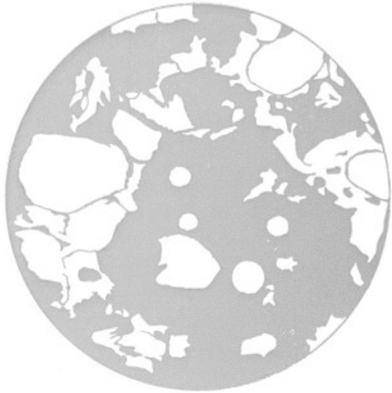
LAPILLI TUFFS AND ASSOCIATED PYROCLASTIC SEDIMENTS

IN UPPER CAMBRIAN STRATA ALONG DENT BRANCH WASHINGTON COUNTY MISSOURI



BY
RICHARD E. WAGNER

AND
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REPORT OF INVESTIGATIONS NUMBER FORTY THREE 1969
MISSOURI GEOLOGICAL SURVEY AND WATER RESOURCES
WILLIAM C. HAYES · STATE GEOLOGIST AND DIRECTOR

PHOTOGRAPH (right) Outcrop of tuffaceous siltstone.

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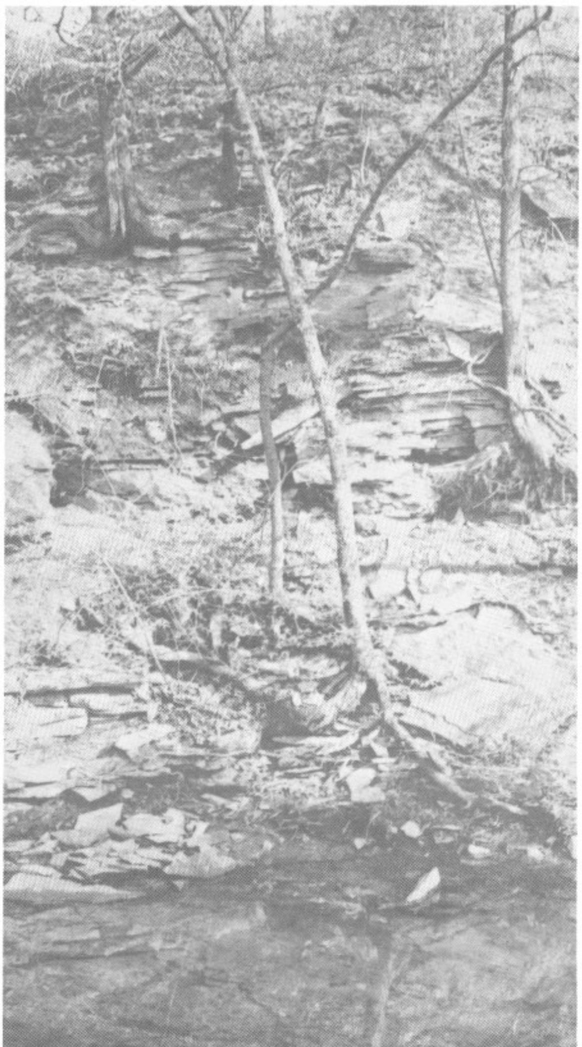

By Richard E. Wagner
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MISSOURI GEOLOGICAL SURVEY & WATER RESOURCES
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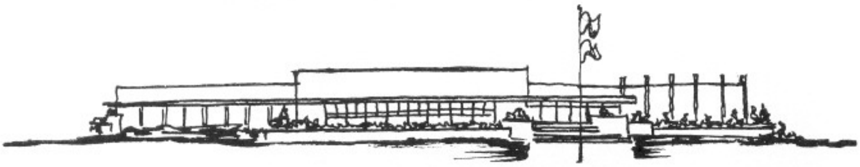

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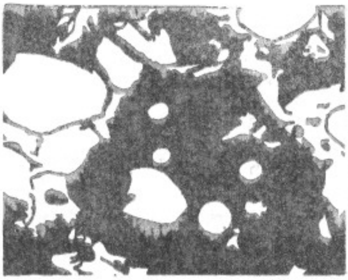

THE COVER

The Dent Branch deposit is thought to be the result of a volcanic vent eruption which has been carefully studied using both field and petrographic methods. The cover drawing represents weathered volcanic fragments in lapilli tuff groundmass.

ILLUSTRATIONS

ILLUSTRATIONS (Continued)

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ABSTRACT

Late Cambrian pyroclastic rocks are exposed along the northwest flank of the St. Francois Mountain region of Missouri. These rocks occur in the lower third of the Bonneterre Formation and are the oldest exposed post-Precambrian pyroclastics in Missouri. They represent a previously unknown center of explosive volcanic activity during early Paleozoic time.

The exposed pyroclastics have a maximum known thickness of 80 feet and consist of lapilli tuffs, tuffaceous sandstones, and tuffaceous siltstones. These rocks occur in scattered outcrops over an area 1,600 by 5,000 feet in extent. To the east and south of these outcrops the underlying Bonneterre dolomite and Precambrian felsite are exposed; to the west and north the pyroclastic rocks are overlain by Bonneterre dolomite. Drill holes indicate that the pyroclastic section thins toward the west of the Dent Branch exposures.

The lapilli tuffs represent pyroclastic material ejected through a vent or vents, deposited in a marine environment, and partially reworked. They consist of brecciated fragments of older rocks (accidental lapilli) and chloritized sideromelane vitrophyre (essential lapilli) in fine grained tuffaceous carbonate mesostasis. The tuffaceous sandstones and tuffaceous siltstones were derived from the lapilli tuffs by reworking.

The exposed pyroclastic rocks are interpreted to have been associated with a diatreme but the underlying pipe could not be located by the field and petrographic methods used. The occurrence may indicate a line of structural instability in the underlying Precambrian basement along which explosive breakthroughs of magmatic material had occurred. The magma that triggered the explosions is assumed to have been basic to ultrabasic in composition, possibly with alkalic affinities. The mode of origin and the composition of the lapilli tuffs resemble those found associated with alkalic ultrabasic complexes in tectonically stable continental areas in other parts of the world.

INTRODUCTION

Lapilli tuffs, tuffaceous sandstones, and tuffaceous siltstones deposited contemporaneously with Upper Cambrian carbonate sediments are exposed in the Dent Branch area, Washington County, Mo. These rocks are unique in Missouri because they are the oldest known post-Precambrian pyroclastics in outcrop. They also indicate a heretofore unknown center of explosive volcanic activity.

The interest in post-Precambrian igneous activity in Missouri has been revived by Snyder and Gerdemann (1965), who summarized previously published information on diatremes, cryptovolcanic structures, and structurally disturbed areas in the State; presented them in a new light as having resulted from explosive igneous activity operating on a regional scale during different periods of post-Precambrian geologic history and controlled by deep-seated tectonic forces; and described a previously unknown center of such activity, the Furnace Creek volcanics of Late Cambrian age. Another occurrence of the same age has been located by drilling in the Bee Fork area of northwestern Reynolds County in the course of mineral prospecting campaigns. The Dent Branch deposit of pyroclastic rocks represents the latest discovery of such activity in the area.

