the Cotter; all are of Lower Ordovician age. The predominant rock type is dolomite, but chert and sandstone are common.

The formational boundaries used in this thesis are those recognized by the Missouri Geological Survey (Koenig, 1961).

B. Precambrian Rocks (Subsurface Data)

A deep well at West Plains (West Plains Municipal Well no. 4, Mo. Geol. Surv. #3014) penetrated gray and red granite from 2,665 to 2,675 feet below the surface. The driller reported granite at 2,437 feet, but no sample was taken at this depth.

The deep well at Pomona (Pomona Oil and Gas, Mo. Geol. Surv. #3011) penetrated 1,315 feet of white granite which is low in orthoclase feldspar between 2,500 feet and 3,815 feet below the surface.

C. Cambrian System

1. Introduction

No Cambrian strata are exposed in the Thayer area or the surrounding region, and only a few water wells reach the Cambrian rocks. Good samples from the Eminence and

Potosi formations are available from deep wells at Thayer, Koshkonong, and West Plains. The Pomona Oil and Gas well at Pomona gives some data on formations lower than the Potosi, but provides little information other than the approximate thicknesses of the formations.

2. Lamotte Formation

The Pomona Oil and Gas well penetrated 285 feet of sandstone assigned to the Lamotte Formation. This sandstone overlies the Precambrian granitic basement rock.

3. Bonneterre Formation

The Bonneterre Formation overlies the sandstone beds of the Lamotte Formation. At Pomona the Bonneterre is approximately 295 feet thick.

4. Davis Formation

Neither the upper nor lower contact of the Davis Formation is definite, but the formation is approximately 220 feet thick in the Pomona area.

5. Derby-Doerun Formation

The Pomona well indicates a thickness of 185 feet for the Derby-Doerun Formation, but this is an approximate figure because of the indefinite upper and lower contacts.

6. Potosi Formation

The Thayer Municipal Well no. 4 penetrated the upper 150 feet of the Potosi Formation. As in other areas the formation can be recognized by the abundant quartz druse and crystals. Dolomoldic chert* is also very abundant in the Thayer well; and in the West Plains Municipal Well no. 7, dolomoldic quartzose chert is common.

The Potosi dolomite taken from the Thayer well is mostly medium crystalline**, although some finely crystalline dolomite is present. The dolomite colors are predominantly light grayish brown and light brownish gray, with lesser amounts of grayish brown and dark grayish brown.

7. Eminence Formation

The thickness of the Eminence formation given by the log of the Thayer Municipal Well no. 4 is 450 feet, and the thickness given by the log of the Shroeder Mining Company well (Mo. Geol. Surv. #18952) at Koshkonong is 390 feet. The difference in thickness is probably in part the result of different interpretations of the contacts; there is also evidence that the Thayer well was drilled on a fault or fault zone, so the thickness indicated

*The insoluble residue classification of Grofskopf and McCracken (1949) and McCracken (1956, unpublished chart) is used in this report to describe cherts and other insoluble residues.

**The grain-size scale for dolomites in this report is that of Folk (1962, p. 74, table 2).

by this well is questionable.

Quartzose chert is the most characteristic insoluble residue of the formation, and oolitic chert is present in several parts of the section. In the upper 100 feet of the formation, smooth opaque cherts, sandy cherts, and sand grains are present, along with the quartzose and oolitic cherts.

The grain size of the dolomite ranges from finely crystalline to coarsely crystalline; the colors of the dolomite are predominately light grayish brown and light brownish gray.

D. Ordovician System

1. Gasconade Formation (subsurface data)

The Gasconade Formation is readily divisible in the subsurface into two distinct parts: the Upper Gasconade and the Lower Gasconade. The Gunter Member lies at the base of the Lower Gasconade and is included with it in this discussion.

The Upper Gasconade, which is approximately 95 feet thick at Thayer, is distinguished by its low content of insoluble residue, which averages less than 10 percent. Quartzose chert is the characteristic residue, although many other types of chert occur in smaller amounts. Dolomite is the predominant constituent of this part of the formation. Most of the dolomite is fine or medium crystalline, and the color is usually either light grayish brown or light brownish gray.

The Lower Gasconade is distinguished from the Upper Gasconade by its much higher content of insoluble residue, which averages over 20 percent. At Thayer the Lower Gasconade is approximately 405 feet thick, including the Gunter Member. Translucent cherts make up the bulk of the residue in the upper half of the Lower Gasconade; quartzose and oolitic cherts are also present in smaller amounts. The residue of the lower half of the Lower Gasconade (exclusive of the Gunter Member) consists mainly of quartzose and dolomoldic cherts, with lesser amounts of smooth opaque, translucent, and oolitic cherts. Quartz druse is scattered throughout the Lower Gasconade beds. The dolomite is predominantly light grayish brown or light brownish gray; most is finely crystalline except the lower 100 feet (including the Gunter Member), in which the dolomites are predominantly medium to coarsely crystalline.

The Gunter Member of the Lower Gasconade consists primarily of light grayish brown, medium to coarsely crystalline dolomite in the Thayer-Koshkonong area. The 5 to 15 percent of insoluble residue present is nearly all rounded or rounded and frosted quartz sand, but small amounts of translucent, quartzose, sandy, and oolitic chert are also found. The Gunter is about 50 feet thick in the Thayer-Koshkonong area.

The total thickness of the Gasconade Formation in the Thayer Municipal Well no. 4 is 500 feet, and in the Shroeder Mining Co. well at Koshkonong the total thickness is 550 feet. This difference may be partly accounted for by a difference in interpretation of the contact between the Gasconade and Eminence formations, since this contact is not clearly defined in the Thayer well; or faulting in the Thayer well may be partly responsible for the difference in thickness.

2. Roubidoux Formation

a. Introduction

The Roubidoux Formation is the oldest of the formations exposed in this area. Outcrop areas are small and only the upper part of the formations well exposed, and as a result a thorough field study of the formation was not possible. Most of the data given in this section were obtained from a study of water well logs and samples, supplemented by field data.

b. Nomenclatural History

Early workers in the state referred to the present Roubidoux Formation as the Second Sandstone. The name Roubidoux was introduced by Nason in 1892, who suggested that "the name Roubidoux sandstone be applied to the rock above described as over-spreading the Ozark region from Cabool to Gasconade City and from Salem to Doniphan" (Nason, 1892, p. 114-115). His extension of the "Roubidoux sandstone" to "...include the areas of so-called First sandstone /present St. Peter Sandstone/ as well", however, was in error.

c. Distribution and Outcrops

Within the area of the geologic map the Roubidoux Formation crops out only where exposed by faulting. The largest area of outcrop is in the northwest corner of the geologic map, and from here northward the formation is exposed along Warm Fork and its tributaries for several miles. Southward within the geologic map area the formation is intermittently exposed along a fault zone which extends from Sec. 1, T. 22 N., R. 6 W. to Sec. 30, T. 22 N., R. 5 W. The southernmost known outcrop of the formation is in the town of Thayer, Missouri, along Highway 19-142 W.

The best exposure of the Roubidoux Formation is at Warm Fork Spring (NE¼, SE¼, NE¼, Sec. 25, T. 23 N., R. 6 W.), where 81 feet of the formation crop out. This section was measured and described (see fig. 1 and plate 12). Outcrops of the formation extending northward along Warm Fork from Warm Fork Spring may be recognized by the massive sandstone and chert.

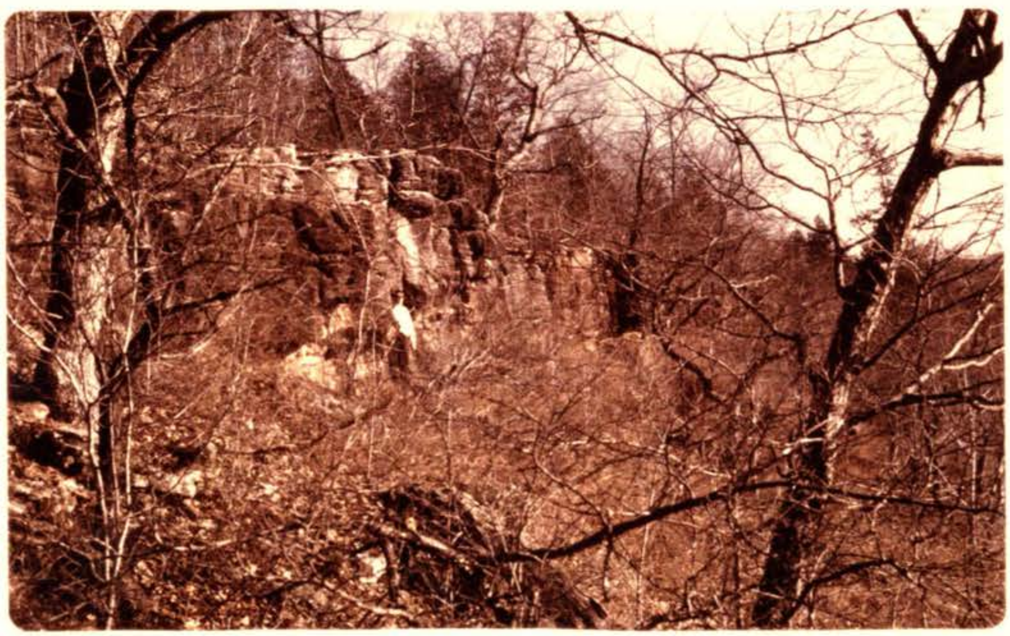

Fig. 1. Massive upper sandstone unit of the Roubidoux Formation at Warm Fork Spring (NE¼, SE¼, NE¼, Sec. 25, T. 23 N., R. 6 W.) Sandstone ledge is 10 feet thick. Note the abundance of shortleaf pine, which is a close associate of the Roubidoux Formation throughout Missouri.

At the point where Millstone Hollow enters Warm Fork (SW¼, SW¼, Sec. 30, T. 23 N., R. 5 W.) the massive upper sandstone beds of the Roubidoux crop out. The sandstone is overlain by a thick smooth (porcelainous) chert, which marks the top of the formation. The top of the Roubidoux is faulted relatively upward against the lower 30 to 40 feet of the Cotter Formation.

An interesting exposure of the massive Roubidoux sandstone crops out in the SW¼, NW¼, SW¼, Sec. 6, T. 22 N., R. 5 W. On the north slope of a ridge, about 25 feet above the valley floor, a large mass of sandstone protrudes from the surface. The beds are vertical and strike N. 35° E. The sandstone is medium to thick bedded*, medium to coarse**, and cross-bedded; the outcrop measures about 30 feet in true thickness and about 50 feet in length. Up the valley to the west much sandstone and massive chert can be traced for about 700 yards. The Roubidoux has been faulted upward against nearly 150 feet of Cotter strata, and the estimated vertical displacement is about 350 feet.

Massive Roubidoux sandstone and thick quartzose chert crop out in a small stream in the NW¼, SW¼, Sec. 13, T. 22 N., R. 6 W. The sandstone is about five feet thick and the chert is about

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*The classification of bedding thickness used in this report is that of Ingram (1954, p. 937-938).

**For sandstones the scale of Wentworth (1922, p. 384, table 2) is used in this report to classify the sand size.

three feet thick. A fault terminates the outcrop area on the east, and the massive sandstone forms a low fault-line scarp along which several small springs issue. This fault brings the Roubidoux in contact with upper Jefferson City beds.

Roubidoux sandstones and cherts crop out in and along Twomile Creek in Sections 13 and 24, T. 22 N., R. 6 W., and Sec. 18, T. 22 N., R. 5 W. Sandstone crops out in the creek bed, and is the main constituent of the residuum along the valley slopes to an altitude of about 670 feet. The Roubidoux is faulted against upper Jefferson City beds.

Along Twomile Creek, in Sec. 19, T. 22 N., R. 5 W., is much residual sandstone overlain by thick porcelainous chert. The chert, which occurs at an altitude of about 610 feet, is used to mark the top of the Roubidoux Formation. This altitude is in agreement with the log of a water well located about 300 feet west of the outcrop, which indicates that the top of the Roubidoux Formation is at an altitude of 606 feet. Faulting has thrown Roubidoux strata against lower Cotter strata.

Near the center of Sec. 30, T. 22 N., R. 5 W., Roubidoux sandstone, sandy translucent chert, and medium-crystalline brown sandy dolomite crop out in the stream bed of Twomile Creek. Much sandstone and chert occur on the slopes of the valley, and a 132-foot well in the outcrop area was logged as entirely in

Roubidoux strata. Apparently this outcrop is a result of the same fault block as the outcrop mentioned in the preceding paragraph.

The southernmost known Roubidoux outcrop in this area is in the south-central part of Sec. 30, T. 22 N., R. 5 W. This outcrop is apparently a result of the same fault block as the outcrops mentioned in the two preceding paragraphs. Massive sandstone (medium to coarse) and sandy chert crop out along a small tributary to Twomile Creek, and the slope on either side of the valley floor is strewn with much residual sandstone and smooth porcelainous chert. The exposed beds of sandstone are strongly folded and brecciated, and several small springs occur in the area. A bed of smooth porcelainous white chert one to three feet thick marks the top of the Roubidoux Formation.

d. Thickness

The maximum exposed thickness of the Roubidoux Formation in the area is 81 feet at Warm Fork Spring (see plate 12). The complete thickness is exposed only by water wells.

At Thayer the thickness of the formation is given by three municipal water wells:

Well no. 2 (Mo. Geol. Surv. #5380)------------245 feet

Well no. 3 (Mo. Geol. Surv. #9221)------------235 feet

Well no. 4 (Mo. Geol. Surv. #25070)-----------240 feet

Of these wells no. 3 is the most reliable, because this log has the best contacts, and because wells no. 2 and 4 are in fault zones and may not indicate the true thickness. In the Thayer area, therefore, the thickness is approximately 240 feet.

Three water wells in Koshkonong penetrate the Roubidoux Formation, and the thicknesses indicated by the logs are shown below:

Shroeder Mining Co. (Mo. Geol. Surv. #18952)-----155 feet

Cudahy Packing Co. (Mo. Geol. Surv. #9673)-------140 feet

City of Koshkonong (Mo. Geol. Surv. #18735)------165 feet

In the City of Koshkonong well some of the samples from the Roubidoux Formation were mixed with some of the samples from the Gasconade Formation; thus this well cannot be considered stratigraphically reliable. The Cudahy Packing Company well log and the Shroeder Mining Company well log indicate very similar stratigraphy, but the contact between the Jefferson City and Roubidoux formations has been interpreted differently on the two logs. The interpretation of the Shroeder Mining Company well log is the most consistent with other subsurface data, so the thickness of the formation in the Koshkonong area is probably about 155 feet.

From the preceding subsurface data it appears that in this area the Roubidoux Formation becomes thinner toward the northwest. Regionally, the isopachous map of the formation (McCracken and

McCracken, 1965) shows that the thickness is rather erratic in the south-central part of Missouri, ranging from 155 feet at Koshkonong to nearly 300 feet about 15 miles to the west of Koshkonong.

No information on the thickness of the Roubidoux Formation is available south of Thayer within the area of this report.

e. Lithology

The Roubidoux Formation consists mainly of dolomite, chert, and sandstone. The greater resistance of the sandstone and chert relative to the lesser resistance of the dolomite results in the preservation of the sandstone and chert as ledges, whereas the dolomite often forms covered slopes; for this reason the field worker may minimize the abundance of dolomite in the formation. The log of the Thayer Municipal Well no. 3 shows the formation to contain an overall average of 73 percent dolomite, as compared with an overall average of only 14 percent and 13 percent, respectively, of chert and sandstone. The percentages of chert and sandstone are somewhat higher in the upper part of the formation; but even in this part, dolomite comprises over one-half of the section. The 81-foot section of upper Roubidoux strata at Warm Fork Spring contains an overall average of 59 percent dolomite, 17 percent chert, and 24 percent sandstone; and for comparison, the upper 80 feet of Roubidoux strata in the Thayer Municipal Well no. 3 contains an overall average of

57 percent dolomite, 26 percent chert, and 17 percent sandstone.

Although sandstone is not as abundant as dolomite in the Roubidoux Formation, sandstone is much more prominent in this formation than it is in the Jefferson City or Cotter formations. The comparatively high percentage of sand in the Roubidoux Formation, in fact, serves to distinguish it from all other Lower Ordovician formations in the Ozark region.

Dolomites

The dolomites of the Roubidoux Formation are generally compact, crystalline, and relatively pure, in contrast to the abundance of argillaceous and siliceous "cotton rock" in the Jefferson City and Cotter formations. The size of individual dolomite grains ranges from very finely crystalline to medium crystalline; the predominant grain size is near the borderline between finely crystalline and medium crystalline. The dolomite beds at the Warm Fork Spring section range from thin bedded to thick bedded; medium bedding and thick bedding are the most common. The colors of the Roubidoux dolomites are generally various light shades of brown, including light brown, light reddish brown, light yellowish brown, and light grayish brown.

Associated with the dolomites are nodular, bedded-nodular, and bedded chert; of these, bedded chert is the most common. The long axes of the nodules are aligned parallel to the bedding.

Occasionally chert is a matrix between individual euhedral dolomite grains and forms a siliceous dolomite. Floating quartz sand grains are also found occasionally in the dolomite.

Sandstones

At the Warm Fork Spring section the sand in most of the sandstone beds is fine, which is a characteristic prevailing in the Jefferson City and Cotter sands as well. However, the 10-foot thick sandstone unit near the top of the Roubidoux Formation consists mostly of medium to coarse sand, which is easily distinguished from the fine Jefferson City and Cotter sands. The sandstones are medium to very thick bedded at the top of the formation at Warm Fork Spring (fig. 1); the lower sandstones in the section are thin to medium bedded. The color of the Roubidoux sandstones on a freshly broken surface ranges from white to light gray in the highly silicified beds to light grayish or reddish brown in the porous beds. Colors are about the same, but much darker, on the exposed surfaces of the various sandstone beds.

The process of silicification appears to be a gradational process in the sandstone, with all stages of silicification represented. Some of the sandstones are quite porous and rather loosely cemented, with many of the rounded and frosted quartz sand grains still preserved; but in the same specimen many of the grains have undergone secondary enlargement. Other sandstones have been thoroughly cemented with clear silica, and many of the sand grains have undergone secondary enlargement; but still some of the rounded and frosted sand grains break free from the cement and have well-preserved surfaces. Still other sandstones have undergone silicification and recrystallization to such a degree that no pore space remains, and none of the original sand grains can be recognized.

Some of the sandstones grade into sandy cherts, which occur both as nodules and beds. Whether these sandy cherts are of primary origin and represent a gradual change in deposition from sand to silica, or whether they are a result of partial secondary replacement of original sandstone by chert, cannot be resolved here. The same question could be applied to the process of silicification discussed in the preceding paragraph: is the silica cement of primary or secondary origin? The evidence available is not sufficient to reach a conclusion.

Cherts

The Roubidoux cherts in this area, for the most part, are lithologically similar to those of the Jefferson City and Cotter. Smooth opaque and translucent cherts--mostly light shades of gray and brown--are abundant, as are dull tripolitic cherts, which are often dolomoldic. Oolitic cherts are found, but they are not characteristic of the formation in this area.

Well logs for the area indicate that the distinguishing feature of much of the Roubidoux chert is the presence of floating sand grains in the chert. However, most of the cherts referred to as "sandy cherts" by subsurface geologists are probably the same rock type as the "silicified sandstones" discussed in the preceding section. At the Warm Fork Spring section much silicified sandstone occurs, but on the other hand, most of the smooth and translucent varieties of chert contain little or no floating sand.

f. Marker Horizons and Insoluble Residue Zones

The Roubidoux Formation in this area can be divided into three zones in the subsurface, based on the percentage of insoluble residue. The upper zone, which is about 50 to 85 feet thick, is the high-residue zone, containing on the average from 40 to 50 percent of insoluble residue. A much thinner middle zone contains only about 5 to 10 percent of insoluble residue; this zone is about 25 to 30 feet thick. The lower 125 feet of the formation is somewhat variable in residue content but averages about 20 to 25 percent. In each zone the amount of sandstone is usually slightly exceeded by the amount of chert. These insoluble residue zones do not correspond to the insoluble residue zones of McCracken (1952, p. 61-64, and undated, unpublished chart).

The base of the formation is marked in the subsurface by an abrupt drop in the insoluble residue percentage from the Roubidoux Formation to the underlying Gasconade Formation, along with a great reduction in the amount of sand. A similar drop in the percent of insoluble residue and quantity of sand from the Roubidoux Formation to the overlying Jefferson City Formation marks the top of the Roubidoux Formation. The upper 5 to 15 feet of the Roubidoux are represented in the subsurface by chert and dolomite, below which is a large amount of sandstone. However, the drop in chert from the Roubidoux to the Jefferson City is often more gradational than abrupt, and as a result the contact is not always easy to determine accurately. The "Quarry Ledge", which is 40 feet above the top of the Roubidoux, is more reliable for a structural datum (see p. 61).

The insoluble residue percentages plotted on well logs are observable in the field, and have been used for mapping the contact between the Jefferson City and the Roubidoux formations. The high percentage of chert which marks the top of the Roubidoux Formation in the subsurface is usually seen in the field as very large residual blocks of chert three to five feet thick; this chert is underlain by much sandstone, and is overlain by an interval of residuum in which the quantity and size of the residual chert blocks and nodules is relatively small. In field mapping the contact is placed at the top of the thick chert bed.

The smooth chert which marks the top of the Roubidoux Formation in this area weathers to a creamy yellowish white, somewhat mottled, porcelainous appearance, and it forms a rather distinctive marker when its identity can be confirmed by the relationships discussed in the preceding paragraph. Locally the unit may be a chert-cemented breccia, and because of the extensive faulting in this area, care must be taken not to confuse this chert with the somewhat similar cherts which mark the top of the Jefferson City Formation.

g. Paleontology

No fossils were found from the Roubidoux Formation in this area. A detailed study of the Roubidoux fauna was published by Heller (1954), and the following information on the fauna is taken from his descriptions.

The Roubidoux Formation is sparingly fossiliferous, but well-preserved specimens may be found locally in the cherts. The fauna is predominantly molluscan and is best developed in southern Missouri. Heller recognizes two, and some places three faunal zones. Brachiopods, gastropods, cephalopods, and trilobites have been found in the formation. The gastropod genus Lecanospira is the most widely distributed and the most characteristic of the elements of the Roubidoux fauna.

h. Topographic Expression

The lithology of the Roubidoux Formation is not sufficiently different from that of the Jefferson City and Cotter formations to produce a topography distinct enough to be recognized on the 1:62500 scale topographic map.

On a smaller scale the different beds within the formation have an influence on the topography. At Warm Fork Spring (the only well-exposed section of the formation) the 10-foot sandstone bed forms a high, sharp ledge, while the relatively thinner sandstone and chert beds form lower ledges. The dolomites form either covered slopes or subdued ledges, according to their resistance to weathering.

i. Type Area Section Comparison

At the type area section (Heller, 1954, p. 57-60), the thickness of the Roubidoux Formation is only 150 feet, as compared to 240 feet in the Thayer area and 155 feet in the Koshkonong area.

As in the Thayer area, the formation at the type area can be divided into three zones, based on the percentage of insoluble residue. The upper 60 feet is high in insoluble residue, which averages roughly 50 percent; the middle 25 feet is low in insoluble residue, which averages less than 10 percent; and the lower 65 feet averages roughly 50 percent insoluble residue (somewhat higher than the lowest insoluble residue zone of the Thayer area).

The overall percentage of sand at the type area is slightly greater than in the Thayer area. The largest amount of sand in the type area section occurs about 100 feet below the top of the formation, rather than near the top of the formation as at Warm Fork Spring; another large quantity of sand occurs near the base of the formation, which is in contrast to the fairly small amount of sand in the lower Roubidoux strata of the Thayer area.

j. Regional Correlations

The Roubidoux Formation has been correlated by Bridge (1930, p. 124) with the Longview Limestone of Alabama; with the Nittany Limestone of Pennsylvania and Tennessee; with the lower part of Division C of the Beekmantown of New York; and with beds in Scotland and Scandonavia; on the basis of the characteristic Lecanospira fauna. Dake (1921, plate 1) correlated the formation with the New Richmond Formation of Iowa, Minnesota, Wisconsin, and Illinois. Ulrich and Cooper (1938, per Mueller, 1951, p. 67) correlated the Middle Canadian of the Arbuckle and Wichita Mountains of Oklahoma with the Roubidoux Formation. Cloud and Barnes (1957, p. 169) correlated the Roubidoux Formation with the Gorman Formation of the Ellenburger Group of central Texas.

The Geological Society of America has published a correlation chart for the Ordovician formations of North America (Twenhofel et al., 1954), in which the correlation of the Roubidoux Formation with other formations of North America is shown.

k. Stratigraphic Relations

Heller (1954) found little field evidence for the existence of an unconformity between the Roubidoux Formation and the underlying Gasconade Formation. He did, however, find evidence for a change in conditions of sedimentation from the Gasconade Formation to the Roubidoux Formation:

> "A gradual change in conditions of sedimentation is indicated...by the appearance of abundant sand grains in the dolomites of the lower part of the Roubidoux and in the development of massive sandstone beds higher in the formation. Sedimentary structures indicative of shallow seas (ripple marks and stromatolites) and subaerial exposure (fillings of dessication cracks), common in Roubidoux strata and relatively rare or absent in Gasconade strata, furnish additional evidence of a change in environmental conditions. The faunal change also indicates a change in conditions if not an interruption of sedimentation." (Heller, 1954, p. 22)

Similar conditions were noted by Heller between the Roubidoux and Jefferson City Formations:

> "The Roubidoux-Rich Fountain [Jefferson City] contact appears to be one of conformity, although slight changes in lithology, and a marked change in the fauna of the overlying Rich Fountain formation indicate an interruption in sedimentation." (ibid.)

McCracken (1952, p. 60-61) has found subsurface evidence of a major break at the base of the Roubidoux Formation:

> "Beneath the Roubidoux, the Upper Gasconade is entirely removed and the Roubidoux rests on Lower Gasconade in parts of western Missouri. In southeastern Nebraska and in places in southeastern Kansas there is strong evidence that the Gasconade is entirely removed and the Roubidoux lies on Van Buren [Lower Gasconade of current usage]. Farther west

> in Kansas studies indicate that residues with Roubidoux characteristics rest on residues with Eminence characteristics."

In the Thayer area no indications of either conformity or unconformity can be found; the Gasconade-Roubidoux contact is far below the surface, and the basal Jefferson City strata are covered.

3. Jefferson City Formation

a. Introduction

One of the main objectives of this research was to study and map the contact between the Cotter and Jefferson City formations, so the name Jefferson City Formation is used here in the restricted sense; it is applied to the same stratigraphic sequence to which that name is applied in the subsurface work of the Missouri Geological Survey (McCracken, 1952, p. 62-66, and McCracken, undated, unpublished chart).

The Jefferson City Formation includes all beds above the Roubidoux Formation and below the Cotter Formation. In this area the base of the formation is drawn at the top of the highest thick chert bed of the Roubidoux Formation, and the top of the formation is drawn at the top of the highest thick chert bed which underlies the 28-foot low residue zone at the base of the Cotter Formation.

b. Nomenclatural History

The name Jefferson City was proposed by Winslow (1894, p. 373) to replace the name "Second Magnesian Limestone" of earlier geologists. Winslow designated the type section for the Jefferson City as a series of sections "From the mouth of the Moreau to Gray's Creek, above Jefferson City..." in Cole County, Missouri.

Ulrich (1911, p. 632-633) applied the name "Jefferson City" to include more of the section than Winslow (1894, p. 373) included in his original definition (according to Cullison, 1944, p. 8).

Bassler (1915, plate 2) published a series of charts in which Ulrich revised his work of 1911. In his new classification Ulrich reapplied the name "Jefferson City" to include only the lower part of the section to which he had originally applied that name in 1911, and he established the name "Cotter" to replace the upper part of his "Jefferson City" of 1911.

Cullison (1944, p. 11) raised the name Jefferson City to group status and divided the group into the Rich Fountain and Theodosia formations.

The Jefferson City Formation as currently recognized by the Missouri Geological Survey embraces approximately all of Cullison's Rich Fountain Formation, and in addition it includes the "Rockaway Conglomerate" chert beds which are at the base of Cullison's Theodosia Formation.

c. Distribution and Outcrops

The Jefferson City has a fairly wide distribution throughout the area of the geologic map. It crops out along Warm Fork and its tributaries where erosion has cut into the upper Jefferson City beds. The formation has also been brought to the surface along the zone of block faulting which extends northwestward from Thayer and along the north side of a major fault in the northwest corner of the map.

Although practically the entire thickness of the Jefferson City is represented on the map in several places, it is mostly covered with residuum. The bluffs in the area are not high enough to expose much of the section, and even along the bluffs most of the bedrock is covered.

The best section available is formed by a railroad cut, and a road cut for one of the access spurs to U. S. Highway 63 from Thayer, which passes over the railroad cut (see fig. 2). The two cuts provide a continuous section through the upper 34 feet of the Jefferson City Formation and the lower 28 feet of the Cotter Formation.

d. Thickness

Fig. 2. Lower Cotter and upper Jefferson City strata; lower part of Thayer composite stratigraphic section. Cotter-Jefferson City contact is indicated by arrow on photograph.

Only one well in the Thayer area, the Thayer Municipal Well no. 3, penetrates the entire thickness of the Jefferson City Formation. If the contacts are interpreted in accordance with other well logs in the area, the log indicates a thickness of 170 feet for the formation.

Two wells (Mo. Geol. Surv. #9303 and #12262) which are near known contacts between the Cotter and Jefferson City formations, and which bottom in the Roubidoux Formation, also indicate a thickness of about 170 feet. The thickness was found by subtracting the elevation of the contact between the Jefferson City and Roubidoux formations indicated by the well logs from the elevation of the contact between the Jefferson City and Cotter formations determined in the field.

One other indirect technique was used to determine the thickness of the formation. A water well (Mo. Geol. Surv. #25423) in Sec. 36, T. 22 N., R. 5 W., about 3 miles east of Thayer, passes through a good contact between the Cotter and Jefferson City formations and bottoms near the base of the "Quarry Ledge" (insoluble residue Zone 4--McCracken, 1952, p. 64). This well was carefully correlated with six wells in the Thayer area (Mo. Geol. Surv. nos. 9221, 9303, 25641, 25496, 25578, and 25469) which pass through the "Quarry Ledge" and into the Roubidoux Formation. Five of these wells (in conjunction with the reference well) indicate a thickness of 170 feet for the formation, and one indicates a thickness of 175 feet.

The wells at Koshkonong indicate a thickness of about 190 feet for the formation, and at Ash Flat, Arkansas, a city water well (Mo. Geol. Surv. #23039) indicates a thickness of 170 to 200 feet, depending upon the interpretation of the contacts. (Ash Flat is about 20 miles south of Thayer).

e. Lithology

The Jefferson City Formation is composed largely of dolomite and chert, with small amounts of sand and still smaller amounts of shale. Dolomite makes up roughly 70 to 80 percent of the formation in the Thayer-Koshkonong area, with the remaining 20 to 30 percent consisting mostly of chert.

Dolomites

The dolomites of the Jefferson City Formation are of four general types*:

1) Mosaic dolomite--pure dolomite, very compact, having a vitreous, translucent, crystalline appearance; grains interlock to form a mosaic pattern; may be of any grain size but most often finely crystalline.

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*It is not the intention of the writer to propose a general classification of dolomites; the terms here defined are used only for convenience and brevity in describing the various kinds of Jefferson City (and also Cotter) dolomites which occur in this area.

2) Sucrosic dolomite--pure dolomite, fairly compact, having a sparkling, sugary-textured, translucent appearance when viewed through a binocular microscope; finely crystalline to aphanocrystalline.

3) Siliceous dolomite--voids between euhedral to subhedral dolomite rhombs filled with a soft, white, lusterless chert (dead chert); occurs in all gradations from slightly siliceous dolomite to very siliceous dolomite, and often grades into a dolomitic ("dolomoldic" after solution) chert; dolomite rhombs may be finely crystalline to coarsely crystalline.

4) "Cotton Rock"--argillaceous, silty or siliceous* form of dolomite, having an earthy, opaque appearance; usually a loosely-packed, poorly sorted aggregate of finely crystalline, very finely crystalline, and aphanocrystalline dolomite grains with interspersed silt or clay, or finely disseminated silica.

In the Thayer area cotton rock is the predominant type of dolomite, but the sugary-textured dolomite and the siliceous dolomite are abundant in certain parts of the section. The compact, crystalline dolomite is relatively uncommon in the Jefferson City of this area.

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*The distinction between a siliceous dolomite and siliceous cotton rock is mainly one of appearance. In a siliceous dolomite, the dolomite grains are euhedral to subhedral, and the matrix of chert is distinctly visible; whereas in a siliceous cotton rock, the chert is disseminated throughout an aggregate of poorly sorted, anhedral dolomite grains, and it cannot readily be distinguished from the dolomite.

No information is available about the bedding of the Jefferson City dolomites except for the upper 35 to 40 feet of the formation, because the lower 130 to 135 feet of the formation are not exposed except in water wells. The upper Jefferson City beds, however, are usually thick bedded to massive.

The color of the dolomite is usually either light brownish gray or light grayish brown, although a number of other light shades of gray and brown are also common. Darker gray and brown dolomites are scattered throughout the section, but they are of minor significance.

A study of the dolomite from five wells (Mo. Geol. Surv. nos. 25578, 25496, 25423, 25641, and 25469) in the Thayer areas has indicated that in this area the Jefferson City Formation can be divided into four distinct lithologic zones, according to the predominant type or types of dolomite occurring in each zone. For reference the zones have been designated by consecutive letters of the alphabet, and beginning with "Zone A" at the base of the formation.

Zone A. The lowest zone lies above the Roubidoux Formation and below the Quarry Ledge, and is 40 feet thick. The zone is easily recognized by the abundance of siliceous dolomite, which is usually finely crystalline to medium crystalline. Dark colored, medium crystalline, mosaic dolomite is also common in this zone.

Zone B. The second zone is the well-known Quarry Ledge of outcrop. It consists entirely of finely crystalline sucrosic dolomite which, along with its very low content of insoluble residue, makes it an easily recognized subsurface marker. In this area the Quarry Ledge is 15 to 17 feet thick, and it is 40 feet above the top of the Roubidoux. Because the top of the Roubidoux Formation is often hard to delineate, the Quarry Ledge is a more reliable structural datum.

Zone C. The next higher zone extends upward for about 80 feet from the top of the Quarry Ledge. It consists mainly of cotton rock with a smaller amount of sucrosic dolomite. Other types of dolomite are present in minor amounts. In this zone practically all of the dolomite is finely crystalline.

Zone D. The upper 25 to 35 feet of the formation consists largely of mosaic dolomites and siliceous dolomites, with some interbedded cotton rock. Much of the dolomite is finely crystalline, but medium crystalline and coarsely crystalline dolomites are common. The medium or coarsely crystalline dolomite is ordinarily darker than the finely crystalline dolomite.

Cherts

Chert is a close associate of the dolomite in the Jefferson City Formation. It occurs in the dolomite as beds, as nodules, as scattered or bedded angular fragments, and as a matrix between the dolomite grains. It may change gradationally from a chert into a dolomitic chert and finally into a siliceous dolomite.

The importance of chert and other insoluble residues for stratigraphic work, correlation, and field mapping of the Jefferson City and Cotter formations cannot be overemphasized. Not only does the chert contain nearly all the fossils of the two formations, but the types and percentages of chert occur in zones which can be correlated throughout Missouri and even to other Midwest areas. In this area most of the marker beds and lithologic zones used for mapping the Cotter and Jefferson City formations are chert beds or zones of distinctive chert nodules.

The various types of chert have been classified for insoluble residue study by Groshkopf and McCracken (1949) and McCracken (1956, unpublished chart), and this system is in current use by the Missouri Geological Survey. Since most of the mapping and stratigraphic work for this report has been based on a study of insoluble residue zones, the classification of Grohskopf and McCracken has been adopted for this research, and it is used to describe the cherts of the Cotter and Jefferson City formations.

The most common, and also the most characteristic, group of cherts in the Jefferson City Formation is actually a modification of the same basic type of chert. Dead chert is the basic type, and the modifications of this type are the rough chert, the dolomoldic chert, and the finely porous chert. Dead chert is described as being tripolitic, chalky, soft, and having no luster, and in the Jefferson City of this area it is almost always white. Rough chert in the Jefferson City is usually a rough-textured form of dead chert. A dolomoldic chert is one that originally contained rhombic dolomite grains, which have since been dissolved away to leave rhomb-shaped cavities in the chert. Practically all of the dolomoldic cherts from the Jefferson City of this area are modifications of dead chert, but dolomolds may sometimes occur in other types of chert. Finely porous cherts are dolomoldic cherts in which the dolomolds are too small to be clearly distinguished at a magnification of 12 or 15 diameters.

The dolomoldic cherts seen in laboratory-produced insoluble residues are dolomitic cherts or siliceous dolomites from which the dolomite has been dissolved with hydrochloric acid. Natural dolomoldic cherts are found only in residuum, where the dolomite has been removed from the chert by ground-water solution; these are usually stained by iron oxide. It has been estimated from a study of insoluble residues that this group of cherts accounts for roughly 40 percent of the Jefferson City cherts; but it must be emphasized that much of the dolomoldic chert and finely porous chert which appears in insoluble residues is masked by enclosing dolomite before the dolomite is removed, and this chert is not always easy to detect in the field.

Dead white bedded chert is common in the upper 30 to 40 feet of the formation. The presence of large amounts of this type of chert in outcrop or residuum should serve as a strong hint that the contact between the Jefferson City and the overlying Cotter may be present slightly higher in the section.