Compared to other known deposits of similar origin in southeastern Missouri, the Dent Branch rocks are the oldest in outcrop. Both the Furnace Creek and Bee Fork volcanics are slightly older but are known only from drill core information. The Avon diatremes (Kidwell, 1946) are not only much younger, but erosion has cut deeper into those structures to expose erosional remnants of volcanic necks. The Dent Branch deposit is pyroclastic material that was ejected through a vent or crater, deposited in shallow marine environment, and subsequently reworked into bedded sedimentary rocks.

The lapilli tuffs were first noted during the summer of 1965 by J. A. Martin and J. H. Williams of the Missouri Geological Survey in a road ditch several hundred feet west of the intersection of State Supplementary Highway C and Dent Branch, in sec. 3, T. 35 N., R. 2 E. (pl. 1). The exposure was subsequently referred to as containing angular fragments of "rhyolite, diabase and limestone", questionably identified as volcanic ejecta (Snyder, Williams, et al., 1965, p. 30). The proximity of the exposure to the Furnace Creek volcanic structure, located about 4 miles to the north-northeast has also been pointed out. At the time of the discovery the alternate possibility that the deposit might be an arkosic conglomerate was considered.

The purpose of this study is to determine the origin of the deposit;to determine textural and compositional variations of the different rock types within the deposit in order to aid in recognition of possible similar deposits elsewhere; and to establish spatial relationships of various rock types within the deposit to each other in order to reconstruct the combined course of events that produced it.

Both field and laboratory methods were applied in this investigation. Intermittent field work during 1966-67 consisted of reconnaissance mapping of the pyroclastic deposits and surrounding rock formations, and sampling. Interpretation of field relationships was difficult because a considerable part of the area is soil-covered and there are no deep cuts or drill holes in the immediate vicinity. Heavy rains occasionally uncovered new evidence during the investigation by causing new exposures on the hillsides and in the creek bed. Although no precise surveying was done the map is considered sufficiently accurate for the purposes of the study.

Approximately 60 samples were collected for microscopic examination and detailed petrographic work was performed on 28 thin sections during the latter part of 1967. A few samples were selected for spectrographic and X-ray diffraction analysis. Both authors collaborated in all phases of the study. R. E. Wagner was mainly responsible for mapping and sampling in the field, and for preparation of the outcrop map and cross sections. The petrographic description and explicit determination of rock types was done by E. B. Kisvarsanyi.

The authors are grateful to Mr. Paul Gerdemann, chief geologist, Southeast Missouri Division, St. Joseph Lead Company, for making available drill hole records and cores in the area; to Mr. Harold Myers, geologist, St. Joseph Lead Company, for some field assistance and map reproduction; to Dr. Sheldon Kerry Grant, assistant professor, University of Missouri-Rolla, for aid in X-ray diffraction analysis and critical review of the petrographic chapter of the manuscript; and to several staff members of the Missouri Geological Survey for constructive discussions. Thanks are also due Messrs. Drew, Rowles, Luther, and Richards, on whose respective lands the outcrops are located, for their cooperation.

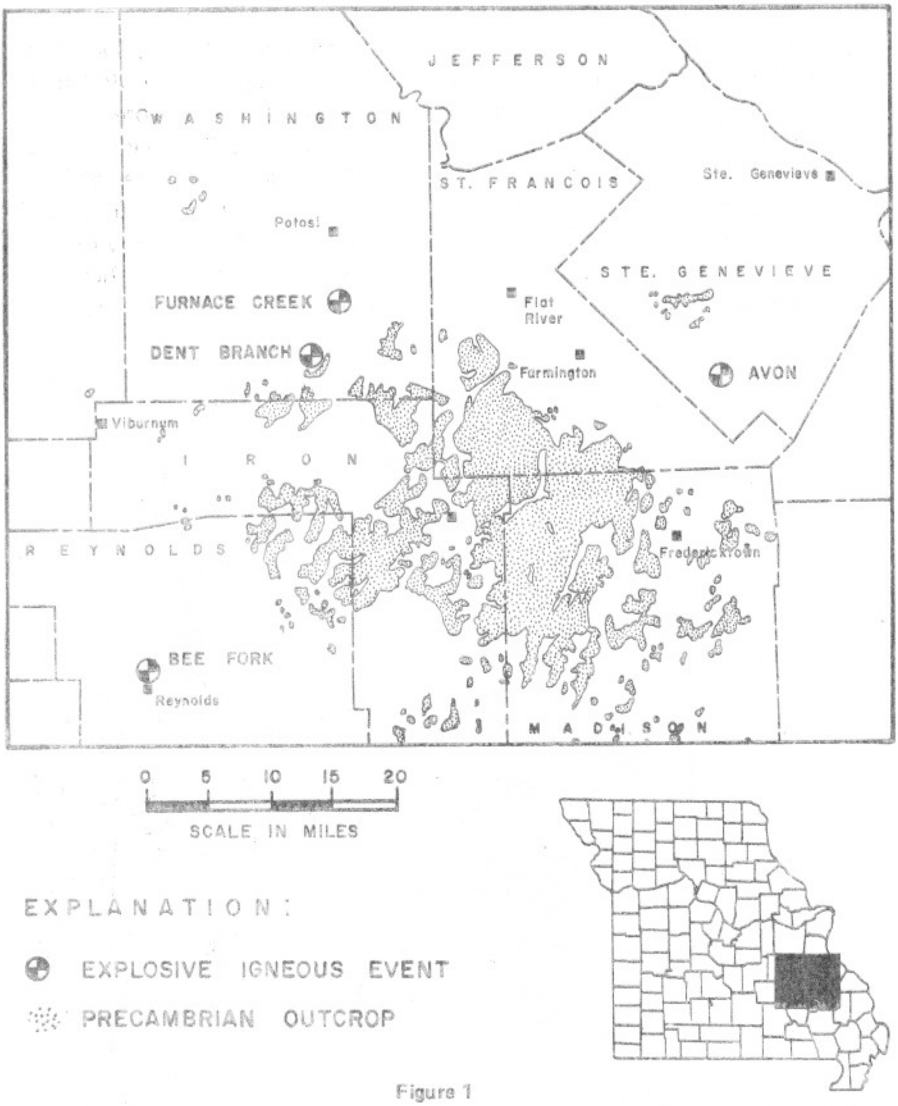


Figure 1

Index map showing the location of the Dent Branch deposit in relation to Precambrian outcrop areas and other explosive igneous events in southeast Missouri.