The Jefferson City chert most often seen in the field is the smooth chert, which is described as opaque, flinty, dense, and brittle (Grohskopf and McCracken, 1949). Smooth chert may be any color, but in the Jefferson City of this area it is usually a light shade of gray, brown, or white. This type of chert makes up about 25 percent of the Jefferson City cherts; and although it is not as abundant in residue as the various forms of dead chert, it is more obvious in the field.

Another common chert of the Jefferson City is the translucent chert, which differs from the smooth chert in its ability to transmit light, as the name implies. Its colors are the same as those of the smooth cherts. This type makes up about 15 percent of the Jefferson City cherts.

Quartzose chert is occasionally found in the Jefferson City Formation. This chert is described as "vitreous, sparkley, shiny; and under high magnification shows heterogenous composition mixture of pyramids, prisms, and crystal faces of quartz" (ibid.). Various light shades of gray and brown are its usual colors.

Oolitic chert is fairly common in the Jefferson City of this area. This chert is a modification of one of the other types of chert, usually smooth or translucent chert. Many different types of oolites are found, among which are radial oolites, concentric oolites, structureless oolites, and sand-nucleus oolites. Radial or concentric structures, if any, are usually quite indistinct. Oolitic chert makes up roughly 5 percent of the Jefferson City cherts.

Sandy cherts, like the oolitic cherts, are a modification of another chert type; they are described as consisting of "sand grains in chert matrix" (ibid.). Usually the chert matrix is smooth or translucent chert. The term "sandy chert" is often applied in well logging, however, to a rock type which might be more properly called an orthoquartzite or silicified sandstone, a rock in which the sand grains are cemented by a clear quartz matrix rather than by a true chert matrix. About 5 percent of the Jefferson City chert is sandy chert (including orthoquartzite).

Other modifications of the basic chert types in the formation are mottled cherts, which are usually smooth or translucent cherts with heterogenous color differences, and banded cherts, which are usually smooth or translucent cherts that have bands of different colors.

Sandstones

The sandstones of the Jefferson City Formation are very similar to the Roubidoux sandstones; except that in the Jefferson City, they are much less abundant, the sand is generally finer, and the beds are usually thinner than in the Roubidoux. Most of the sandstones are silicified to some degree, and they range from slightly silicified to almost completely silicified or recrystallized. The individual sand grains, if still preserved, are usually well rounded and frosted.

Some sandstones are cemented by dolomite, and gradations from dolomitic sandstone to sandy dolomite are often found.

The color of the highly silicified beds is usually white to light gray on the freshly broken surface; whereas the less silicified beds, being more porous and thus more susceptible to iron staining, are often light reddish brown. The weathered surface is usually gray or reddish gray.

f. Marker Horizons

Field Marker Horizons

The most useful marker for field mapping is the "Rockaway conglomerate" chert beds which Cullison (1944, p. 25) assigned to the lower Theodosia Formation, but which are now assigned to the upper Jefferson City. These beds consist of angular fragments of smooth or translucent chert in a matrix of smooth or dead chert. The fragments range from a fraction of a millimeter to several centimeters in maximum dimension. The beds may consist almost entirely of the angular chert fragments with only a small amount of matrix, or they may consist mainly of dead chert with only scattered angular chert fragments. In this area one type frequently grades laterally into the other type in a very short distance. The thickness of the beds varies greatly, ranging from less than a half foot to over five feet. Similar beds sometimes occur at the top of the Roubidoux Formation, but in this area the upper Jefferson City chert beds can be identified by the presence of the distinctive Cotter oolitic chert (see p. 81), which is 28 feet above the top of the Jefferson City in a complete original or residual stratigraphic section. The southernmost known occurrence of the breccia beds in this area is immediately below the dam in the NE¼, Sec. 20, T. 21 N., R. 5 W. Farther south, the upper Jefferson City cherts are smooth or translucent cherts, which occur as streamers, nodules, and nodular beds.

Throughout the area of this report the upper 15 to 25 feet of the Jefferson City is characterized by the common occurrence of sparry calcite, which fills vugs and fracture openings. This characteristic has been useful in making correlations between

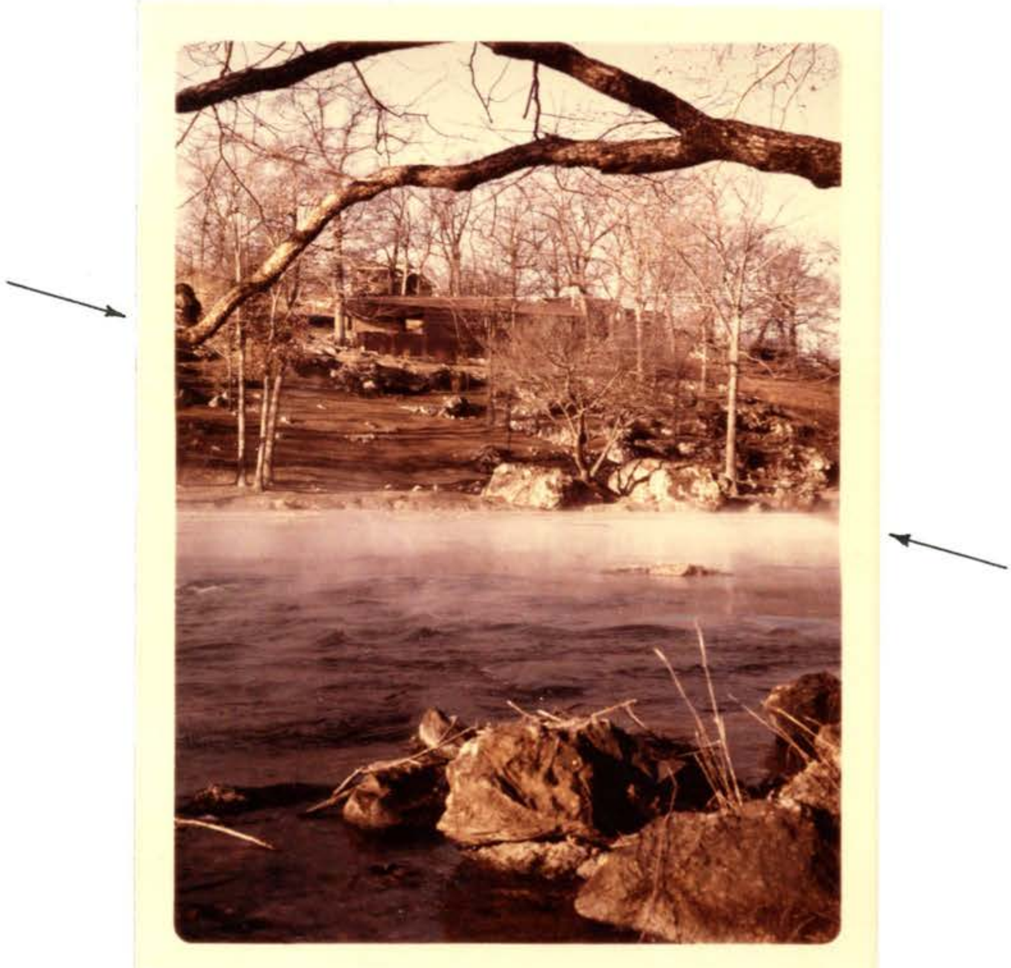

Fig. 3. Massive "Rockaway Conglomerate" chert beds of the upper Jefferson City, looking west across Spring River at Mammoth Spring, Arkansas (NW¼, SE¼, NW¼, Sec. 8, T. 21 N., R. 5 W.) Probable fault trace indicated by arrows in margin.

Fig. 4. "Rockaway Conglomerate" chert along the east side of Mammoth Spring at Mammoth Spring, Arkansas.

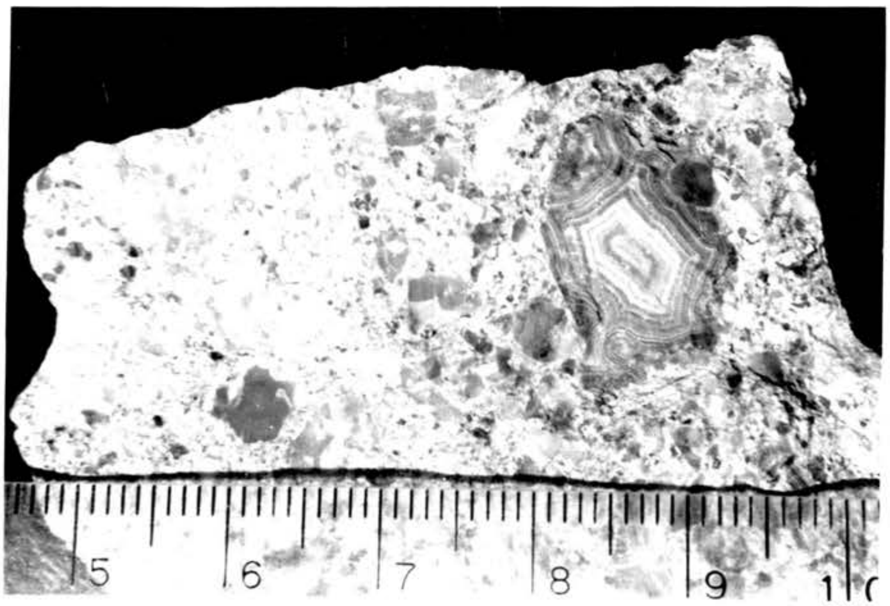

Fig. 5. "Rockaway Conglomerate" chert from a bluff four miles north of Thayer (SE¼, NE¼, SE¼, Sec. 6, T. 22 N., R. 5 W.) Agate-like cavity filling in this chert is common here and at several other localities in the area. Scale is in centimeters.

sections in the Thayer area and sections farther south along Spring River.

Subsurface Marker Horizons

The most valuable marker in the subsurface is the Quarry Ledge. It is distinctive for two reasons: 1) the fifteen foot interval of the Quarry Ledge consists almost entirely of finely crystalline, sucrosic, light grayish brown or light brownish gray dolomite; 2) it contains less than 5 percent insoluble residue. In this area the slight amount of residue consists mostly of finely porous chert with some crystalline quartz. The base of the Quarry Ledge is 40 feet above the base of the Jefferson City, and the top of the Quarry Ledge is about 115 below the top of the Jefferson City.

The high percentage of chert found at the top of the Jefferson City, coupled with the overlying 28-foot low residue zone of the lower Cotter, is useful in marking the contact between these two formations. The upper Jefferson City chert is usually made up of a fairly high proportion of dead, finely porous, or dolomoldic chert.

The four dolomite zones of the Jefferson City, in conjunction with the insoluble residue zones, are also useful in this area for determining the stratigraphic position of a given section.

g. Insoluble Residue Zones

The Jefferson City Formation has been divided by McCracken into five zones on the basis of percentage and type of insoluble residue (McCracken, 1952, p. 64-66, and McCracken, undated, unpublished chart). The Jefferson City zones are part of his twelve "residue zones of the Canadian" (Lower Ordovician), which begin at the base of the Roubidoux and continue to the top of the Cotter. Zones 1 and 2 are in the Roubidoux Formation, and Zone 3 starts at the base of the Jefferson City. The Jefferson City section in the Thayer area has been correlated with McCracken's zones.

Zone 3: This zone is easy to recognize in the Thayer area, since by definition it lies below the Quarry Ledge and above the Roubidoux Formation. The zone is 40 feet thick in this area. It contains as a residue an abundance of dolomoldic chert, which is especially characteristic of this zone; in several parts of the zone this type of chert makes up 50 to 80 percent of the residue. Smooth and translucent chert are also abundant but are not diagnostic, and quartzose chert is locally abundant. Zone 3 includes the same part of the formation as dolomite Zone A, which consists mainly of siliceous, finely crystalline to medium crystalline dolomite.

Zone 4: This 15 foot zone is the "Quarry Ledge" which is so well known in its areas of outcrop, and it is also identical to the dolomite Zone B already discussed. The zone is very low in insoluble residue, which usually averages less than 5 percent. The residue of the zone in this area consists mainly of a very finely porous white chert and a small amount of crystalline quartz.

Zone 5: The lower boundary of this zone in the Thayer area is easily correlated with the lower boundary of McCracken's Zone 5, since this boundary is also the upper boundary of the Quarry Ledge. Zone 5 of this area is tentatively defined as the 35 feet of section above Zone 4 which has a higher percentage of residue (10 to 50 percent) than Zone 4, and which is overlain by a 10-foot section of low residue. Finely porous chert is abundant, and it is especially characteristic of the lower 15 to 20 feet of the zone, in which it may constitute as much as 75 to 80 percent of the residue. The finely porous chert is derived from the very finely crystalline siliceous cotton rock, which makes up most of the dolomite in this part of the section. The abundance in this zone of finely porous chert derived from the very finely crystalline cotton rock is an interesting comparison to the abundance of dolomoldic chert derived from the medium crystalline siliceous dolomites of Zone 3. The upper 10 to 20 feet of Zone 5 usually has a considerable amount of translucent oolitic chert. Smooth and translucent chert are abundant, and other types of residues are present; but only the finely porous chert and translucent oolitic chert are diagnostic. Both of these cherts continue upward into higher zones; the upper boundary of this zone is drawn on the basis of a sharp decrease in residue for the 10-foot interval above Zone 5.

Zone 6: This 10-foot zone is tentatively correlated with McCracken's Zone 6 on the basis of its low residue content. It separates the high-residue Zone 7 from the high-residue Zone 5. This zone is not characterized by any particular type of the residue.

Zone 7: This 70-foot zone usually has a higher percentage of insoluble residue than any of the other residue zones in the formation; a given sample may contain as much as 65 to 70 percent of residue. The lower boundary of this zone is tentatively correlated with the lower boundary of McCracken's Zone 7, but it is not definite because the correlation of the underlying Zone 6 is not definite. The upper boundary is well defined, however, by a sharp break between this zone and the 28-foot low-residue Zone 8 of the basal Cotter. Smooth and translucent cherts are predominant throughout most of the zone, but in the upper 15 to 20 feet of the zone the predominant residue is dead, finely porous, and dolomoldic chert. The upper part of this zone also includes the "Rockaway conglomerate" chert beds, but the conglomeratic or brecciated texture is not recognizable in drill cuttings. The brown oolitic chert and the large free brown oolites used to mark the top of the Jefferson City over much of Missouri and other Mid-continent areas (ibid.) are not present in this area.

h. Paleontology

Cullison (1944, p. 23) described and zoned the fauna of the Rich Fountain (which includes most of the Jefferson City) of Missouri in considerable detail. Most of his work in southern Missouri was done in Ozark and Taney counties, about 50 to 75 miles west of the Thayer area. According to him, trilobites are the dominant fauna of the formation. He found a zone of trilobites, cephalopods, and gastropods extending upward from the top of the Quarry Ledge for a distance of 40 feet. Another zone characterized by the sponge Ozarkocoelia was found by Cullison immediately below the 40-foot zone, and within the upper beds of the Quarry Ledge. He found no faunal zones, however, in the upper part of the Rich Fountain.

In the Thayer area the only Jefferson City fossils found have been in the "Rockaway conglomerate" beds. Here a few straight and coiled cephalopods, and a few small low-spired gastropods, can often be found; but none of these has been identified.

i. Local Correlations

The top of the Jefferson City can be most reliably correlated in this area by the high percentage of chert overlain by the 28-foot low chert zone of the basal Cotter, and the oolitic chert immediately above this zone. These relationships will be discussed in more detail in the section on Cotter marker horizons.

The "Rockaway conglomerate" or breccia is easily correlated on the basis of its lithology where it is thick and well-developed and where its identity can be confirmed by other relationships. Care should be exercised, however, to avoid confusion of these beds with certain very similar beds of the upper Roubidoux.

Correlation of the base of the formation in the field has already been described in the discussion of the Roubidoux Formation.

Subsurface correlations can be easily made by use of the insoluble residue zones and dolomite zones of the formation.

Outcrop sections southward along Spring River beyond the area of established marker beds were correlated, along with the Cotter Formation, by insoluble residue techniques. (See section on local correlations for the Cotter Formation for a description of this method.)

j. Topographic Expression

The Jefferson City strata crop out mostly in stream valleys in the Thayer area, so there is little opportunity to study all of the topographic features which could be developed on the formation if it cropped out more extensively. Bluffs formed in the Jefferson City strata along Warm Fork are fairly gentle, and the rock beds usually are mostly covered. The lack of steepness of the bluffs, however, is probably more the result of the lack of vigorous erosive action by Warm Fork, than it is the result of the weathering characteristics of the Jefferson City strata; because to the south some very steep, high bluffs form along the actively eroding Spring River in similar rocks.

In places where the Jefferson City strata have been brought to a topographically high position by faulting, the formation appears to have a topographic expression identical to that of the Cotter. (See the discussion on p. 96 on the topographic expression of the Cotter Formation.)

k. Type Section Comparison

The comparison between the type section of the Jefferson City Formation and the section of Jefferson City in the Thayer area has been based on a restudy by Rapp (1956, p. 9-18) of Winslow's original type section. Exact correlation with the type section is difficult, because an accurate record of the insoluble residue percentage for each unit is not available. A rough estimate of the insoluble residue percentages has been made from Rapp's descriptions, however, and this, in conjunction with his lithologic descriptions, has made an approximate correlation with McCracken's (1952, p. 62, and undated, unpublished chart) idealized sections possible. Approximate correlations with the Thayer section were thus indirectly made.

Cullison (1944) also measured a section along Moreau Creek in Cole County, but it apparently is not the same outcrop section that Rapp studied. Correlations of the type section and the Thayer section with Cullison's section, however, appear to confirm the correlation of the Thayer section with the type section based upon Cullison's identification of his section as Rich Fountain.

The type section as described by Rapp apparently begins in the Quarry Ledge, continues upward through about 140 feet of Jefferson City strata, and includes about 20 feet of Cotter strata at the top. The interval between the Quarry Ledge and the top of the Roubidoux apparently does not crop out in the type section.

The following similarities between the type section and the Thayer section can be seen:

1. Both sections consist of interbedded crystalline dolomite, siliceous dolomite, and cotton rock.
2. Practically all of the dolomite above the Quarry Ledge is fine-grained in both sections.
3. The two sections are both characterized by an abundance of dead white chert, which is often dolomoldic or finely porous.
4. Both sections can be divided into insoluble residue zones, which are approximately correlative with McCracken's (ibid.) idealized insoluble residue charts.

1. Regional Correlations

Some references state that Bridge (1930, p. 129) correlated the Jefferson City Formation with the Shakopee Dolomite of Wisconsin, the Newala Limestone of Alabama, and the upper part of Division C of the New York Beekmantown. Bridge, however, did not state specifically whether the correlation was with the Jefferson City, the Cotter, or both. Cullison (1944, p. 23) believed that Bridge was using fauna of the upper part of the Theodosia for his regional correlations.

Cullison (1944, p. 23) found Rich Fountain fauna in the lower part of the post Nittany division of the Knox Dolomite of the Appalachian Valley.

Cloud and Barnes (1957, p. 169) correlated the Honeycut Formation of the Ellenburger Group of central Texas with the Jefferson City Formation.