GEOLOGIC SETTING

The outcrop of the Dent Branch pyroclastic rocks is on the northern flank of the Precambrian St. Francois Mountain region which lies near the eastern end of the Ozark dome (fig. 1). The normal geologic column in the immediate area consists of Precambrian extrusives and overlying Upper Cambrian and Lower Ordovician sediments as shown in plate 1. In ascending order the Upper Cambrian formations include the Lamotte Sandstone and the Bonneterre, Davis and Derby-Doerun formations. The general nature of these formations has been described by Buckley (1909), Weller and St. Clair (1928), and others. Local geologic relationships have been described in detail by Dake (1930) but he made no reference to the pyroclastics.

The pyroclastic rocks are exposed near the center of an area of Bonneterre outcrop about 4 by 6 miles in extent (pl. 1). The regional dip of the Bonneterre Formation here is to the northwest and it passes under the overlying Davis Formation in that direction. On the southeast the underlying Lamotte Sandstone and Precambrian felsite hills are exposed. On the northeast the Bonneterre outcrop area is bounded by a graben in the Palmer fault system, which drops the Eminence Dolomite into juxtaposition with the Bonneterre on the north side of the graben, a throw of 800 to 900 feet. On the southwest the Johnson and Pruitt Mountain Precambrian exposure cuts off the Bonneterre Formation. Some of the overlying Davis and Derby-Doerun formations are preserved on the higher flanks of this igneous area that is part of the northern edge of the St. Francois Mountain region.

The gentle northwestward dip of the Bonneterre is interrupted in the central part of its outcrop area by a north-northeast trending exposed felsite ridge (Akers and Kitchell Hills) which is part of a buried Precambrian ridge extending northeastward from the Johnson-Pruitt Mountain exposure. The outcrop of the pyroclastic rocks roughly parallels this ridge about 500 to 1,500 feet to the west, and generally follows the course of Dent Branch.

The pyroclastic rocks incorporate fragments derived from Precambrian rocks, the Lamotte Sandstone and the Bonneterre Formation and their study requires identification of these fragments. The age relationships of the formations involved in the development of the pyroclastic rocks are important to the understanding of the origin of the deposit. Pertinent features of these formations are described accordingly in the following sections. The sedimentary rocks deposited above the Bonneterre Formation are not involved in the development of the pyroclastic deposit and need no discussion here.

PRECAMBRIAN ROCKS

The rocks of the Precambrian ridge along the eastern edge of the pyroclastic exposures have never been studied in detail. Robertson and Tolman (1960) classify them as felsitic and associated extrusives of unassigned Precambrian age. Reconnaissance examination by the authors indicates that the dominant rock type in the exposure is flow-banded rhyolite porphyry, red to black in color. Similar rocks on the southern part of the ridge are gray and show very little flow banding. The felsite exposed over a considerable area in the vicinity of the shut-in between Akers and Kitchell Hills contains inclusions of rhyolite and diabase fragments ranging upward to 80 mm in diameter. These rocks have been tentatively classified as flow breccias. One thin section from this area shows ophitic diabase fragments in a rhyolitic vitroclastic groundmass with both flow banding and welded glass shards. It is possible that detailed study would identify ignimbrites and other extrusive types in outcrop. However, rhyolite porphyry composes the bulk of the exposure. Other Precambrian exposures shown on plate 1 are of the same general character.

LAMOTTE SANDSTONE

The Upper Cambrian Lamotte Sandstone is not exposed within several miles of the pyroclastic deposit but is known to be present in the subsurface where not truncated along the buried flanks of the felsite ridge. It is the first sediment of record deposited on the Precambrian land surface. In its purest form it is a clean, white, fairly well cemented orthoquartzite. Due to its proximity to the felsite ridge many of the beds are arkosic or shaly and may be gray or red in color, depending on the presence of iron sulfides or oxides, respectively. Generally it is cemented with clay, often poorly so, and some beds have a small amount of carbonate cement. Silica cement is rare. Dake (1930) has described the formation locally and Ojakangas (1960) described it regionally.

Dake gives no estimate of the average thickness of the Lamotte Sandstone in the area as it varies according to the erratic elevations of the underlying Precambrian erosion surface. Using all of the information available from areal geology and drill core records, the elevations of the Lamotte and the Precambrian have been estimated. On this basis a thickness of 170 feet for the Lamotte is indicated at a point on Dent Branch 800 feet north of Highway C. The thickness decreases to zero toward the Precambrian ridge on the south and east, and increases toward the north and west.

BONNETERRE FORMATION

The dominant rock type of the Bonneterre Formation in association with the pyroclastic deposits is a light-colored, coarsely crystalline dolomite, defined and described by Howe (1968) as dolomitized burrowed carbonate mud. Two other rock types are exposed in a small area east of the deposit, beginning from 800 feet north of Highway C and continuing for a distance of about 1,400 feet along Dent Branch. They are (a) tan or gray-tan finely crystalline dolomite, sometimes with sugary texture, and (b) gray, tan, or brown finely crystalline algal dolomite. The tan dolomite is the dominant rock in the 10 zone of the Bonneterre subdivision described by Snyder and Odell (1958) and was deposited as an oolitic calcarenite. The algal dolomite is the characteristic rock of the 7 zone of the same classification. Beds of digitate stromatolite with a matrix of dense, gray-tan dolarenite surrounding brown algal columns occur in the latter. These beds alternate with those of the tan dolomite.

The thickness of the Bonneterre in the area inferred from drill hole and surface information varies between 330 and 360 feet. In this report the formation has been divided into three equal sections, each 110 to 120 feet thick, and designated as the lower, middle, and upper Bonneterre sections. The lower section and the base of the middle section are associated with the development of the deposit and will be described in detail.

The basal part of the middle Bonneterre consists of 30 to 40 feet of light-colored and coarsely crystalline dolomite. Some layers show "netted" boxwork structure and contain relatively minor amounts of greenish-white clay. This part of the formation shows no lateral variation and consistently weathers out into 1-to 3-foot beds. In outcrop it is confined to the western part of the area.

The lower Bonneterre is divided into three approximately equal sections, each about 40 feet thick. The upper third consists in part of alternating beds of tan and algal dolomite. These grade laterally into coarsely crystalline dolomite similar to that at the base of the overlying middle Bonneterre. The middle third also consists of the coarsely crystalline dolomite but is more erratic in bedding, has a higher clay content, and tends to have pinkish-white or greenish-white color. The upper third of the lower Bonneterre covers more area than the middle third in outcrop.

The basal third of the lower Bonneterre section was observed only in drill cores from the adjacent area. It usually consists of gray sandy dolomite and dolomitic sandstone. The upper part of this horizon is often coarsely crystalline and light-colored but sandy. Gray and black arenaceous shale beds are fairly common in the lower portion, as are arkosic beds derived by the erosion of the adjacent felsite ridge. Conglomerate beds from the same source are present at the base of the Bonneterre at and near its contact with the Precambrian.

All of the described rock types, with the possible exception of the algal dolomite, are considered to have been deposited as limestones. They were probably only partially dolomitized at the time of deposition of the pyroclastic rocks.

* * *

DESCRIPTION OF THE DEPOSIT

The pyroclastic rocks are a mixture of various lithologic units and were produced by the cooperation of two major rock-forming processes: volcanism and sedimentation. They consist of pyroclastic ejecta deposited in a sedimentary environment. To add to their complexity various transitional types between those distinctly pyroclastic and those distinctly sedimentary are present. The former are typically unsorted, non-bedded lapilli tuffs ***in situ***; the latter are well sorted, bedded sandstones and siltstones that were formed by selective reworking of the lapilli tuffs by water, but transported only relatively short distances. Gradational types are apparently more widespread in exposure and their proper classification is most difficult. Pyroclastic ejecta are ubiquitous, however, and constitute the basis for relating these rocks to volcanic activity.

By mode of emplacement all the rocks are sedimentary; their components were deposited in water during conditions of carbonate sedimentation. They are clastic sediments with a varying amount of chemical matrix. The ultimate source of the clastic components, however, is volcanic; they were produced by volcanic explosions that tore vents through and fragmented pre-existing rock formations estimated at several hundred feet in thickness. The fragmented rocks were mixed with primary magmatic material, expelled through the openings as ejecta of various size, shape, and lithology, and were subsequently deposited in marine environment.

The fragmented rocks were derived from Precambrian igneous rocks, the Lamotte Sandstone and the Bonneterre Formation, the latter represented by both limestone and dolomite. Fragmentation of the igneous and the carbonate rocks produced typically angular ejecta of a wide size range; the sandstone, being the most friable of the overlying rocks, was broken into its component quartz sand grains and fragments thereof. Sandstone fragments are rare among the ejecta but whole and comminuted sand grains are ubiquitous. The result is that even the unreworked lapilli tuffs are quite sandy. Selective reworking of the pyroclastic material during quiet periods between the volcanic events concentrated the quartz sand ejecta to form rocks much like detrital sedimentary sandstones; the comminuted silt-size quartz fragments were concentrated into laminated siltstones.

DEFINITION OF TERMS

The present classification follows that suggested by Wentworth and Williams (1932) for pyroclastic rocks and that outlined by Pettijohn (1957) for sedimentary rocks in that it considers grain size as the primary diagnostic feature. Terms used are briefly summarized below.

Pyroclastic ejecta in general refer to fragmented material of any size, shape, and composition that were produced by explosive ejection from a volcanic vent. They are characterized by the fact that their size and shape are primary; that is, in no way were determined by the action of epigene geomorphic agents.

Pyroclastic ejecta are classified according to size as ***blocks*** (>32 mm in diameter), ***lapilli*** (4-32 mm) and ***ash*** (<4 mm). Blocks are interpreted as having been solid at the time of ejection and include the occasional large fragments torn from pre-existing formations that the vents passed through. As none of the rock types in the Dent Branch area are made up entirely or even dominantly of blocks, the corresponding rock term "breccia" will not be used here.

The term ***lapilli*** will be used strictly as a size term according to the generally accepted definition of Wentworth and Williams (1932, p. 47), denoting ejecta in the 4-32 mm size range. Rocks made up predominantly of lapilli size ejecta in a matrix of finer ejecta and/or sedimentary materials will be called ***lapilli tuffs.***

The adjectives essential, accidental, and accessory refer to the nature of ejecta in any size range. ***Essential*** denotes primary magmatic material, still liquid or plastic when ejected, including pumiceous and scoriaceous fragments; ***accidental*** is used to designate ejecta derived from previously solidified rocks through which the vent was developed. The latter include igneous, metamorphic, or sedimentary rocks not genetically related to the volcanic activity. ***Accessory*** refers to "...pyroclastic materials derived from previously solidified volcanic rocks of consanguineous origin, i.e., the debris of earlier lavas and pyroclastic rocks from the same cone..." (Wentworth and Williams, 1932, p. 45). This type ejecta were not positively identified in the deposit. Rocks composed predominantly of essential or accidental lapilli are called essential or accidental lapilli tuffs, respectively.

In pyroclastic terminology ***ash*** is defined as "...uncemented pyroclastic debris consisting of fragments mostly under 4mm in diameter. Coarse ash is from 4 to ¼mm in grain size; fine ash is under ¼mm. Without a qualifying adjective ash should be applied only to essential or juvenile ejecta; accessory ash is due to the comminution of already solid material; accidental ash refers to finely pulverized rocks of completely foreign origin, fragments of bedrock, etc." (Wentworth and Williams, 1932, pp. 45-46). Rocks consisting predominantly of indurated volcanic ash are called ***tuff***, accessory tuff or accidental tuff, depending on the nature of the ash-size ejecta.

If the above terminology were strictly applied to the rocks in the Dent Branch area, those composed predominantly of quartz sand ejecta 2 to ¼mm in size would be called coarse accidental tuff, and those composed of quartz sand and silt ejecta less than ¼mm in size would be called fine accidental tuff. It is impractical to apply these terms to rocks that are mostly sedimentary and consist of reworked volcanic material. The appropriate sedimentary terms sandstone and siltstone are more descriptive. Therefore, rocks made up predominantly of quartz sand grains 2 to 1/16mm in size and containing lapilli and both essential and accidental ash are defined here as ***tuffaceous sandstones***; those consisting chiefly of quartz silt grains less than 1/16mm in size and containing essential and accidental ash are referred to as ***tuffaceous siltstones***. Transitional rock types are named according to their dominant aspect. Sandy lapilli tuff indicates a coarse pyroclastic rock with visible sand grains.

The term ***mesostasis*** is used in reference to the microcrystalline and crystalline matrix in which the clastic components of the lapilli tuffs and tuffaceous sandstones are embedded. Exclusive usage of the term for this material serves to distinguish it from the groundmass or matrix within the clastic components themselves, such as that within the rhyolite fragments or that within the vitrophyre fragments.

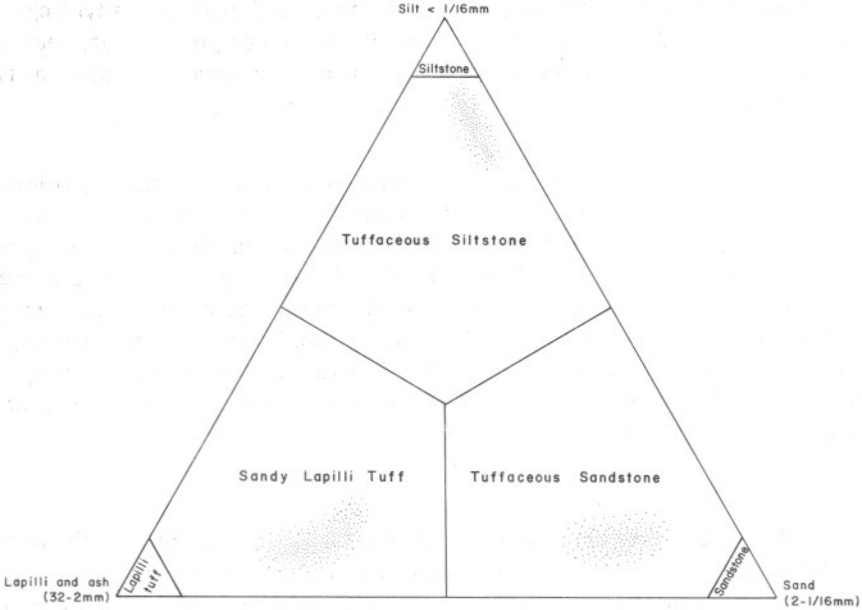


Figure 2

Classification of the pyroclastic rocks.