According to McCracken (1952, p. 64) the Quarry Ledge has been recognized as an insoluble residue zone in the Ellenburger of Texas and the Arbuckle of Oklahoma and Kansas.

Correlation of the Rich Fountain (which is approximately equivalent to the Jefferson City Formation) with other formations throughout North America is indicated in the correlation chart of the Geological Society of America (Twenhofel _et al_., 1954).

m. Stratigraphic Relations

As already mentioned in the section on the Roubidoux Formation, the contact between the Jefferson City and the Roubidoux is not well enough exposed in this area to provide evidence for either conformity or unconformity between the formations.

The Cotter and Jefferson City formations appear to be conformable. This relationship is discussed in the section on stratigraphic relations of the Cotter Formation.

4. Cotter Formation

a. Introduction

The Cotter Formation is stratigraphically the highest formation remaining in this area which has not been stripped away by erosion, with the exception of a single Mississippian (or Cretaceous) outlier. It is immediately underlain by the Jefferson City Formation, and was presumably overlain by the Powell Formation before erosion. The Powell is known to overlie the Cotter as near as Ash Flat, Arkansas, which is only 20 miles south of Thayer; and it has been tentatively identified above the Cotter about 5 miles east of Thayer, capping the prominent escarpment in that area.

The stratigraphic boundaries of the Cotter, as used in this report, are those established on the basis of insoluble residue zones by the Missouri Geological Survey. The base of the formation is drawn at the base of the 28-foot low-residue zone which overlies Zone 7 of the Jefferson City (McCracken, 1952, p. 66, and McCracken, undated, unpublished chart); and the top of the formation has been placed at the top of a 50-foot, shaly, low-residue zone immediately below the finely porous chert zone at the base of the Powell (McCracken, undated, unpublished chart).

b. Nomenclatural History

The name "Yellville formation" was applied by Adams, Purdue, Burchard, and Ulrich (1904, per Cullison, 1944, p.18) to rocks in Arkansas which were partly equivalent to Winslow's Jefferson City, but which also included "older and slightly younger beds" than the original Jefferson City. Ulrich (1911, p. 667-671) restricted the name Yellville to include only an upper part of the original Yellville, and applied the name "Jefferson City" to the remaining lower part of the original Yellville. Both the "Yellville" of 1904 and the "Jefferson City" of 1911 included strata of the present Cotter Formation.

According to McCracken (1952, p. 66), Ulrich (1912, unpublished) introduced the name "Cotter" to replace the upper part of his "Jefferson City" of 1911. The name "Cotter" was first published by Bassler (1915, plate 2).

Cullison (1944) has applied the name Theodosia to at least the lower part of what is here recognized as Cotter, and also included part of the upper chert beds of the present Jefferson City in the Theodosia. Comparison between Cullison's lithologic descriptions and thickness of the Theodosia and McCracken's (undated, unpublished) insoluble residue zones chart has led to the conclusion that, exclusive of the upper Jefferson City chert beds, Cullison's "Theodosia" is equivalent to the Cotter as defined by McCracken.

Further detailed comparison between Cullison's lithologic descriptions and thicknesses and those indicated on McCracken's chart has led to the conclusion that Cullison applied the name "Cotter" to approximately the same strata that are referred to as "Powell" by McCracken; and that Cullison's "Powell" is approximately equivalent to McCracken's "Smithville".

The conclusion that Cullison's "Cotter" is approximately equivalent to the McCracken's "Powell" is further substantiated by the fact that McCracken (1952, p. 66) tentatively assigned 490 feet of strata to the Cotter in the city well at Cotter, Arkansas, having found the top of the Jefferson City at a depth of 490 feet; and at that time he tentatively assigned an additional outcrop interval of 250 to 275 feet to the Cotter, giving a total thickness of approximately 750 feet tentatively assigned to the Cotter. On his more recent chart (McCracken, undated, unpublished chart) he assigned only 335 feet to the Cotter. Assuming that this thickness can be approximately applied to the interval at Cotter, Arkansas, the well should strike the contact between the Powell and Cotter of McCracken's revised chart at a depth of about 150 feet. This would give an elevation for the contact which corresponds roughly to Cullison's prediction of a "Cotter-Theodosia" contact at river level near the city of Cotter. Therefore, the probable contact between the Powell and Cotter of McCracken's revised chart is at least approximately equivalent to the contact between the Cotter and Theodosia of Cullison (1944).

Purdue and Miser (1916) imply a type area for the Cotter in the vicinity of Cotter, Arkansas, but give no exact location for a type section. Cullison designated the type section for his Cotter, and states:

> "This section, starting at the valley bottom just upstream from the west end of the White River bridge at Cotter and extending to the top of the hill westward along U. S. Highway 62, is here designated the type section of the Cotter."

Since Cullison's Cotter is probably equivalent to the Powell of current usage, the Cotter Formation as presently recognized by the Missouri Geological Survey apparently has neither type area nor type section.

c. Distribution and Outcrops

The Cotter is the most widely distributed of the formations cropping out in this area. It occupies nearly all the hill and ridge tops, slopes, and minor drainages. However, it is not often seen along the bluffs of the main streams except in the north part of the area of the geologic map, and along Spring River between Mammoth Spring and Hardy. The best exposures of the lower 100 feet of the formation, and of the contact with the Jefferson City, are in the railroad and highway cuts along and near the U. S. Highway 63 bypass at Thayer. An additional 60 feet is partly exposed along a bluff in the SE¼, SE¼, Sec. 30, T. 23 N., R. 5 W. The total thickness available for stratigraphic study in outcrop, therefore, is about 160 feet.

Nearly the entire thickness of the formation is probably present under cover in some of the highest hills just southeast of Mammoth Spring, but this has not been confirmed. No outcrops of Cotter strata over 160 feet above the base of the formation are known to occur in this area, although a sandstone about 200 feet above the base occurs in residuum throughout the area.

d. Thickness

The greatest thickness identified as Cotter in this area is about 200 feet, but it is estimated that approximately another 150 feet originally existed above this interval.

The city well at Ash Flat, Arkansas (Mo. Geol. Surv. #23039) indicates a total thickness of 370 feet for the Cotter, assuming a correct interpretation by the writer of the contact between the Cotter and the overlying Powell.

e. Lithology

The lithology of the Cotter Formation is very similar to that of the Jefferson City Formation. Dolomite makes up roughly 70 to 80 percent of the rock in the formation; the remainder is mostly chert, with some sand and a very small amount of shale.

Dolomites

The four general types of dolomite which were described for the Jefferson City Formation--mosaic dolomite, sucrosic dolomite, siliceous dolomite, and "cotton rock"--also are found in the Cotter Formation.

Cotton rock is by far the predominant type of dolomite in the lower 130 feet of the Cotter. Several beds of siliceous dolomite and a few thin beds of mosaic and sucrosic dolomite do occur in this part of the section, however.

The Cotter Formation in the Thayer area has been divided into four dolomite zones, based on the predominant or characteristic type of dolomite occurring in a given interval; the alphabetical lettering of the zones for reference has been continued from the upper dolomite Zone D of the Jefferson City.

<u>Zone E</u>. This 28-foot zone consists entirely of slightly silty

cotton rock; no pure dolomites or siliceous dolomites have been found in this interval. The zone corresponds exactly to McCracken's insoluble residue Zone 8, (McCracken, 1952, p. 62, 66 and McCracken, undated, unpublished chart), lying in this area between the top chert bed of the Jefferson City and the distinctive oolitic chert bed at the base of insoluble residue Zone 9.

Zone F. This zone, which is 30 feet thick, is characterized by an abundance of cotton rock in which the voids between dolomite grains are filled with a matrix of soft, white, dead chert. Argillaceous and silty cotton rock is nearly as common here as the siliceous rocks, however, and a few very finely crystalline sucrosic and mosaic dolomite beds occur. This zone is between 28 and 60 feet above the base of the Cotter.

Zone G. This 75-foot zone is between 60' and 135' above the base of the Cotter. The interval is well represented by good outcrops in the lower 40 feet, in which argillaceous and silty cotton rock predominates, and a few thin beds of finely crystalline sucrosic, mosaic, and siliceous dolomite occur. The upper 35 feet is not well exposed, but is apparently similar to the lower part of the zone.

Zone H. This 25-foot zone consists mainly of medium crystalline sucrosic dolomites and some finely crystalline sucrosic dolomites. The medium crystalline dolomites are distinctive either in outcrop or in the subsurface, since this is the only significant occurrence of medium crystalline dolomites in the lower 160 feet of the formation. Two of the dolomite units in this zone form easily recognized marker beds in the field because of their other distinctive characteristics (see section on marker horizons, p. 85). These dolomites are the highest Cotter strata known to crop out in this area.

These dolomite zones are applicable throughout the mapped area, and for several miles southward into Arkansas.

Cherts

An estimate of the relative abundance of each Cotter chert type was made from two measured sections in the Thayer area. It was found that smooth chert makes up about 42 percent of the chert; translucent chert, 35 percent; oolitic chert, 18 percent; and sandy chert, 5 percent. Quartzose chert and dead chert were found only in very small quantities. However, well samples indicate that, in residue, finely porous and dolomoldic cherts are equally as abundant as either translucent or smooth chert; but these are concealed as a matrix within the dolomite, and they are not easily detected in the field.

Chert in the Cotter occurs as nodules, beds, nodular beds, and occasionally as angular fragments within the dolomite; and in a siliceous dolomite or cotton rock, dead chert fills the voids between the dolomite grains. Nodules have their long axis aligned parallel to the bedding of the enclosing dolomite.

The Cotter cherts are often banded or mottled, and they are usually white or some light shade of gray or brown, although some dark cherts are occasionally found. The bands of the nodular chert are usually concentric, and the bands in bedded chert usually parallel the bedding. The individual bands are often fairly broad and indistinct, and they cannot usually be seen in the fine cuttings from well drilling.

Sandstones

The Cotter sandstones are petrographically similar to the Jefferson City and Roubidoux sandstones. They are generally fine; usually white to light gray unless stained red with iron oxide; and usually are at least partly silicified. Dolomite is often the cement in the sandstones, and a dolomitic sandstone often grades vertically into a sandy dolomite.

The sandstones may occur as individual beds, as irregular lenses in dolomite, or thinly interbedded with dolomite. Within the sandstone beds, nodules of sandy chert or orthoquartzite are commonly found.

Sandstones and sandy dolomites are conspicuous in certain parts of the Cotter section, and for local correlation and mapping, certain sandy zones are quite useful when other criteria for identification are available (see section on marker horizons and insoluble residue zones). However, even in the sandy zones, the sand does not make up a large percentage of the rock by volume.

Most of the sandstones are evenly bedded, and are devoid of primary structures. However, the more massive sandstones found as residuum about 200 feet above the base of the Cotter usually have abundant dessication cracks, current ripple marks, and occasionally small-scale cross-bedding.

Southerly Facies Changes

Outcrop sections and well logs in the Cotter and the Jefferson City formations have been studied along a north-south line from about 6 miles north of Thayer to Ash Flat, Arkansas, which is about 20 miles south of Thayer. The study was extended southward into Arkansas to ascertain whether any facies changes occur in the section toward the south.

The most conspicious change in the subsurface is a significant decrease in the amount of chert in both the Cotter and Jefferson City formations. This change appears to occur rather rapidly from about 5 to 10 miles south of Thayer. The decrease in chert is also evident in outcrop sections, in which the decrease is the result of both a smaller thickness of the chert beds, and a less frequent occurrence of chert throughout the section.

Another significant change which has been noticed in outcrop sections is a decrease in the amount of cotton rock and an increase in the amount of pure, finely crystalline dolomite toward the south. This change appears to coincide with the decrease in chert.

A very pronounced increase in the amount of sand in the sandy zone which is about 70 feet above the base of the Cotter is apparent toward the south. Sand zones in the Cotter are known to be very erratic, however, and this increase is probably only a local fluctuation and not a regional trend.

In connection with the observations noted for this area, Caplan (1960, p. 7-8) has found a very low percentage of chert in the Cotter and Jefferson City in Arkansas wells to the southeast. Two wells about 55 to 60 miles south of Ash Flat (Arkansas Oil Ventures No. 1 Doggett, Sec. 31, T. 10 N., R. 3 W., Jackson County; and Mangolia Petroleum Company No. 1 Sturgis, Sec. 30, T. 9 N., R. 3 W., Woodruff County) show "...a marked decrease in chert [in comparision to sections to the northwest, which] ...adds to the difficulty in separating the two [Cotter and Jefferson City] formations." (ibid.) He also notes a change toward the southeast from dolomite to dolomitic limestone and pure limestone. The two wells just mentioned both indicate the resence of dolomitic limestone in the Cotter-Jefferson City equence. In another well about 60 miles southeast of Ash Flat Tennark No. 1 Martin, Sec. 35, T. 14 N., R. 3 E., Craighead County) the Jefferson City section "...consists principally of gray limestone, sandy in part, and occasional gray to brown chert." (ibid.)

It is quite possible that the decrease in chert toward the south in the Thayer area may be the beginning of a lateral change to the low-chert section which is found to the southeast; and the increase in the amount of pure dolomite toward the south in this area could possibly be related to the lateral change from dolomite to dolomitic limestone and pure limestone farther southeast.

All of these facies changes may be related to a sedimentary basin to the southeast of the Thayer area, which McCracken (1968, personal communication) has indicated as existing in northeast Arkansas.

f. Marker Horizons

The most valuable marker bed in the Thayer area is an oolitic chert bed which ranges in thickness from about 0.3 feet to 0.6 feet. It is present throughout the area of the geologic map, and it extends for several miles into northern Arkansas. It has not been found along Spring River south of the Dam 3 section (Sec. 21, T. 21 N., R. 5 W.), but other oolite beds which occupy

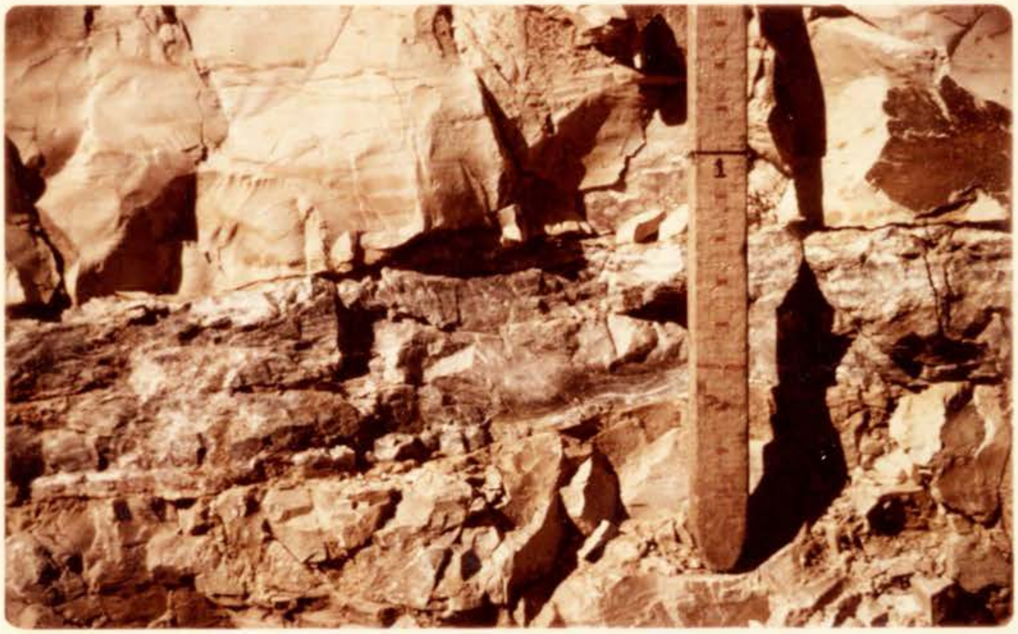

Fig. 6. Oolitic chert marker bed 28 feet above the base of the Cotter. Scale is in feet.

the same stratigraphic position in the Bayou Access section (Sec. 32, T. 21 N., R. 5 W.) and the Biggers Bluff section (Hardy, Arkansas) may be equivalent to it.

The oolite bed is 28 feet above the base of the Cotter, and it marks the upper limit of the low-residue zone which lies just above the Jefferson City. It has been used extensively for mapping the contact between the Cotter and the Jefferson City formations, and it is especially useful where only residual control is available.

This chert can be easily recognized by its dark color, and by the scattered light-colored oolites contrasted with the dark matrix. Upon closer inspection it can be seen that many dark-colored oolites are also present in the chert, and that elongated cavities (one-fourth to one inch long) filled or almost filled with crystalline quartz are scattered throughout. The oolites vary somewhat in a single specimen. The color may be white, cream, gray, or brown. Some of the oolites have no internal structure whatever; some have indistinct concentric bands; and others are very sharply concentrically banded. The matrix is a brown to dark bluish gray quartzose chert.

Immediately above the oolite bed is a two to five foot interval of buff cotton rock, with sandy dolomite and sandstone lenses. Above this is a three to five foot interval of cotton rock, with large, irregularly shaped, banded, smooth or translucent chert nodules surrounded by wide haloes of darker siliceous cotton rock. The dark-colored oolitic chert bed with the sand lenses and distinctive chert nodules above provides a very reliable and easily recognized marker.

The next marker bed, 90 feet above the base of the Cotter and within a 20-foot sandy zone (see following paragraph), is a fossiliferous, conglomeratic, sandy chert bed about one inch thick. The upper surface of this chert is nearly covered with low-spired gastropods, trilobite fragments, and echinoderm fragments, which are often in an excellent state of preservation. The ornamented gastropods are primarily of one species, and they have been tentatively identified as <u>Orospira</u> <u>bigranosa</u> by comparison with Cullison's (1944, pl. 28) plates. The usefulness of this bed as a marker is limited by its being rather difficult to find, apparently because the fossils are preserved only under certain conditions of weathering. It is present over a fairly wide area, however, because it has been found at several localities in the north half of the mapped area; at Grand Gulf in Sec. 20, T. 22 N., R. 6 W.; and along Highway 142 immediately west of English Creek in Sec. 3, T. 21 N., R. 6 W.

The sandy zone in which the <u>Orospira</u>-bearing sandy chert described in the preceding paragraph is found begins about 70 to 80 feet above the base of the Cotter and continues upward for about 20 feet. This zone, which is probably equivalent to the "Swan Creek" sandstone, has been quite useful for local correlations. In the vicinity of Thayer, the zone usually consists of sandy dolomite, sandy chert, and a few thin lenses of sandstone interbedded with non-sandy dolomite; but the amount of sand in the zone increases toward the south. This zone should not be used for mapping or for correlation without other stratigraphic data to confirm its identity, because there are other sandy zones and local sand lenses in the section with which it might be confused.

The medium crystalline dolomite units, which form sharp, distinct ledges, have been very useful for mapping in the northern part of the area. The lower unit is about 130 feet above the base of the Cotter. This five-foot unit is a thick bedded, medium crystalline, light gray dolomite which weathers to a very rough surface. The surface is highly pitted, and it is covered with tiny ribbons of quartzose chert which weather out of the dolomite. The pits are small (roughly one-fourth to one-half inch in diameter) but very closely spaced. The upper unit, which is about 17 feet above the lower unit, is a massive, light gray, medium crystalline dolomite which is very deeply pitted. The pits in this unit are from one-half inch to two inches in diameter and depth (fig. 8).

The dolomite between these two units crops out on a bluff along Warm Fork in the north-central part of Sec. 6, T. 22 N., R. 5 W. Part of this dolomite is also pitted, but the pits are arranged in mound-like patterns which are very suggestive of Cryptozoon colonies (fig. 9).

This sequence of medium crystalline dolomites is thought to be persistent throughout the entire area, but it is too high in the section to crop out in most parts of the area. It has been identified in a well (Mo. Geol. Surv. #25423) in Sec. 36, T. 22 N., R. 5 W., about four miles east of Thayer, as a zone of medium-crystalline dolomite between 135 and 155 feet above the base of the Cotter. At the Biggers Bluff section (plate 11) near Hardy, Arkansas, two crystalline dolomite units are found about 150 feet above the base of the Cotter, which are probably equivalent to these beds. The lower unit is five feet thick, forms a prominent, sharp ledge, and consists of dark gray, medium to coarsely crystalline, thick bedded dolomite, which weathers to a rough pitted surface with abundant quartz masses and quartzose chert fragments. The upper unit is about 2.3 feet above the lower unit, and it is six feet thick. This unit is very similar to the lower unit except it is tan to gray and medium crystalline.

The 50-foot interval above the medium crystalline dolomites described in the preceding paragraph is not known to crop out in this area. However, a prominent ledge of sandstone is frequently found in the residuum, capping some of the higher hills in the

Fig. 7. Typical appearance from a distance of the lower unit of the two ledge-forming, medium crystalline, dolomite marker units, appx. 130 feet above the base of the Cotter. Position of this five-foot ledge is indicated by arrows in the margin. Looking east toward bluff in the northeast corner of Sec. 31, T. 23 N., R. 5 W.

Fig. 8. Upper pitted unit of two ledge-forming, medium crystalline, dolomite marker units, appx. 150 feet above the base of the Cotter. Exposed on bluff, north-central part of Sec. 6, T. 22 N., R. 5 W.

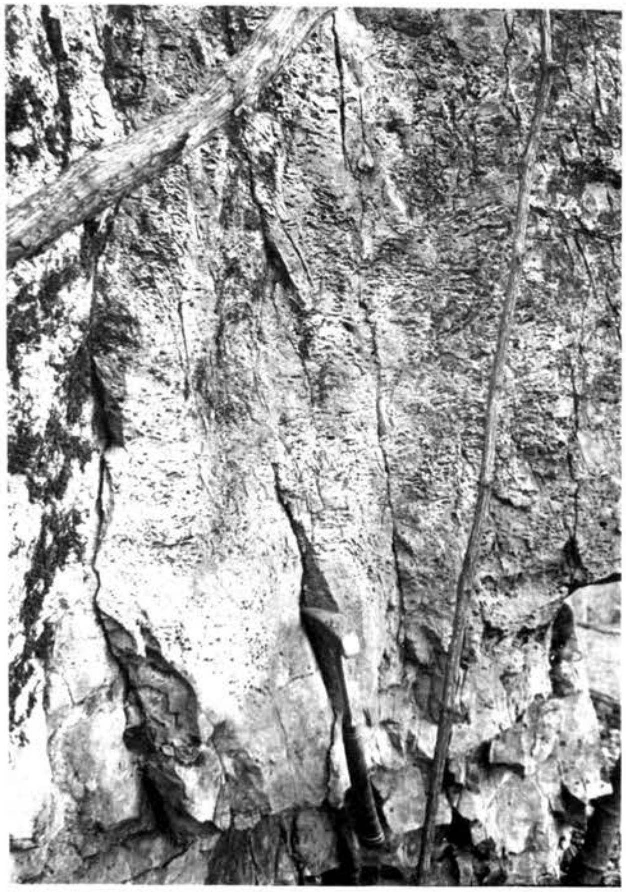

Fig. 9. Massive, pitted dolomite between the two ledge-forming, medium crystalline, dolomite marker units, appx. 135 feet above the base of the Cotter. Note the mound-like structure above the hammer head (possibly a Cryptozoon algal structure). Exposed on bluff, north central part of Sec. 6, T. 22 N., R. 5 W.

Thayer area. This sandstone is 50 feet above the top of the crystalline dolomites, and 200 feet above the base of the Cotter; and it persists throughout the entire area. Although it is commonly seen in residuum, it has been found in place at only one locality in this area: along Tracey Creek, near Highway 142, in the SE¼, Sec. 30, T. 22 N., R. 4 W. Here the sandstone ledge is 4.5 feet thick, and the sandstone is fine to medium, very thin to medium bedded, ripple-marked, and light grayish brown. Throughout the area the sandstone maintains an estimated thickness of three to five feet; it is often dessication-cracked and ripple-marked, and small-scale cross-bedding is occasionally seen. Much orthoquartzite is usually associated with the sandstone. Because of its thickness, it is a conspicuous and useful marker. This ledge of sandstone is probably equivalent to the sand indicated at the top of insoluble residue Zone 11 on McCracken's revised chart (McCracken, undated, unpublished chart), and it is probably the sandstone referred to by Cullison (1944, p. 31) as the "Gainesville sandstone".

g. Insoluble Residue Zones

The Cotter Formation has been divided into five insoluble residue zones by McCracken (1952, p. 62-66 and undated, unpublished chart), continuing his numbering system from Zone 7 at the top of the Jefferson City to Zone 8 at the base of the Cotter. The Cotter section in the Thayer area was compared with McCracken's revised (undated, unpublished) insoluble residue chart and divided into zones which correspond to his residue zones. The following descriptions were made from outcrop sections.

Zone 8: This 28-foot zone at the base of the Cotter contains almost no insoluble material other than a little sand, silt, and shale, and a small amount of translucent chert in the upper part of the zone. The total insoluble residue averages less than 5 percent. In the Thayer area the cotton rock in the lower half of the zone often contains scattered cavities lined with quartz and small calcite or dolomite crystals. In the upper half of the zone are a number of small, finely banded or mottled, translucent chert nodules.

Zone 9: This cherty zone is approximately 45 to 55 feet thick in most of this area. It is marked at the base by the distinctive oolitic chert and the overlying nodular chert. Above this is an alternating sequence of chert beds, nodular cherts, and non-cherty dolomites. Large amounts of disseminated chert occur in many of the dolomites. The zone is slightly gradational at the top into the overlying sandy zone.

Zone 10: This sandy zone is often referred to as the "Swan Creek". On the basis of its stratigraphic position, this 20-foot zone of sandy dolomites, sandy cherts, and thin sandstone beds is considered equivalent to McCracken's Zone 10. This is the same 20-foot sandy zone which was described in the section on marker horizons.

Zone 11: Only the middle part of this zone is well exposed in the Thayer area. The lower part is apparently very cherty, judging from the very cherty residuum which develops from the strata of this part of the zone. The sequence of medium crystalline, pitted dolomites described in the preceding section begins in about the middle of this zone, and this 25-foot sequence is low in residue compared to the beds below and above it. Although no outcrops are known above the pitted dolomites, the slope above these beds is very cherty. This cherty sequence is terminated about 50 feet above the pitted dolomites by the prominent sandstone zone already discussed in the section on marker horizons, which is probably equivalent to the sandstone that marks the top of this zone on McCracken's chart.

Zone 12: This zone is not exposed in the Thayer area.

h. Paleontology

Cullison (1944) has published the most recent comprehensive work on the paleontology of the Jefferson City, Cotter, and Powell formations. It should be remembered, however, that the formational names which he used do not correspond to the formational names used in this report. His descriptions of the fauna of the "Theodosia" are applicable to the Cotter Formation of this report, but his descriptions of "Cotter" fauna apply to rocks above the present Cotter. Cullison described a number of gastropods, trilobites, and ceratopea for the Theodosia.

Gastropods appear to be the most common of the Cotter fauna in the Thayer area, although trilobite fragments and echinoderm columna are often found with them.

i. Local Correlations

Correlation between sections has been made on the basis of insoluble residue zones and marker horizons. Most individual units of dolomite and chert are not continuous throughout the area, so a unit-to-unit correlation cannot often be made between sections. The most useful technique for correlating outcrop sections has been to plot the section on a well-log strip such as those used by the Missouri Geological Survey. The outcrop sections are divided into the 5-foot intervals of the log strips and the percentage of insoluble residue for a given interval is estimated and plotted on the log. The types of chert occurring in that interval are plotted, using the symbols of Grohskopf and McCracken (1949). Also the types of dolomite and other features such as calcite-filled vugs are noted on the log. It was found that certain features tend to occur in zones, and because the zones are more conspicuous with smaller scale plotting, the log strips have been much more useful for correlation than a detailed plotting of individual beds on a large scale. The small-scale log strip sections and their correlations are shown on plate 13.

Since completion of the field work the writer has experimented with the following technique, which would undoubtedly have made identification and correlation of the sections much less difficult: A log strip section had been made for each of the measured sections by the procedure already described; but it was noticed that the percentage of chert was much less than that shown by actual insoluble residues made from well samples taken from the same part of the Cotter of this area. Also a 20X binocular microscopic study of the dolomites indicated that some of the dolomites contained a high percentage of disseminated chert. Because it was often difficult to distinguish between the silica and the dolomite in very fine-grained samples a high silica content was frequently overlooked.

Residues were prepared from a set of samples from the Thayer Bypass section to ascertain which dolomite units contained enough disseminated chert to yield a high residue. Samples had been taken at 2-foot intervals, or closer if a unit was less than two feet thick. Only the dolomites were taken for the residue; all chert which could be seen was removed, since it had already been logged by visual estimation. The samples were crushed, and the dolomite dissolved with hydrochloric acid, in the laboratory of the Missouri Geological Survey. The residue which was left ranged from less than 1 percent to over 50 percent of the original dolomite sample; and with only a few exceptions, it consisted almost entirely of finely porous or finely dolomoldic chert.

The additional residue percentage was calcalated for each five-foot interval, and this was added to the previous log-strip of estimated chert percentages. This procedure almost doubled the insoluble residue percentage in the Zone 9 (high residue) part of the section, whereas the Zone 8 (low residue) part of the section remained essentially unchanged. The greatly increased contrast between Zone 8 and Zone 9 is very significant, because the 28-foot low residue zone is one of the most important criteria for identifying the contact between the Cotter and Jefferson City formations in an outcrop section by the insoluble residue method.

If an outcrop section need not be described in detail, the procedure could be simplified by dividing the outcrop section into five-foot intervals instead of lithologic units. The percentage of visible chert in each five-foot interval would be estimated in the field, and chert samples would be taken for examination with a binocular microscope. Dolomite samples should be taken at intervals close enough within each five-foot interval to insure a representative sampling, and the dolomite should be kept separate from the chert. Residues would be prepared from the dolomites only, and the percentage of residue would be added to the field-estimated percentage of visible chert. This total percentage would be logged on a well-log strip such as those used by the Missouri Geological Survey; and both the collected samples of chert and the residues would be examined and logged on the strip.

The preparation of insoluble residues from outcrop samples is nothing new, but the technique described above should be much more accurate than attempting to collect a sample of dolomite and chert of representative proportions in the field, and then preparing residues from the samples of dolomite and chert thus obtained.

j. Topographic Expression

The Cotter Formation forms a rather gentle, rounded topography in that there are no thick, resistant beds to form cliffs or breaks in the slopes, even though the relief may be quite high. Even the bluffs along the actively-eroding streams are fairly well rounded. The topographic development on the Cotter dolomites appears to be influenced considerably by ground-water solution, as evidenced by the many broad, shallow "solution valleys" and scattered sinkholes.

k. Regional Correlations

Cullison (1944, p. 32) suggested that his Theodosia (approximately equivalent to the Cotter of this report) has fauna in common with the Shakopee Dolomite at Cannon Falls, Minnesota, and

Fig. 10. Typical development of the topography on the Cotter Formation along Spring River, near Hardy, Arkansas. Note the accordance of summit elevations. Aerial photograph looking southwest toward Stillhouse Hollow, in Sec. 4, T. 19 N., R. 5 W. Spring River is indicated by the heavy line of timber crossing the light green field from left to right. Lake Thunderhead at Cherokee Village is visible over Stillhouse Hollow, immediately below and near the middle of the horizon.

that the genus Orospira reaches its climax of development in both the Theodosia and the upper Knox Dolomite of Virginia. In regard to Bridge's (1930, p. 129) correlations he stated that:

> "It is probable that the beds here included in the Theodosia formation are equivalent to those which Bridge...included in his Jefferson City-Cotter formations, which he correlated with the Newala of Alabama and the upper part of Division C of the New York Beekmantown."

The G. S. A. correlation chart for Ordovician formations of North America (Twenhofel et al., 1954) follows Cullison's (1944) formation names and boundaries. This chart indicates the correlations of the Theodosia with other Lower Ordovician formations.

1. Stratigraphic Relations

The relationship of the Cotter Formation to the underlying Jefferson City Formation has not been completely resolved. Some workers believe that the contact is one of disconformity, while others believe that sedimentation was continuous from the Jefferson City to the Cotter.

In this area there is no evidence to indicate any kind of a break between the Cotter and the Jefferson City formations. If any evidence of an unconformity in the section does exist, it would be at the base of the "Rockaway conglomerate" beds as Cullison (1944, p. 17, 23, 32) suggested.

E. Mississippian (or Cretaceous) System

A patch of Mississippian chert occurs in the NW¼, Sec. 16, T. 22 N., R. 5 W., about two miles north of Thayer (see geologic map). The chert contains a great number of cavities, which are the external molds of crinoid columna, bryozoans, brachiopods, and other fauna. The chert has been identified by Spreng (1967, personal communication) as belonging to the Osagean Series of the Mississippian System.

Most of the chert, however, occurs as well-rounded cobbles, which indicates that the chert has been reworked; also the chert occurs in the same area as an upland gravel deposit. McCracken (1968, personal communication) believes that this deposit is the result of reworking during Cretaceous time, and that these cherts have been transported from some other area.

In regard to the theory of Cretaceous reworking, it is of interest to note the occurrence in this region of a deposit which contains sediments similar to Cretaceous sediments from the southeast Missouri embayment area. This deposit, which is at the junction of Highway 19 and Highway E at the south edge of Alton, Missouri, and about 11 miles northeast of the Mississippian chert deposit, consists of white and purple clay, and a white sandstone which is made of fine, sharply angular quartz sand grains. Both the clay and the sandstone contain small (appx. one-fourth to one-half inch dia.) limonite concretions. According to Mc-

Cracken (ibid.) this deposit, with its clay, angular sand, and limonite concretions, is identical to the Cretaceous sediments of southeast Missouri.

F. Recent Fossil Vertebrate Remains

A rock cut for U. S. Highway 63 south of Mammoth Spring (SE¼, SW¼, NW¼, Sec. 16, T. 21 N., R. 5 W.) exposed a small collapsed cave. In the clay between the floor and the collapsed roof are a great number of small vertebrae (1.5 to 10mm. in length) and a few other tiny bones, which are in an excellent state of preservation. Many of the bones have been cemented by travertine to form a "bone conglomerate". Mehl (1964, written communication) identified the remains as "Recent fish, lizards, and small snakes." Since this time a few small claws have been found, but these have not been identified.

IV. STRUCTURE

A. Faulting

The area of this report has undergone faulting to a considerable degree. In several fault zones the faults are quite closely spaced, and displacements as great as 350 feet have been found in these zones. The two general trends of faulting are about N. 45° W. and N. 60° E. (see structural map, plate 2).

Very few of the faults can actually be seen in the field, but their presence is quite evident by the large structural displacements which exist within the area; and the fault traces are obvious on aerial photographs. The structural elevation of a given bed or other plane of reference is uniform within a given area, but in an adjacent area a very different but uniform structural elevation is observed for the same bed or reference plane. This "structural juggling" is mostly restricted to certain zones, which also follow a general northeast and northwest trend.

The structural displacements can best be explained as near-vertical block faulting for the following reasons:

1. Airphoto lineations, which are an indication of the fault traces, intersect to form a mosaic pattern; dividing the faulted areas into blocks, most of which are parallelograms.
2. Within each block the structural elevation of a reference

plane is relatively uniform.

3. The faulting is probably nearly vertical because the airphoto lineations, which represent the fault traces, are straight even where they cross ridgetops or valleys.

Three distinct zones of faulting exist in this area. One zone passes through Thayer in a direction of about N. 45° W. The largest vertical displacements in this zone are in and to the northwest of Thayer, where displacements on the order of 200 feet are common. To the southeast of Thayer the displacements are smaller, usually on the order of 50 feet. This zone intersects a northeast trending zone near Mammoth Spring; and airphoto and structural evidence indicates that this zone continues to the northwest at least as far as Koshkonong, Missouri, where it probably intersects one of the most important fault zones in this region. No significant structural displacement exists from one side of this zone to the other, at least in the area of the geologic map; the only displacements which have occurred are <u>within</u> the zone. The entire zone is actually a horst-like structure, because the relative displacements of the fault blocks have been upward within the zone.

Another fault zone passes through the town of Mammoth Spring in a N. 60° E. direction. Both upward and downward displacements occur within this zone with respect to the structural elevation of reference beds outside the zone; and a net structural drop of about 100 feet occurs from north to south across this zone. Mammoth Spring, the second largest spring in the Ozarks, rises along a fault in this zone with a 40-foot displacement. The extent of this zone beyond the mapped area is not known.

The fault zone which crosses the northwest corner of the geologic map in the Warm Fork Spring area is very probably of regional significance. This zone has a trend of approximately N. 60° E. The southernmost fault in the zone brings the Roubidoux Formation on the north side of the fault into contact with the Cotter Formation on the south side of the fault, raising the top of the Roubidoux abruptly from an elevation of about 400 feet to about 650 feet. Within a half mile another fault brings the top of the Roubidoux to an elevation of about 740 feet, giving a net displacement of about 340 feet. The structural rise toward the north does not stop here, but continues gradually in a northerly direction (judging from a few widely separated structural control points). Strong airphoto lineations and a few structural control points indicate that the zone continues to the west-southwest, through and to the north of Koshkonong. To the northeast of Warm Fork Spring, the set of lineations which represent this fault zone continues for several miles toward Alton in an east-northeast direction; but outcrops indicate that the fault zone must change direction and continue for at least several miles to the southeast to account for Roubidoux outcrops along Frederick and Piney creeks south of Alton.