Figure 2 illustrates the adopted classification on a composition triangle. The average mechanical composition of the major rock types is represented by the shaded areas. Their overall composition in terms of the essential and accidental ejecta and the mesostasis is shown in figure 3 in a generalized way. Actually, all the lapilli tuffs in the Dent Branch area are sandy, as seen in figure 2, but the adjective will not always be used in the text.

ROCK TYPES

The primary subject of this investigation is the main area of outcrop of pyroclastic rocks as shown in plate 2. This outcrop is elongated in a north-northeast direction mainly along Dent Branch and its western bank, has a length of more than 5,500 feet, and varies in width from 50 to 1,600 feet. Two smaller exposures of pyroclastic rocks, about 4,500 feet downstream along Dent Branch and near its confluence with the Big River on the north, are shown in plate 1.

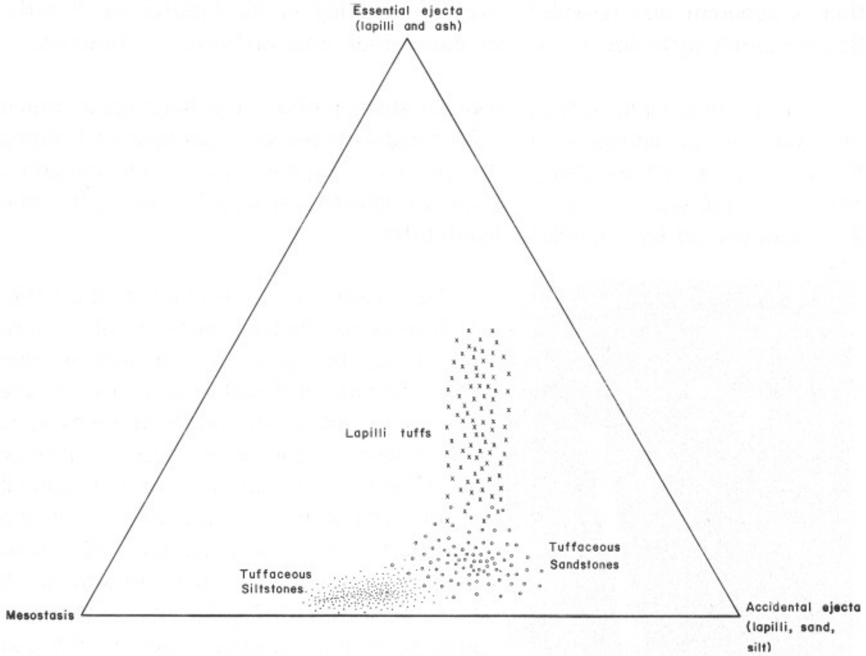


Figure 3

Composition of the pyroclastic rocks.

LAPILLI TUFFS

Lapilli tuffs are the most widespread of the Dent Branch pyroclastics and comprise about 60 percent of their outcrop area (pl. 2). For the most part these are primary rocks (meaning that the material has not been moved from its place of deposition before its lithification) in contrast to the reworked sandstones and siltstones. This factor determines both the lithology and texture of the lapilli tuffs. Their bulk composition represents most closely the material expelled from the vents. They are not sorted and are typically non-bedded, but primary gravity settling of the ejecta in water developed a crude stratification that is apparent and resembles irregular bedding in the massive lapilli tuffs. Bedded lapilli tuffs also occur and these grade into tuffaceous sandstones.

In the field lapilli tuff outcrops are distinguished by differences in degree of induration, percentage of essential material, presence or absence of bedding features, and, to some extent, in the size and composition of accidental lapilli. Three principal types of lapilli tuffs are recognized: (a) type 1, massive; (b) type 2, porous; and (c) type 3, bedded lapilli tuffs.

Figure 4
Outcrop of type 1 lapilli tuff in the discovery area, north of Highway C.

The massive rock identified as type 1 (fig. 4) is an extremely hard, dense, weather-resistant rock, dark gray in color and mottled green. Its outcrop is restricted to a small area along and just to the north of Highway C (pl. 2) where it can be traced in outcrop for about 500 feet. It contains essential material in the best state of preservation of all the pyroclastic rocks and display the crude primary bedding features of ***in situ*** lapilli tuffs. Graded bedding is observed that results from thin irregular layers of ash and sand alternating with those of essential and accidental lapilli. These layers are not sharply defined and floating grains of coarser ejecta may be seen in the dominantly fine grained layers, and vice versa. The rock contains red rhyolite, white limestone, and tan dolomite fragments and green chloritic lapilli in dark gray tuffaceous mesostasis with visible sand grains. The mesostasis also contains

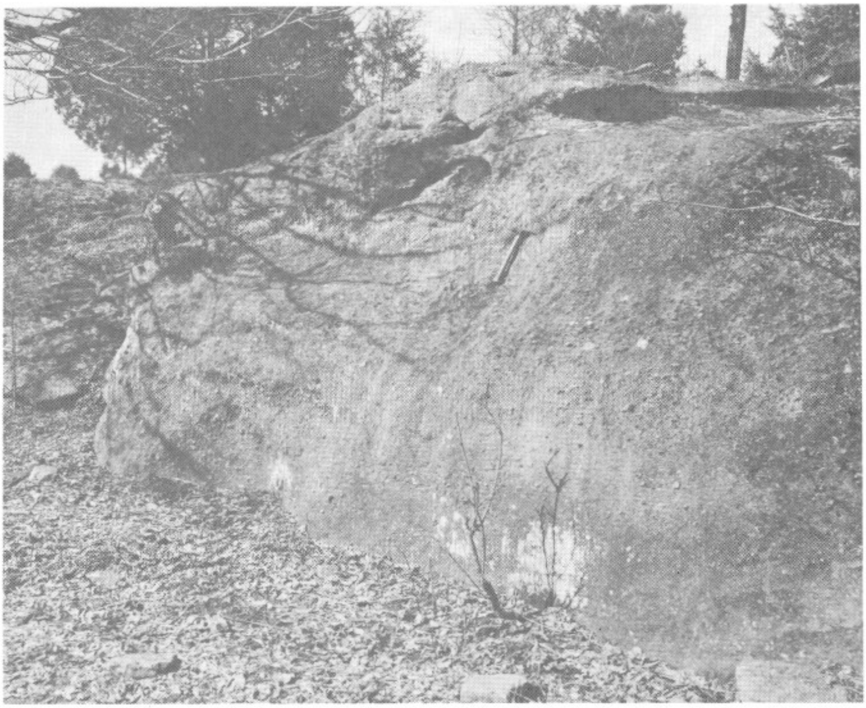


Figure 5

Mound of type 2 lapilli tuff with overlapping tuffaceous sandstone (Middle Sand beds).

calcite as indicated by its effervescence in cold dilute hydrochloric acid, but the calcite is not visible in hand specimen. This type of lapilli tuff is distinguished from type 2 primarily on the basis of its extreme hardness and darker color.