It is the writer's opinion that this local fault zone could be part of a regional fault zone extending in a generally east-west direction across much of south-central and southeast Missouri. On the Geologic Map of Missouri (McCracken, 1961) a number of southward-extending outcrops of the Roubidoux Formation can be seen, including the one in the Thayer area which is terminated on the south end by the local fault zone. It is possible that the other southward-extending Roubidoux outcrops may also be terminated on their south ends by a regional fault zone of which the local zone is a part. McCracken (1968, personal communication) believes that a fault of considerable magnitude passes across the south end of the Roubidoux outcrops at Tecumseh, Missouri, and north of the Everton-St. Peter outliers near Bakersfield, Missouri. To the east of the Thayer area, Dake (per McCracken, 1968, unpublished notes) mapped an east striking fault, passing immediately south of Doniphan in Ripley County, which has brought the Roubidoux Formation on the north against the Jefferson City Formation on the south. He mapped the fault from Sec. 24, T. 23 N., R. 2 E. to Sec. 30, T. 23 N., R. 1 E. This fault has been extended by James H. Williams of the Missouri Geological Survey to Sec. 24, T. 23 N., R. 1 W. (ibid.) All of these faults could be part of the same regional fault zone.

Another possible regional connection of the faulting in the Thayer area is with the Graydon Springs fault zone, which has been mapped from about six miles northwest of Eldorado Springs, Missouri, through the Springfield area, to about 10 miles southeast of Mansfield, Missouri. This zone of faulting is in a direct line with the Thayer area. Beveridge (1963, p. 47) suspects that the "Graydon Springs fault zone may extend farther to the southeast"; and the writer believes that it may continue southeastward to intersect the suspected regional east-west trending fault zone previously discussed. In fact, the southeast-trending fault zone which passes through Mammoth Spring may be a further extension of the Graydon Springs fault zone. The maximum known vertical displacement along the Graydon Springs fault zone is 250 feet near Mansfield (ibid.), which is comparable in magnitude to the faulting in the Thayer area.

The faulting in this region has no topographic expression to aid in mapping, since for the most part, the only rocks on the surface are the uniformly resistant cherty dolomites of the Cotter and Jefferson City formations. As previously mentioned, however, the fault traces may be quite easily seen on aerial photographs as lineations, and this is an almost indispensable aid to mapping the faults.

B. Folding

Folds of low displacement and fairly low dip angle can be seen in practically any large outcrop in this area. Most of the folds are monoclines, and even those that appear to be anticlinal or synclinal are probably double monoclines. The structural displacement does not often exceed 20 feet, and the dip angle is usually less than 30 degrees.

The monoclinal folding is evidently a result of the same non-uniform uplift that produced the faulting in the area. The monoclines for which the strike of the axis could be determined have a strike that is parallel to the general trend of the faults (N. 45° W. and N. 60° E.).

V. SOLUTION PHENOMENA

A. Introduction

This area as a whole is not a karst region in the classical sense, despite the predominance of carbonate bedrock. This lack of a well-developed karst topography is probably a result of certain unfavorable characteristics of some of the dolomites. Many of the dolomite units possess a sponge-like "skeleton" of dead chert, so that even if the dolomite is dissolved away, the "skeleton" of chert remains to occupy the original volume. Other dolomites are difficult to dissolve because they are finely crystalline and tightly packed, and do not readily admit water between the grains. Another unfavorable factor is the presence of much chert interbedded with the dolomite. Even if solution does occur in favorable dolomite, the effect of solution is obscured by the thick accummulation of residual clay and chert on the surface.

Despite these unfavorable conditions, several outstanding karst features and numerous scattered sinkholes in the Thayer-Koshkonong area indicate that an extensive system of underground drainage has developed. The more striking solution phenomena are described in this section, and in addition, their subsurface connections and their relationship to faulting or other fracturing are discussed.

B. Mammoth Spring

Mammoth Spring is the second largest spring in the Ozark region. Its flow of about 279,000,000 gallons per day* is exceeded in this area only by Big Spring in Carter County, near Van Buren, Missouri. The spring is at the town of Mammoth Spring, Arkansas, and it is roughly 100 yards south of the state line.

The spring is dammed for the production of hydroelectric power, and the resulting several-acre lake completely submerges the outlet of the spring. Even when the lake is drained the outlet cannot be seen, because the spring emerges into a sink-like structure, which forms a deep natural pool.

A spring with a discharge of this magnitude must undoubtedly have a large source area. Beckman and Hinchey (1944, p. 90) describe what they believe to be the source area of the spring:

> "The source of Mammoth Spring includes a large area to the north and northwest of the spring outlet. This region is one in which surface drainage is poorly established, and in which there is abundant evidence that much of the rainfall enters the ground through sinkholes and similar solution-formed openings and thus contributes appreciable amounts of water to the subsurface drainage system. The area is characterized by broad, shallow valleys which carry very little or no surface runoff except at times of very heavy rainfall. Many sinkholes and sink-depressions dot a large upland area of low relief--an area northwest of the spring outlet which extends at least as far north as the town of West Plains and west into southern Howell County. A remarkable sinkhole region extends west and south of the town of Koshkonong."

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*Flow measured on April 28, 1942 (Beckman and Hinchey, 1944, p. 91)

Fig. 11. Lake formed by the damming of Mammoth Spring. Submerged outlet of the spring is near the lower right corner of the photograph. Outcrops on the far bank, near the left margin of the photograph, are the "Rockaway Conglomerate" chert beds at the top of the Jefferson City. Looking southeast.

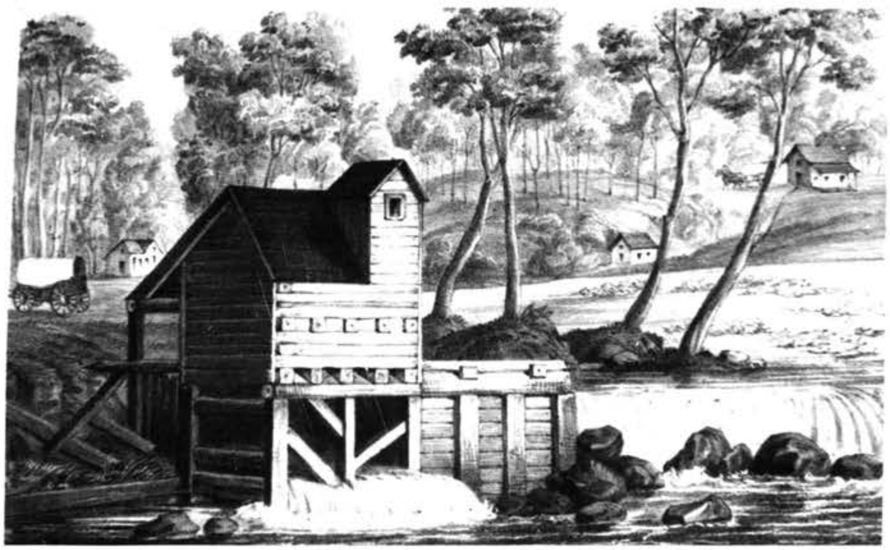

Fig. 12. Mammoth Spring in 1858. Reproduction of a drawing in Owen (1858, plate 5).

Within the area outlined by Beckman and Hinchey (ibid.) and to the west and south of Koshkonong, a drainage basin of about 20 square miles which has no surface outlet drains into Grand Gulf, a collapsed cavern, which is about 7 miles northwest of Mammoth Spring. It has long been suspected that Grand Gulf has underground connections with Mammoth Spring, and local residents have long told of a bundle of hay which was thrown into the underground stream at Grand Gulf, and which reappeared at Mammoth Spring. These reports have never been confirmed, however.

Tony Aid, a student at West Plains High School, traced the connection from Grand Gulf to Mammoth Spring in 1967 for a science fair project (Aid, 1967, unpublished report). He used Uranine Soluble, a fluorescent dye, for a tracer, and packets of activated charcoal at Mammoth Spring to absorb the dye. The dye was placed into a small temporary stream flowing into the cave outlet of Grand Gulf after a day-long rain. The results indicate that the dye first reached the spring between 12 and 24 hours later on October 17, reached a peak on October 20, and could no longer be detected on October 23.

One of the faults in the fault zone previously described, which passes in a N. 60° E. direction through the Mammoth Spring area, passes directly through the spring outlet. This fault has a displacement of 40 feet and a strike of about N. 60° E., and is one of the few faults in this area which can be seen in the field.

A monocline in which the rocks have been highly fractured passes only a few feet from the spring outlet, intersecting the fault just described. The monocline strikes about N. 45° W. and has an effective structural displacement of about 30 feet.

The fault zone previously discussed, which passes in a N. 45° W. direction through Thayer and continues toward Koshkonong, intersects the zone at Mammoth Spring very near the spring outlet. The main underground stream which emerges at the spring may follow this fault zone, because it probably passes through the source area of the spring as outlined by Beckman and Hinchey (op. cit.). Further evidence for an underground stream along the fault zone is a report from the driller of the Thayer Municipal Well no. 4 that the well, which was drilled in the fault zone, struck a large underground stream.

C. Grand Gulf

Grand Gulf is probably the most unique and spectacular feature of its kind in the Ozark region. It is sometimes referred to as the "Little Grand Canyon of Missouri" because of its impressive size, and because in appearance, part of the Gulf is more like a canyon than a sinkhole.

This deep, precipitous chasm is about three miles south of Koshkonong, and it is in Sec. 20, T. 22 N., R. 6 W. The Gulf is about a half mile long, but in most places it is less than

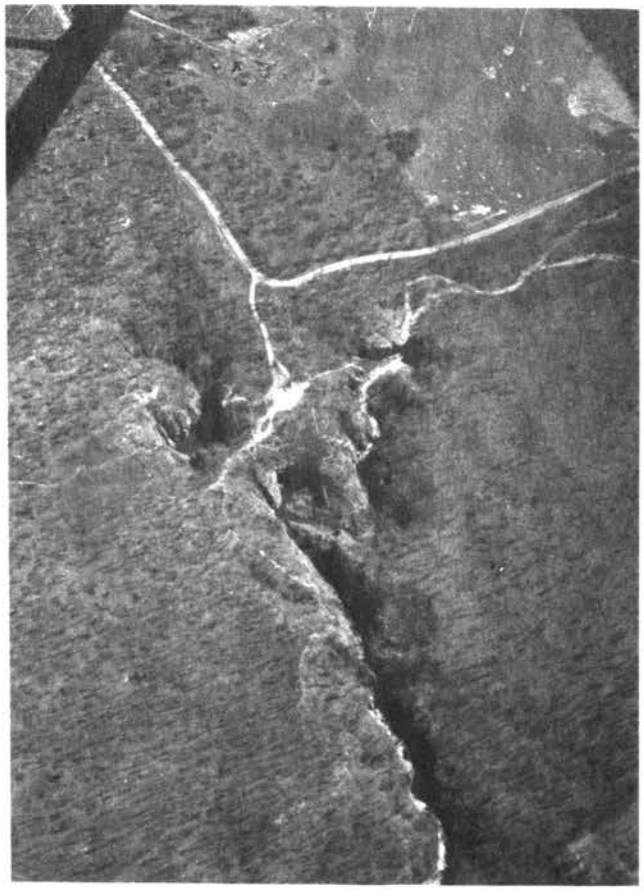

Fig. 13. Aerial photograph of Grand Gulf, looking east-southeast (main roads run east and south). Bussell Branch in foreground; outlet is in sinkhole to left of parking area.

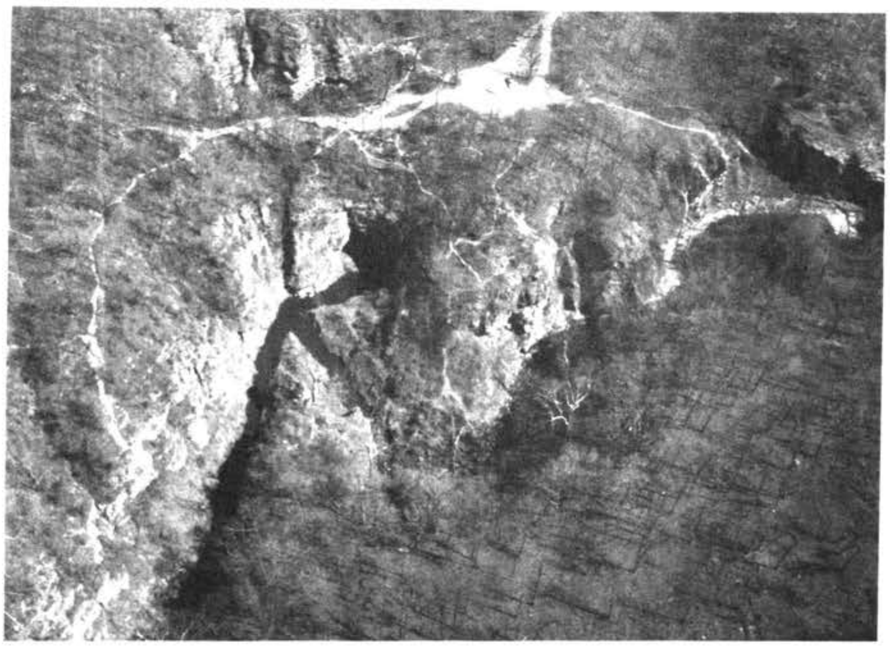

Fig. 14. Close-up aerial photograph of Grand Gulf looking east toward opening of natural bridge. Outlet cave is in isolated sinkhole, upper left part of photo. Note automobiles in parking area for approximate scale. Water standing in Gulf results from blocking of outlet.

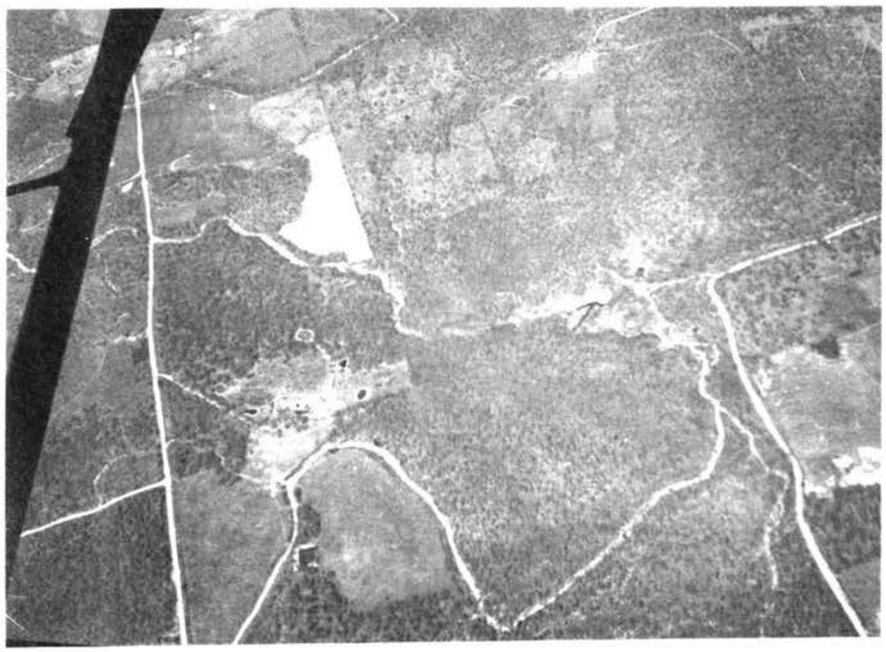

Fig. 15. Higher altitude oblique aerial photograph of Grand Gulf (near center of right half of photo) and surrounding area looking approximately north-northeast. Close inspection will reveal several airphoto lineations, which probably represent faults.

100 feet wide. At its deepest point it is about 150 feet deep. In many places the walls are vertical to overhanging and up to 100 feet high.

Grand Gulf is divided naturally into two parts by a narrow strip of land; and the two parts are connected by an impressive natural bridge, or more accurately, a natural tunnel. The part of the Gulf to the west and south is canyon-like in appearance, and the part to the northeast has more the appearance of a very deep, steep-walled sinkhole.

The surface water from an area of about 20 square miles goes underground at Grand Gulf. Most of this is to the northwest, and the intermittent stream into which most of this area is drained is known as Bussell Branch. A small area to the west and south also drains into the Gulf. With the exception of a very small amount of water which drains directly into the northeast side of the Gulf, the water which enters must pass through the natural tunnel and into the northeast part, and it then disappears into a cave at the floor level. Fluorescent dye tracing by Aid (1967, unpublished report) indicates that the water reappears at Mammoth Spring, which is about 7 miles southeast of the Gulf.

Grand Gulf has been interpreted as being formed by the collapse of a large cavern system. According to Bretz (1956,

p. 350-355) the original cavern was formed along the brecciated zone of a fault. Because solution of the dolomite was controlled by the near-vertical fault, the cave was narrow but very deep. At one point, the site of the natural bridge, the cave followed a pair of intersecting joints instead of the fault. Those parts of the cave which followed the faults had a weak roof because of the brecciation, and here the roof collapsed into the deep cave to form Grand Gulf. However, the roof of that part of the cave which did not follow the fault was strong; this part did not collapse, and thus a natural bridge [or tunnel] remained.

Grand Gulf is a geologically recent occurrence, for the slopes are not yet stabilized (ibid.). Further evidence can be seen in some places several yards back from the rim of the Gulf, where low, vertical to overhanging escarpments in the residual soil are still retreating from the rim.

Bussell Branch once formed the headwaters of English Creek, flowing over what is now Grand Gulf. When the Gulf was formed, however, Bussell Branch was pirated to a subterranean channel, and English Creek was beheaded. Part of the broad, abandoned valley of Bussell Branch still remains to the immediate southeast of the Gulf (fig. 16). The western part of the abandoned valley has reversed its flow and now drains into the Gulf, and two small former tributaries of Bussell Branch now exist as high hanging valleys at the rim of the Gulf. During heavy rainfall these

Fig. 16. Abandoned meander loops of Bussell Branch east of Grand Gulf (shown as large, S-shaped, lighter-toned, cultivated area in center and right half of photograph). Note also: main part of Grand Gulf, lower left corner of photo; English Creek crosses upper left corner of photo. Looking east.

hanging valleys form impressive waterfalls.

Grand Gulf probably has some of the most clear examples of faulting which can be seen in the state of Missouri. Displacement of strata, smooth fault planes, breccia zones, drag folding, and solution work associated with faulting are all clearly demonstrated in the rock walls of the Gulf. Often the coarse fault breccia is filled with sparry calcite.

According to statements from several local residents, the cave which now drains Grand Gulf could once be followed to a large underground river. One senior resident of Mammoth Spring, who often visited the underground river, states that the river was so wide that one could not throw a stone across. The cave can only be traversed for an estimated 100 feet now, for the passage is blocked by debris. The Mammoth Spring resident just cited attributes the blocking of the passage to a tornado, which uprooted much timber upstream from the Gulf in the early 1920's. The debris resulting from the tornado washed into the cave, where it jammed and blocked the cave passage.

D. Sinkhole Plain

In the introduction to this section the statement was made that this area as a whole is not a karst region in the classical sense. However, an area of several square miles immediately west of Koshkonong is a karst area in every respect. The topography of this area is almost entirely the result of the dissolving away of the dolomite bedrock by ground-water. The sinkholes are so closely spaced that many have coalesced, and a number of solution valleys have developed.

Surface drainage is practically nonexistent here; for rain-water falling in the area can travel only a short distance on the surface before being intercepted by a sinkhole which funnels the water into underground passages. Only during periods of very heavy rainfall does any water flow for an appreciable distance on the surface; at such times the water may fill the sink-holes faster than the sinkholes can drain it away, and the excess water may produce temporary surface streams. Any water leaving the area must drain into Bussell Branch, however, and the water is still destined to enter the subsurface via Bussell Branch and Grand Gulf.

This sinkhole plain is certainly unique in the southern Missouri region. Just why this isolated karst area exists here within a region that is not characterized by a karst topography is not known, but probably a number of factors contributed to its development and preservation. Some of the possible factors involved are discussed in the following paragraphs, but no conclusions have been reached.

For a sinkhole area to be so well developed, the bedrock in the area must be susceptible to attack by ground-water. The karst area has not been geologically mapped; however, the bedrock is probably Cotter dolomite. The petrology of the dolomite in the karst area is not known, so it cannot be definitely stated whether or not this factor is favorable for karst development.

Aerial photographs indicate a very high density of lineations within the karst area. Evidently the bedrock is highly fractured, creating a very favorable condition for the development of a karst topography. However, this karst area is apparently no more fractured than certain other areas; so this is not the only factor which led to the karst development, although it is probably significant.

Probably the most important factor in the preservation of this sinkhole area is its position on the broad divide between Warm Fork and Myatt Creek, where it has not been reached by the headward erosion of the tributaries of these two streams. Over much of the surrounding area a sinkhole plain would have been destroyed by fluvial erosion if it had ever existed. Again, this is not the only factor in the existence of this karst area, because other broad, flat divides in this region have not developed into similar karst areas.

This sinkhole plain is within the area outlined by Beckman and Hinchey (1944, p. 90) as the source area of Mammoth Spring.

Underground connections between these sinkholes and Mammoth Spring have not been definitely traced, but the connections are probable.

E. Other Solution Features

Two large sinkholes, which are aligned in an east-west direction and are practically joined at the rims, are about two miles west of Thayer in the south half of Section 26, T. 22 N., R. 6 W. The sinkhole on the west is about 0.4 mile in diameter and 80 feet deep, and has a broad, flat bottom about 0.3 mile in diameter which is cultivated. The sinkhole on the east is about 0.2 mile in diameter and 100 feet deep; the bottom is only about 0.1 mile in diameter, but it is very flat and is cultivated. A road passes between the two sinkholes.

Harbeston Sink is less than one mile southeast of Brandsville, Missouri, and about three miles northwest of Koshkonong, and is in the SW¼, SW¼, Sec. 24, T. 23 N., R. 7 W. It is about 0.2 to 0.3 mile in diameter and 100 feet deep. The walls are quite steep, but little bedrock is exposed. This sinkhole is easily found by following the boundary between Howell and Oregon counties due south from U. S. Highway 63.

A large, elongated, double sinkhole is found about a mile north of Brandsville in Sec. 11, T. 23 N., R. 7 W. This sinkhole is about 0.5 mile long and 0.1 mile wide. It is 80 to 100 feet deep in the east and west parts of the sinkhole, but it is less than 30 feet deep in the middle. The axis is approximately aligned with a few smaller sinkholes which are about 0.7 mile and 1.9 miles to the west, respectively.

VI. RESOURCES

A. Iron

Brown iron ore (limonite) is quite abundant in this area. Hayes (1957, p. 16-18) includes this area in the "West Plains District", which includes all of Oregon and Howell counties, and also parts of Texas, Shannon, Douglas, and Ozark counties. The West Plains District is separated from adjacent iron ore districts on the basis of the type and origin of the ore deposits.

The brown iron ore deposit is usually seen on the surface of hillsides and ridges as scattered masses of limonite, and the surface deposit may be an indication of a deposit which continues at depth. The ore beneath the surface occurs as scattered masses and fragments of limonite in the blanket of residual clay, chert, and sandstone.

Both the deposits and the ore have been described by Hayes (1957) and Crane (1912). Crane discusses the origin of the ore and deposits, in addition to describing them in detail. Hayes gives summary descriptions of the ore and deposits, but most of his publication is devoted to information on the prospecting, development, and marketing of the ore deposits. The reader is referred to these sources for detailed information on the ore and its deposits.

Brown iron ore occurs on the surface at many localities in this area, so the ore reserve is probably large. Attempts to mine and market the ore in this area have often met with failure, however, because of high shipping costs, and also because of the undesirable phosphorous content of the ore.

B. Dolomite

Since the bedrock in this area is predominantly dolomite, the supply of this rock is inexhaustable. Most of the dolomite is suitable for aggregate, except possibly for concrete aggregate meeting Missouri Highway Department specifications.

Only one active quarry operates in this area, and much of the dolomite from this quarry is used for agricultural lime. Analysis of the rock being quarried for this purpose is necessary, however, because some dolomite units may contain over 50 percent disseminated silica. The crushed dolomite is also used in this area for road surfacing. For most private driveways it is spread on the surface without a binder; and for public roads and streets, alternating layers of crushed dolomite and tar are laid down to make a "blacktop" surface.

C. Surface Water

North of Mammoth Spring the supply of surface water is small. Warm Fork maintains a small but continuous flow of water downstream from Warm Fork Spring. Mammoth Spring, however, with its flow of about 279,000,000 gallons per day, provides an almost inexhaustible supply of water from the spring southward. Two dams have been constructed along Spring River for hydroelectric power; one immediately downstream from the spring, and another larger one several miles downstream. The only present uses of this water are for power and recreation.

D. Ground-Water

The supply of ground-water is plentiful in this area, and it is of excellent quality except for its hardness, if the well is cased below the point of possible contamination. Most private farms obtain an ample supply of water from wells around 150 feet deep. At this depth, however, there is the possibility of contamination from the surface, since the water comes from solution channels in the dolomite which are in turn connected to the surface. The municipal wells in the area are usually at least 500 feet deep, and they are cased to a depth approved by the Missouri Geological Survey to exclude the possibility of contamination from the surface. Because of the variable depth of solution work throughout the area, the approved casing point depends upon the conditions at each individual well. For a well to be state-approved, all solution openings must be cased out. No certain aquifer is used consistently in this area.

VII. GEOLOGICAL ENGINEERING PROBLEMS

A. Rugged Terrain

The rugged terrain in this area is often a problem in highway construction. In parts of the area highways may be planned along long, straight, flat divides, but in other parts of the area, deep valleys and steep ridges necessitate deep cuts and fills. The highways are usually designed so that the material taken from cuts will be equal to the amount of material needed for fills, with a minimum of "borrowing" from quarries or of excess material to dispose of. Additional problems encountered in planning and making cuts are discussed in sections to follow.

B. Residuum

1. Introduction

The dolomite bedrock in this area contains large quantities of insoluble material, including clay, bedded and nodular chert, disseminated chert, sand, and sandstone. If the dolomite is dissolved by ground-water, the insoluble materials will remain essentially in place. This is the origin of the mantle of soil which blankets most of the area. It is referred to as "residuum" because it is the insoluble residue which remains after the dolomite is dissolved away. This residuum, then, consists of varying proportions of red plastic clay, bedded and nodular chert, finely porous chert, and some sandstone and sand.

The thickness of the residuum ranges from 0 (rarely) to over 200 feet in this area; more commonly it is from 20 to 50 feet thick.

The red plastic clay is the main subject of this section, because this clay presents a variety of engineering problems. The composition, precise origin, and some of the properties of this red clay are not fully understood, and there is a great need for research in this field.

2. Foundations

The residuum will settle under a heavy load; therefore, it does not provide an adequate foundation for heavy structures, without designing the structure to account for the possibility of settling. Additional problems may arise if the clay becomes saturated with water, for it is highly plastic when it is saturated and changes volume appreciably from dry to wet state.

Roads constructed upon a base of the residual clay are likely to develop very rough surfaces because of differential settlement around boulders in the clay. Thin pavements laid down on a residual clay base are likely to break up as a result of freezing and thawing (with resulting expansion and contraction) of the clay, and as a result of the high plasticity of the clay when it is saturated with water.

3. Slope Stability

Residual clay slopes are usually stable under normal conditions, providing the slope is not too steep. However, the clay is subject to rapid erosion by surface water on a grade, but this can be prevented by sodding the slope. The Missouri Highway Department covers the seeded slopes with straw, which is held in place by spraying with tar, to protect the slope until the sod becomes established.

4. Excavation

The residual clay is quite easy to work if it is fairly dry. However, if the clay contains excess water, it becomes very plastic and "sticky" and almost impossible to work. Encountering a spring during the process of excavation may cause problems if much residual clay is present. If a spring is encountered, steps should be taken to prevent excessive wetting of any clay which must be worked.

5. Reservoir Leakage

Residual clay cannot be depended upon to hold water in a reservoir, for despite its plasticity, the clay is quite permeable. If it is necessary to design a reservoir in an area of residual soil, the cost of treating the clay should be taken into account. Effective treatments are available to seal the clay, but methods currently in use are quite expensive.

6. Aquifer Recharge

The permeability of the residual clay, which is a nuisance in the case of reservoir leakage, is very valuable for the recharging of aquifers. Practically the entire area is blanketed with residual clay, and much of the rainfall soaks into the clay and continues downward to the saturated zone, especially on the broad, flat interstream divides. If the clay were not permeable, the water would run off into streams and be lost, but with the blanket of permeable residuum, much of the rainfall is captured and stored beneath the surface as ground-water.

C. Solution Cavities

1. Introduction

The dissolving action of ground-water charged with carbon dioxide upon the dolomite in this area has produced a complex network of underground caverns and channels, which are mutually connected to each other and to sinkholes which have developed on the surface. The caves, springs, sinkholes, underground streams, and other solution cavities thus produced often present some unique engineering problems.

2. Sinkholes

a. Introduction

Sinkholes are topographic depressions on the surface which have formed either by the sudden collapse of some underground cavity, or by the gradual slumping of surface soil into underground passages. It is probable that all sinkholes connect either directly or indirectly with subterranean passages.

b. Aquifer Recharge

Sinkholes have an important part in the recharge of aquifers in many areas. In this area the sinkhole plain west of Koshkonong contributes a significant amount of water to the ground-water supply, because there is practically no surface runoff from that area. Grand Gulf also makes a significant contribution since it receives all the water from the Bussell Branch drainage basin and from two smaller drainage basins. Most of the other sinkholes in the area, however, catch only the rainfall which falls directly into them.

c. Aquifer Pollution

The same sinkholes that help recharge the ground-water supply may also contaminate it. The dolomite aquifer in this area consists of a network of enlarged fissures, cavities, and other open passages; therefore, the dolomite aquifer does not provide the natural filtration which is usually provided by other types of aquifers, such as sandstone. Any contaminant which enters a sinkhole may be funneled directly into the subterranean waterways and carried for great distances without being removed by filtration.

The Missouri Geological Survey considers all water from shallow dolomite aquifers to be polluted. If the only available source of water is from these aquifers, the water should be treated to render it safe for human consumption. If possible, a water well should be drilled through the shallow aquifers and into deeper aquifers less subject to pollution, and the upper part of the well in the shallow aquifer should be cased to keep polluted water out of the well.

Care should be taken to avoid introducing any contaminant into a sinkhole or other solution passage, for the contaminant is very likely to find its way into the ground-water supply.

d. Reservoir Leakage

Sinkholes have a long history as the culprits which are often responsible for reservoir leakage. Failure to recognize the hazards of sinkholes in a reservoir site may result in much expense in attempting to locate and stop a leak through a sinkhole. Loss of water through sinkholes is certainly to be expected, in view of their direct connections to underground channels. Reservoir water simply drains out through a sinkhole much as water goes down the drain in a bathtub. Although grouting may be used to stop leakage through sinkholes, locating leaks once the reservoir is filled may be very time-consuming, and grouting is in itself quite expensive. Site investigation before construction is much more economical and effective.

e. Sinkholes and Surface Drainage

The problems discussed so far which are related to sinkholes have resulted from the direct connections of sinkholes with underground waterways. However, the failure of sinkholes to drain water from surrounding areas at a sufficiently rapid rate may result in flooding of the area. This problem does not exist in most of this area, but the sinkhole plain west of Koshkonong depends largely upon sinkholes for its drainage, and the possibility of flooding should be kept in mind for this part of the area.

3. Caves

Caves will cause reservoir leakage in much the same way as sinkholes, except they are usually much more effective because of the larger size of the opening. Site investigation for a reservoir should include a search for caves anywhere within the reservoir basin. Large caves are not common in this area, but even very small caves and other solution openings can drain a considerable amount of water from a reservoir.

Caves and other solution openings are a constant source of trouble to well drillers in this area. Encountering a cavity in drilling may result in the loss of drilling tools, or the bit may be deflected and cause the hole to run crooked. They may also necessitate expensive casing.

4. Springs

Springs are often a problem in excavations in this area. If a spring is encountered during the process of excavation, pumping may be necessary to remove water from the excavation site. The problem of encountering a spring in excavations involving residual clay have already been discussed.

Under a sufficient hydrostatic head, a small spring may reverse its flow and provide an escape for reservoir water. Springs which exist in the reservoir area should be studied to ascertain whether or not they constitute a potential reservoir leak.

D. Cutters and Pinnacles

1. Introduction

When dolomite is dissolved by ground-water and removed in solution from the bedrock to form a residual soil, a very irregular surface develops between the remaining bedrock and the residuum which covers it. The irregular surface develops partly as a result of the more rapid solution along joint planes and other fractures, while unfractured rock is dissolved much more slowly. The resulting bedrock peaks or highs are called pinnacles, and the intervening residuum-filled depressions in the bedrock are called cutters. In this area both very large pinnacles and very small pinnacles can be found; and often a large pinnacle may be covered on its

Fig. 17. Cutters and pinnacles in highway cut along the U.S. Highway 63 bypass at Thayer, Missouri.

upper surface with many small, closely spaced pinnacles.

2. Depth to Bedrock

It is impossible to predict the depth to bedrock in this area, for the cutters and pinnacles have no topographic expression or other surface indication of their presence. At one point bedrock may be found only a few feet beneath the surface, while at another nearby point the bedrock may be many feet beneath the surface.

3. Isolated Boulders--Slide Hazard

Large boulders of dolomite often remain in a cutter, isolated from bedrock by the plastic residual clay. If a road cut is made through a cutter in such a way that the boulder is exposed, a slide hazard results. A driver on the newly-constructed U. S. Highway 63 bypass at Thayer was killed while passing through one of the road cuts in 1967, when a large mass of rock isolated in a cutter suddenly slid from the 50-foot road cut onto the highway. The slide was triggered by a heavy rainfall that saturated the clay in which the mass of rock was perched; the clay became highly plastic, and the mass of rock slipped out of place and fell to the highway. The driver was struck by one of the falling rocks, which passed through his windshield. Several potential slide hazards still exist in this and other highway cuts in the Thayer area.

4. Foundations

The problem of settling of residuum under the load of a structure is especially serious if part of a structure is constructed over an underlying pinnacle, while another part of the structure is constructed over a cutter. The part of the structure over the cutter will settle much more than the part over the pinnacle, and serious damage to the structure may result. Closely-spaced exploratory drilling in the residuum is necessary to assure a uniform foundation.

5. Excavations

Exploratory drilling is necessary to determine whether an excavation or highway cut will be in rock, soil, or both. Excavation in closely-spaced cutters and pinnacles may be a difficult and expensive operation, because the pinnacles are sometimes so closely spaced that earth-moving equipment cannot be used to remove the soil surrounding the pinnacles. Even if this difficulty is not encountered, the many pinnacles must be blasted individually to remove them.

E. Aggregate

A very abundant supply of dolomite suitable for many aggregate uses is available. Because the dolomite units vary widely in their physical properties, however, tests may be necessary to determine the suitability of a dolomite for a particular purpose. Many of the dolomite units are cherty; this may exclude certain units for some aggregate uses, especially for concrete aggregate, since the chert may be alkali-reactive. It should be remembered that disseminated chert, which cannot be detected by a visual inspection, is present in much of the dolomite.

A small amount of gravel may be found along streams as alluvial deposits. The gravel consists mostly of chert, however, which may preclude its use for some purposes.

VIII. GEOLOGIC HISTORY

Precambrian granite has been found in deep wells at West Plains and Pomona. The age relationship of this granite to other rocks of the Precambrian basement complex cannot be determined from available information, but the emplacement of this granite is the first recorded geologic event in the area.

The length of time between the emplacement of the granite and the first recorded sedimentation is not known. The first known deposition of sediment is recorded in the Lamotte Formation of Upper Cambrian age; following this the remainder of Cambrian and early Lower Ordovician geologic history is recorded in the subsurface by the Bonneterre, Davis, Derby-Doerun, Potosi, Eminence, Gasconade, and Roubidoux formations. No evidence is available in this area to ascertain whether sedimentation has been continuous, but neither can evidence of significant uplift and erosion be found in this area.

The earliest event recorded in rocks cropping out in this area is the deposition of the upper part of the Roubidoux formation. The sea in which it was deposited was probably deeper than it was in some parts of the Ozark region, for the sandstones do not have ripple marks, dessication cracks or cross-bedding.

A change in conditions of sedimentation is indicated from

Roubidoux time to Jefferson City time by the smaller quantities of sandstone and chert in the Jefferson City. However, evidence for a break in sedimentation has not been found.

The Jefferson City and Cotter dolomites record a time of unstable and rapidly changing sedimentary conditions, since the lithology of these formations is quite variable both laterally and vertically. Overall conditions were much the same throughout Jefferson City and Cotter time, but many types of interbedded dolomite and chert, along with sandstone and shale, indicate that conditions of sedimentation were quite variable within certain limits. Lateral changes in lithology throughout most of the section indicate non-uniform sedimentation over the area during most of Cotter and Jefferson City time; most individual beds can be traced laterally for only a short distance. However, a few strikingly uniform marker beds indicate that there were some periods during which sedimentary conditions were uniform and stable throughout the area.

The Powell Formation has been tentatively identified about 5 miles east of Thayer, capping the prominent escarpment in that area, and the formation has been identified in well logs at Ash Flat and Viola, Arkansas. Sedimentation was probably continuous in this area throughout Jefferson City, Cotter, and Powell time, continuing until the end of Smithville (or possibly Black Rock) time. Following deposition of the Smithville (or

Black Rock) Formation, however, the seas retreated from the area as the Ozark region was uplifted. A long period of erosion occurred, truncating several previously deposited formations before the St. Peter and Everton sandstones were deposited upon the erosional surface.

Following deposition of the St. Peter and Everton sandstones, no record of sedimentation is found in this region until Mississippian time. An outlier of Burlington limestone northeast of Rover, Missouri (Beveridge, 1967, personal communication) is evidence that the Mississippian seas once covered the area. The patch of Mississippian cherts near Thayer were probably reworked after Mississippian time, and they may have been transported by streams from another area.

The area has undergone a period of faulting which, if it is a continuation of and contemporaneous with the faulting in the Graydon Springs fault zone, probably occurred some time after deposition of the Krebs Subgroup of the Pennsylvanian System. From evidence in this area, however, it can only be reliably dated as following deposition of the lower Cotter strata.