The buff-colored earthy rock that weathers easily has been defined as the type 2 lapilli tuff. It is present in outcrop as large massive mounds up to 10-feet high (fig. 5), is non-bedded and unsorted. Its clastic composition is generally the same as that of the more indurated type 1 lapilli tuffs, but its mesostasis is porous, relatively soft and earthy, and dolomitic. Its color is more uniform because both the clastic components and the mesostasis have a bleached effect.

Lapilli tuffs of type 2 grade imperceptibly into slightly reworked types, the latter exhibiting increasingly apparent bedding, but with lapilli-size material still predominating and not showing the effects of transportational wear. These transitional, type 3 lapilli tuffs are the most widespread in outcrop. It is usually impossible to tell what has been moved and what has not, but evidently the distances involved were not great and there are no valid criteria to distinguish between ***in situ*** and slightly reworked porous lapilli tuffs. The slightly reworked lapilli tuffs grade into tuffaceous sandstones with a marked decrease of lapilli-size material and development of massive bedding.

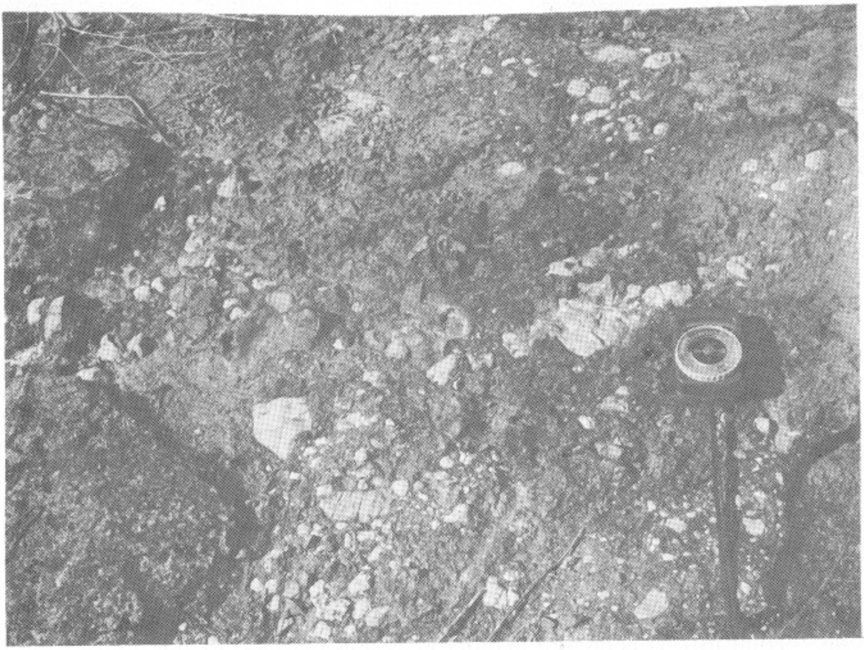


Figure 6

Sandy lapilli tuff with predominance of light-colored limestone and Precambrian rhyolite lapilli.

In addition to the bedding features described above, the lapilli tuffs display sub-horizontal zones that show a preponderance of different kinds of accidental ejecta. Practically all lapilli and blocks may consist of white limestone and red rhyolite in one zone (fig. 6); in another these may be sandstone and tan dolomite. These zones are somewhat vague but can be traced for short distances from one outcrop to another. Some exposures are notable for the inclusion of unusually large amounts of accidental blocks up to 2 feet in diameter. Other beds show a high percentage of ash and small essential lapilli with only a minor amount of larger ejecta. In some areas the amount of essential material is very low. Sand grains are ubiquitous in all lapilli tuffs but do show some variation in amount.

In conclusion, the lapilli tuffs (although subject to the variations described) constitute a single pyroclastic rock type because they are composed of differing percentages of the same materials, derived from the same sources, deposited in the same fashion, and are readily recognizable as belonging to a single rock type.

TUFFACEOUS SANDSTONES

Bedded and sorted tuffaceous sandstones comprise approximately 30 percent of the pyroclastic rocks in outcrop. They are distinguished from bedded lapilli tuffs primarily on the basis of the grain size of their clastic constituents, which is generally less than 2 mm. However, they do contain variable amounts of lapilli-size material.

The overall composition of both the lapilli tuffs and the tuffaceous sandstones is essentially the same. All of the clastic components observed in the lapilli tuffs are present in the tuffaceous sandstones; only their relative proportions, grain size, and state of preservation are different. More significant is the fact that the sandstones do not contain any clastic components that are not present in the lapilli tuffs. In fact, the two types are seen in the field to grade imperceptibly into each other by changes in proportion of lapilli-size material. The sandstones are directly derived from the lapilli tuffs by selective reworking of the finer-grain size fraction of the latter.

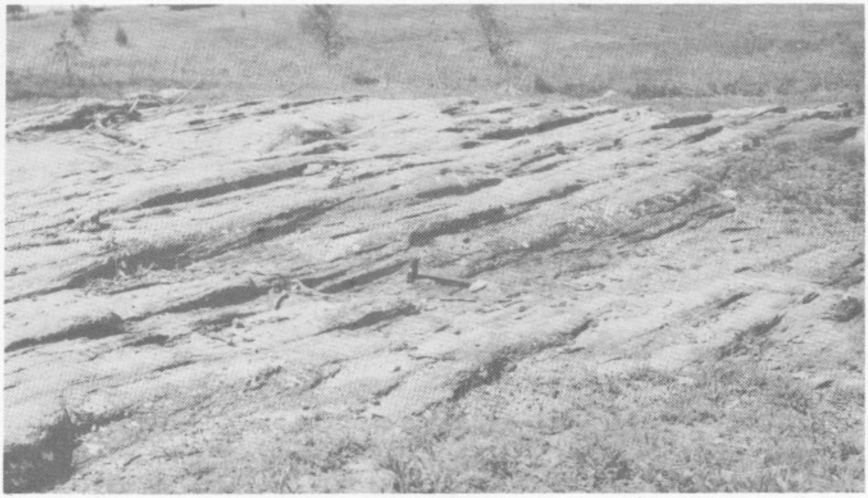
The sandstones are described as the Lower, Middle, and Upper Sands* based on their vertical position in the column of exposed pyroclastic rocks. They are similar to each other in that the dominant constituent is quartz sand but differ in the nature and proportion of essential and accidental ejecta and in the character of the mesostasis.