The geologic history of this area is not clear after Mississippian time, but it is generally agreed that the Ozark region has been a positive area since the close of Pennsylvanian time. The post-Pennsylvanian geomorphic history of the Ozark region is currently a subject of debate, and the reader is referred to Bretz (1965) and Hack (1960) for a discussion of the problem. The Ozark region has been uplifted appreciably, however, and it is presently undergoing erosion.

IX. CONCLUSIONS

1) The contact between the Cotter and the Jefferson City formations can be mapped in the Thayer area by using several marker beds and zones. The stratigraphic position of the marker horizons with respect to the contact can be determined by measuring and describing outcrop sections containing the marker horizons, giving particular attention to the percentages and types of insoluble residue present; logging the section in the same way and to the same scale that the Missouri Geological Survey logs insoluble residues of well cuttings; and correlating the log strip of the outcrop sections with actual well logs in the area and with McCracken's (undated, unpublished) insoluble residue chart. The accuracy of the log strip sections is greatly increased by taking representative samples of the dolomite for each measured interval, preparing insoluble residues of the dolomite, and adding the percentage of disseminated chert contained in the dolomite to the percentage of residue visible in outcrop.

Several reliable marker beds which are useful for mapping the contact between Cotter and Jefferson formations exist in the Thayer area. Because the insoluble residue zones of the Cotter and Jefferson City formations are recognizable throughout the state of Missouri in the subsurface, and because local marker horizons are probably available for the section anywhere the formations crop out, mapping of the contact between the two formations should be possible anywhere within their outcrop area by applying subsurface techniques to outcrop sections.

2) Correlation between measured sections and well logs is possible for the Cotter and Jefferson City formations in this area by using marker beds, insoluble residue zones, dolomite zones, and other distinctive zones. With these methods local and regional correlations should be possible between outcrop sections throughout the Ozark region.

3) The Quarry Ledge is recommended as a structural datum for subsurface work, because of its uniformity and its easily recognized characteristics. The top of the Roubidoux Formation is erratic and not always easy to delineate.

4) Certain facies changes in the Cotter and Jefferson City formations have been noted from the Thayer area to the Ash Flat, Arkansas area. The most significant changes are a southerly decrease in chert, with an increase in the overall purity of the dolomite. These facies changes may be the beginning of a southeasterly gradation into the almost chert-free dolomitic limestones and pure limestones described by Caplan (1960, p. 7-8) for areas about 60 miles south and southwest of Ash Flat, Arkansas. They may also be related to a sedimentary basin in northeast Arkansas, which has been indicated by McCracken (1968, personal communication).

5) The Thayer area has undergone a period of block faulting, much of which involves vertical displacements on the order of 100 to 300 feet. The faulting in this area may be part of a regional fault zone which the writer believes to cross much of southern Missouri in a general east-west direction. It may also be related to the Graydon Springs fault zone, which has been mapped from near Eldorado Springs, Missouri to near Mansfield, Missouri, and which is directly in line with the Thayer area. The strikes of individual faults are almost impossible to trace in the field, but aerial photographs are of great benefit in mapping the faults because the fault traces are visible on the airphotos as lineations.

6) The Thayer area does not lend itself well to a stratigraphic study because of extensive faulting in the area; but on the other hand, a stratigraphic study is necessary before faulting can even be detected.

7) Some of the solution features have been related to faulting in the area, but much work on the solution phenomena of the area is yet to be done. The existence of the sinkhole plain west of Koshkonong, which stands alone in an area not characterized by karst topography, has not been satisfactorily explained; and the origin of Grand Gulf has not been explained entirely to the writer's satisfaction. The subsurface connection between Grand Gulf and Mammoth Spring has been established by Aid (1967,

unpublished report). Mammoth Spring has been found to rise along a fault plane and near the intersection of two fault zones.

8) The literature pertaining to the Jefferson City, Cotter, Powell, and Smithville formations is confusing. It is evident from examining various references pertaining to these formations that the names have been applied by different writers to different parts of the Lower Ordovician section. For example, the writer is not convinced that the part of the section currently assigned to the Cotter Formation by the Missouri Geological Survey even crops out in the Cotter, Arkansas "type area". Perhaps this confusion could be at least partly resolved by reexamining the outcrop sections which have been described by various workers, applying subsurface techniques to these outcrop sections, and correlating them with McCracken's (undated, unpublished chart) standard insoluble residue chart. The writer is not certain that the formation boundaries of this chart agree with the formation boundaries as originally defined; but on the other hand, the original boundaries are so poorly defined that the only logical solution is to accept McCracken's chart as the standard Lower Ordovician section without regard to previous definitions. This view is held because of the great strides that have been made by the Missouri Geological Survey in their subsurface work on these formations since their adoption of the insoluble residue technique; and because of the great amount of subsurface data available on these formations in the form of well

logs, all of which is based on McCracken's insoluble residue chart.

Cullison's (1944) work is an excellent reference on the Lower Ordovician section, and his descriptions would provide a valuable basis for a re-study of the section. It should be remembered, however, that his formations do not correspond to the formations recognized by the Missouri Geological Survey.

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XI. VITA

William Jesse Hedden was born on July 16, 1943, in Thayer, Missouri to Wilbur Jesse Hedden and Henrietta Elizabeth Hedden. He received his primary education at Thayer Grade School, and graduated as salutatorian from Thayer High School in May of 1961.

In September of 1961 he began his undergraduate study in the Department of Physics at the University of Missouri at Rolla (then the University of Missouri School of Mines and Metallurgy), but he transferred to the Department of Geology in 1963. He left the University in 1965 to fill a temporary vacancy at Thayer Senior High School, where he taught mathematics and physics for one year. He returned to the University in September of 1966 as a dually-enrolled student, and he also began service as a teaching graduate assistant at that time. In January of 1967 he graduated with First Honors and received a Bachelor of Science Degree in Geology, and was also commissioned as a reserve officer in the United States Army Corps of Engineers.

Following graduation he began full-time study in the Graduate School of the University of Missouri at Rolla as a geology major. While enrolled there, he was married to Neoma Fay Jones on August 12, 1967. After completing requirements for the Master of Science Degree in Geology in September, 1968, he will begin a two-year period of active duty in the United States Army Corps of Engineers.

GEOLOGIC MAP OF THE THAYER AREA

by William J. **Hedden**

PLATE I.

LEGEND

Mo (?) MISSISSIPPIAN (Osagean) fossiliferous chert, probably reworked.

ORDOVICIAN

Oc COTTER FORMATION

Ojc JEFFERSON CITY FORMATION

Or ROUBIDOUX FORMATION

_________ VISIBLE CONTACT

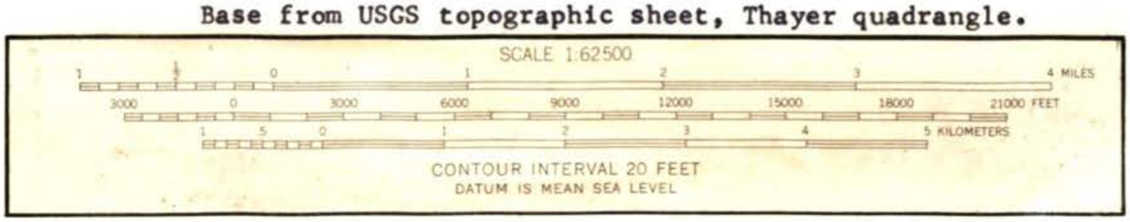
--------- INFERRED CONTACT

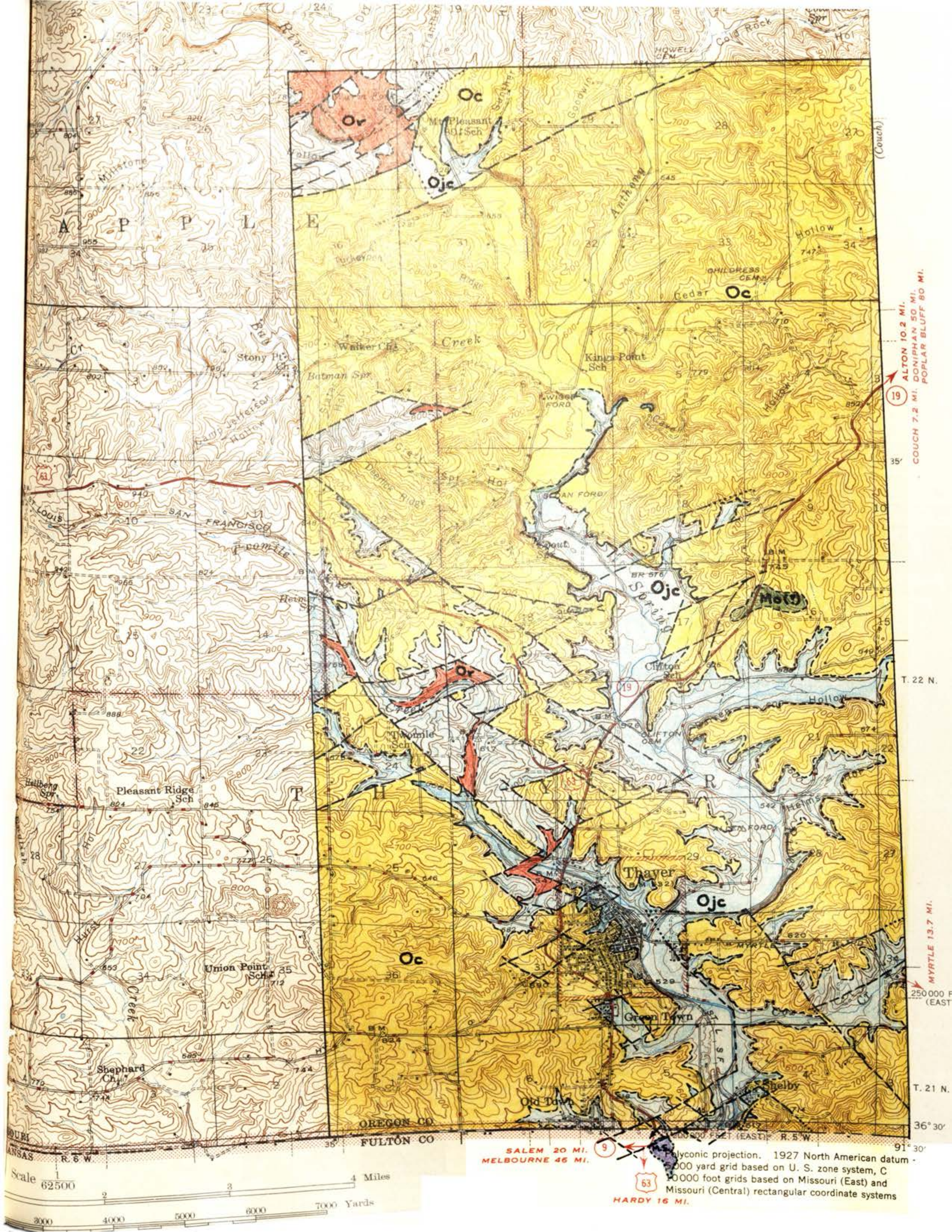
\- - - - - FAULT INFERRED FROM STRUCTURAL CONTROL AND AIRPHOTO LINEATIONS

.... FAULT INFERRED FROM STRUCTURAL CONTROL, BUT EXACT POSITION UNKNOWN

MONOCLINE

Base from USGS topographic sheet, Thayer quadrangle.





Scale 1/62500

Polyconic projection. 1927 North American datum - 5000 yard grid based on U. S. zone system, C 10000 foot grids based on Missouri (East) and Missouri (Central) rectangular coordinate systems

STRUCTURAL MAP OF THE THAYER AREA

by William J. Hedden

PLATE II.

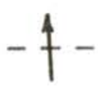
Structural Datum: Top of Roubidoux Formation

Figures are datum elevation within a fault block or spot elevations in unfaulted areas.

LEGEND

\- - - - - FAULT INFERRED FROM STRUCTURAL CONTROL AND AIRPHOTO LINEATIONS

.... FAULT INFERRED FROM STRUCTURAL CONTROL, BUT EXACT POSITION UNKNOWN

 MONOCLINE

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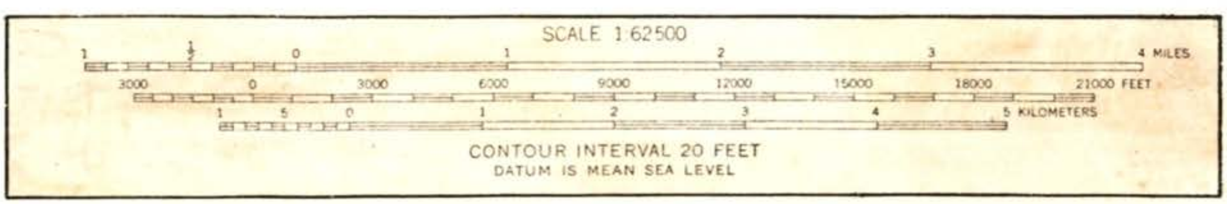
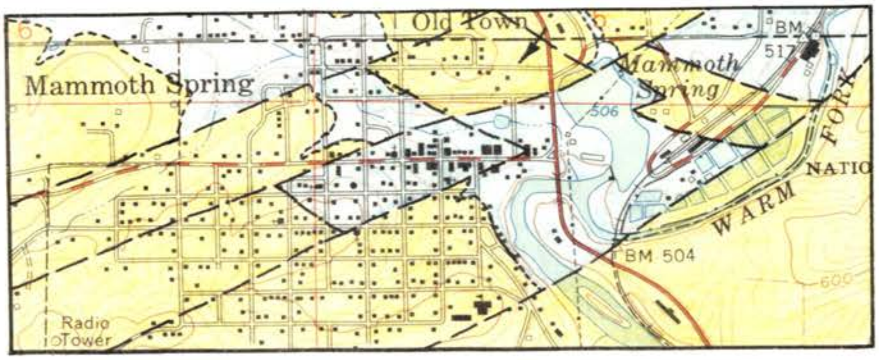


GEOLOGIC MAP OF THE MAMMOTH SPRING AREA

by William J. Hedden

PLATE III.



L E G E N D

ORDOVICIAN

Oc	COTTER FORMATION
Ojc	JEFFERSON CITY FORMATION

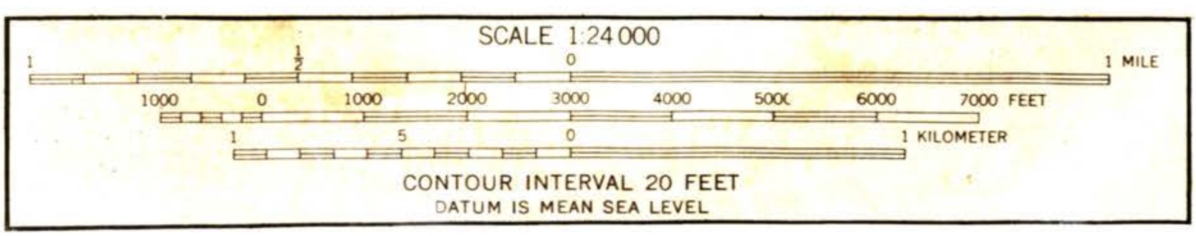
———— VISIBLE CONTACT

------------ INFERRED CONTACT

– – – – – – FAULT INFERRED FROM STRUCTURAL CONTROL AND AIRPHOTO LINEATIONS

–†– MONOCLINE

Base from USGS topographic sheet, Mammoth Spring quadrangle.



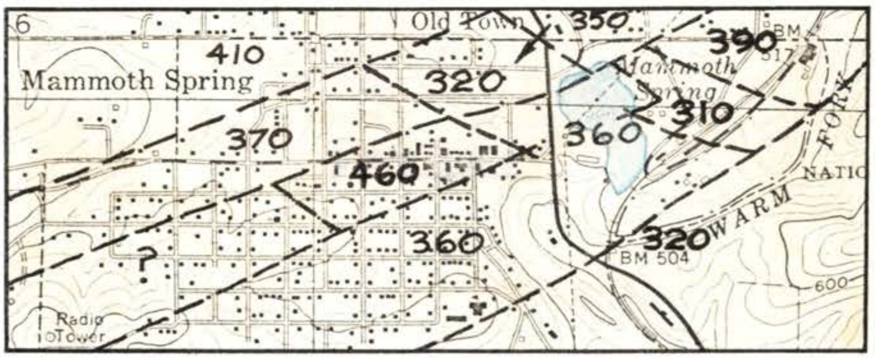
STRUCTURAL MAP OF THE MAMMOTH SPRING AREA

by William J. Hedden

PLATE IV.

Structural Datum: Top of Roubidoux Formation

Figures are datum elevation within a fault block or spot elevations in unfaulted areas.



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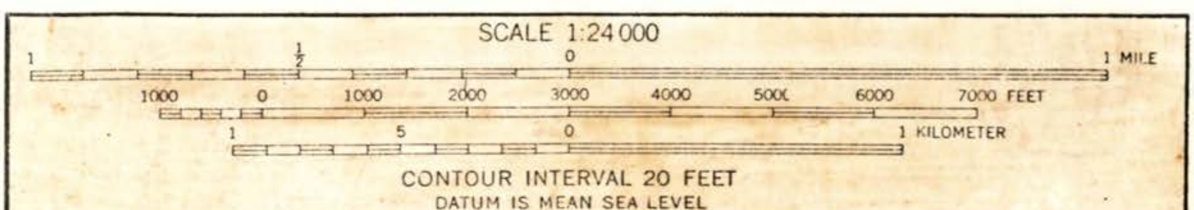
MONOCLINE

Base from USGS topographic sheet, Mammoth Spring quadrangle.



LIST OF ABBREVIATIONS FOR STRATIGRAPHIC SECTIONS

PLATE V

I. ROCK AND MINERAL TYPES

cot rk---------------------------"cotton rock"
dolo-----------------------------dolomite
qtz------------------------------quartz

II. DOLOMITE CRYSTAL SIZES

aphx-----------------------------aphanocrystalline
vfx------------------------------very finely crystalline
fx-------------------------------finely crystalline
mx-------------------------------medium crystalline
cx-------------------------------coarsely crystalline

III. SAND SIZES

vf-------------------------------very fine
f--------------------------------fine
m--------------------------------medium
c--------------------------------coarse

IV. CHERT TYPES

d--------------------------------dead
sm-------------------------------smooth
tr-------------------------------translucent

V. COLORS

bn-------------------------------brown
bnsh-----------------------------brownish
gy-------------------------------gray
gysh-----------------------------grayish
wh-------------------------------white

VI. MISCELLANEOUS

bed------------------------------bedded
brec-----------------------------brecciated, breccia
dk-------------------------------dark
frag-----------------------------fragment (s), fragmental
IR-------------------------------insoluble residue
irreg----------------------------irregular
lt-------------------------------light
med------------------------------medium
mot------------------------------mottled
nod------------------------------nodule (s), nodular
vy-------------------------------very
xln------------------------------crystalline