The Lower Sand is not continuous with either the Upper or the Middle Sand beds. Individual beds are several feet thick and are uniform in thickness and composition. The amount of essential and accidental ejecta is uniformly low, lapilli are few in number and are widely scattered, and thin zones of nearly pure sand are present. The rock is well cemented with iron stained carbonate. Both the fine rhyolite fragments and the nearly pure sand sections tend to be concentrated in vague, thin layers. Only a few small carbonate rock fragments were observed.

The Middle Sand is exposed only in one area south of Highway C and may represent downward continuation of the Upper Sand deposited in depressions between lapilli tuff mounds. It is classified separately because it is not in actual contact with the Upper Sand and is somewhat different in other respects. The Middle Sand forms even beds, 8 to 15 inches in thickness, that are continuous laterally, dip uniformly 15 to 20 degrees N 60^{o} W, and contain greater amounts of accidental ejecta than the Upper Sand (fig. 7). The purity of the individual beds varies considerably. Fragment size increases with depth and some of the lower Middle Sand beds are actually bedded lapilli tuffs.

The Upper Sand consists of relatively thin, discontinuous beds of sandstone with minor and variable amounts of fine essential and accidental ejecta incorporated in the different beds (fig. 8). Some beds are well indurated, almost pure sandstones that weather out in relief, while others are highly tuffaceous and less resistant to weathering. The tendency is for the tuffaceous nature to increase downward, with the purest beds occurring in the top few feet of the section.

***The terms Lower Sand, Middle Sand, and Upper Sand are used for convenience in this report. Formal stratigraphic nomenclature is not intended or implied.**



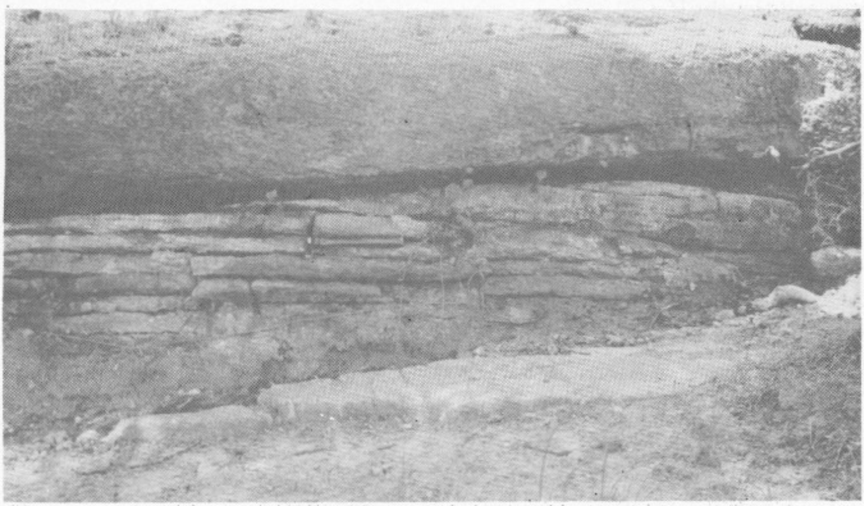


Figure 7 and Figure 8

(Top) Outcrop of tuffaceous sandstone (Middle Sand beds) located in the western part of the central area. (Bottom) Contact between middle Bonneterre dolomite and underlying tuffaceous sandstone (Upper Sand beds) near the western boundary of the central area.

TUFFACEOUS SILTSTONES

The tuffaceous siltstones comprise less than 10 percent of the pyroclastic rocks in outcrop. Their composition is uniform throughout their outcrop. Contacts between the tuffaceous siltstones and the lapilli tuffs are sharp; gradational contacts were noted between the siltstone and the underlying Lower Sand beds in the bluff along Dent Branch, about 400 feet south of Highway C, at a point where the sandstone approaches lapilli tuff in character.

The siltstone is a hard, well-indurated, light-colored rock, with dark gray rhythmic color banding. In hand specimen fine silt-size quartz grains embedded in an impure dolomitic matrix can be recognized. Beds of siltstones are nearly flat lying and are generally thin bedded and laminated. They weather out as thin plates and flakes. Several of the beds in the bluff mentioned above weather out in slabs 1 to 2 feet thick. Outcrops in the creek bed are notable for long, log-like rolls and troughs (fig. 9).

STRATIGRAPHIC RELATIONSHIPS

The pyroclastic rocks occur in the upper part of the lower division of the Bonneterre Formation as defined earlier and depicted in figure 10. Basal Bonneterre beds are in contact with the Precambrian along the ridge to the east (pl. 2). No exposure of the Lamotte Sandstone was found between the Precambrian and Bonneterre outcrops, but the presence of sandy basal conglomerate float in a few locations indicates that the Bonneterre beds in contact with the Precambrian are near the base of the formation. This estimate is supported by comparison with drill core sections in the area.

On the west side of the area the Upper Sand forms a key reference horizon along the full length of the outcrop (pl. 2). It can be traced for a distance of about 5,000 feet along the western slope of Dent Branch and represents the highest exposed beds of the deposit. Coarsely crystalline, uniformly-bedded middle Bonneterre dolomite rests unconformably upon the Upper Sand and their contact is visible for over half the length of the deposit (fig. 8). In the exposures near Highway C the admixture of sand in the overlying dolomite is minor indicating that the surface of the pyroclastic deposit had become fairly well stabilized at the time of deposition of the carbonate. About 400 feet south of Highway C several beds of sandy, coarse crystalline dolomite are

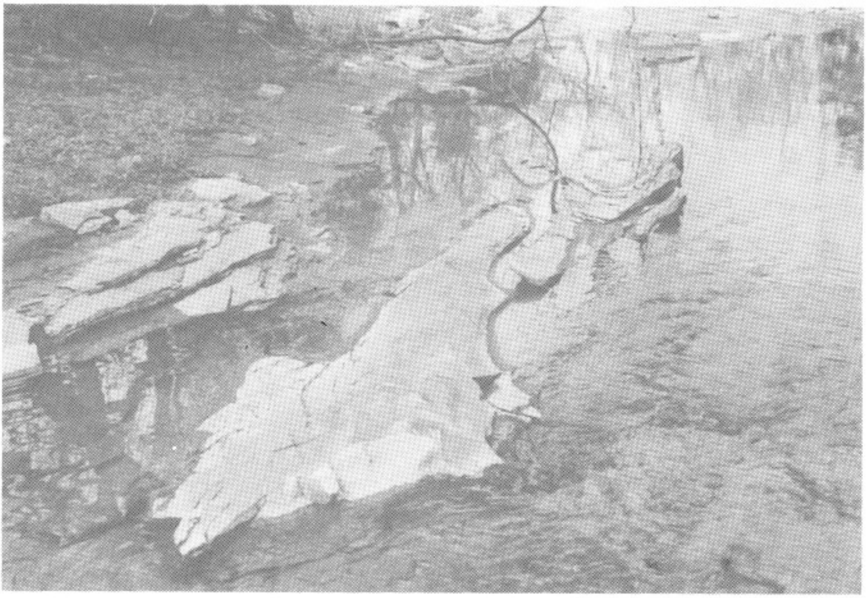


Figure 9
Crumpled and folded beds of tuffaceous siltstone found in the Dent Branch creek bed in the central area.

present near the base of the Upper Sand. These beds dip toward the southwest and are unconformably overlain by the middle Bonneterre. Southward from this point the contact between the Upper Sand and the middle Bonneterre is characterized by a gradational change between the two rock types.

The Upper Sand rests on lower Bonneterre dolomite beds in drill holes located several thousand feet to the northwest, west, and southwest of the outcrop area. Upper Sand beds are from 85 to 110 feet above the Lamotte Sandstone and their thicknesses range from 4 to 10 feet in these holes. Taking into

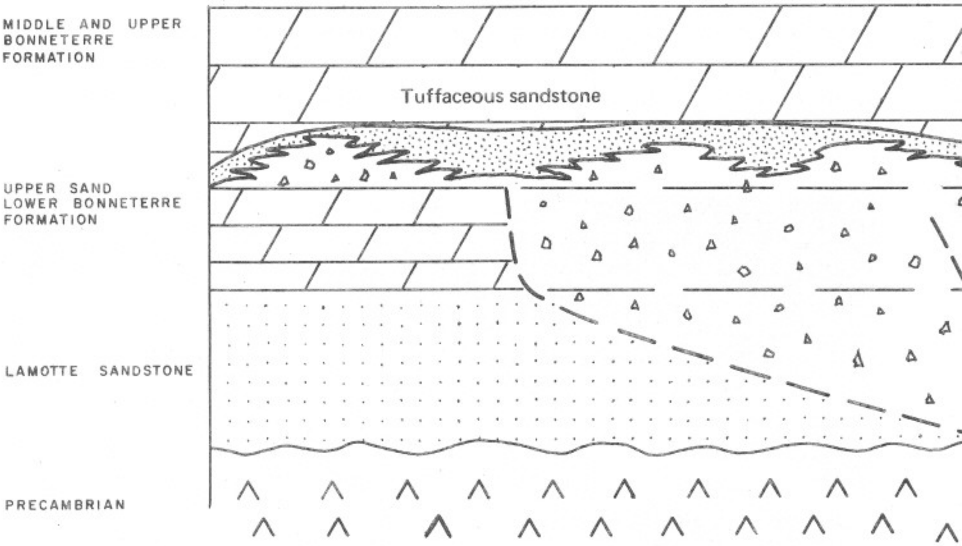
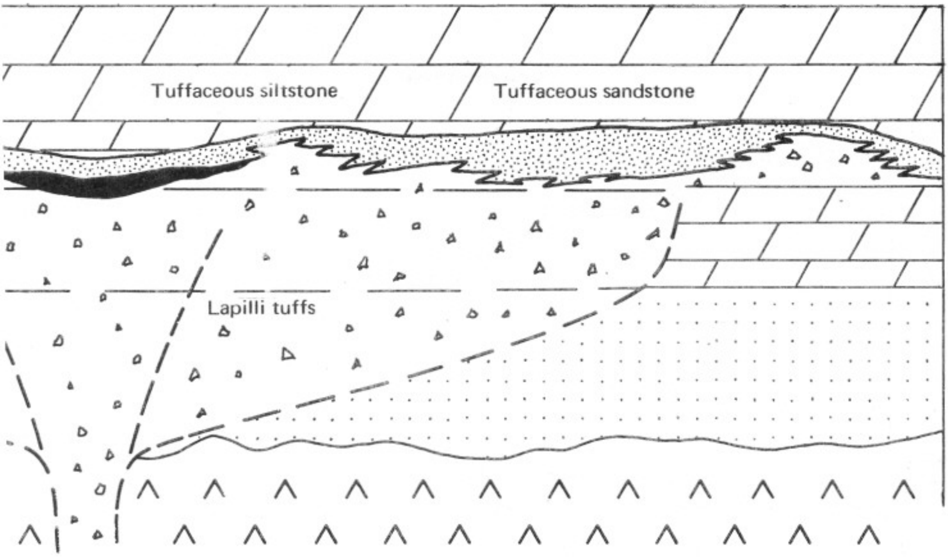


Figure 10

Diagrammatic section through the Dent Branch pyroclastic deposit, showing local stratigraphic relationships and hypothetical shape.

account the probable configuration of the top of the Lamotte in relation to high Precambrian areas, it is estimated that the base of the Upper Sand in the outcrop area would be about 110 feet above the Lamotte. Since this is about one third of the thickness of the Bonneterre in the area it was the basis for the subdivision of the Bonneterre into lower, middle and upper sections of about 110 feet each. It also determines the approximate position of the pyroclastic deposit in the local geologic column as shown in figures 10 and 11.

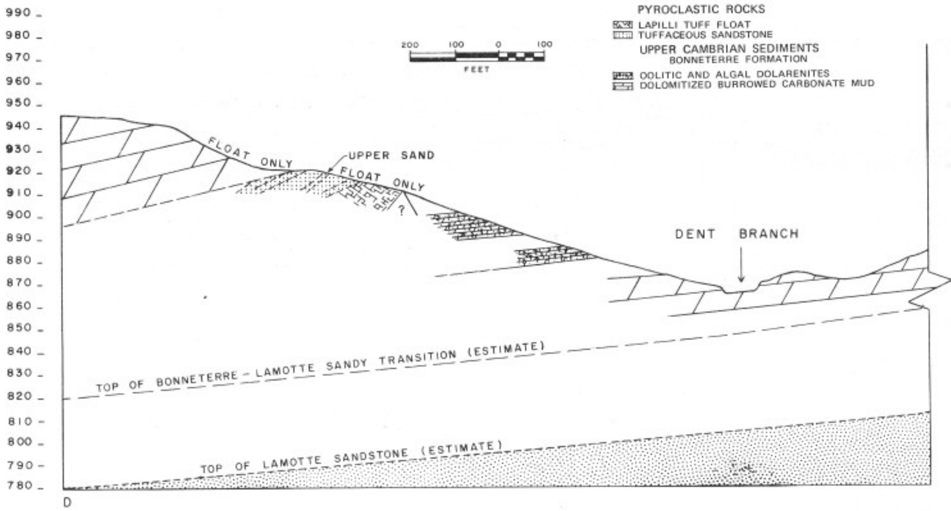
The lower Bonneterre-Upper Sand contact is not always present in outcrop. The Upper Sand is underlain by coarse pyroclastic deposits of various thicknesses at three locations; between these areas the Upper Sand is underlain by lower Bonneterre dolomite that contains no pyroclastic materials. For descriptive purposes the three areas of pyroclastic deposits have been designated the Central, South, and North areas (pl. 2). The northernmost exposures of pyroclastic rocks shown in plate 1 and two other possibly related occurrences are discussed separately.



CENTRAL AREA

The Central area is about 2,200 feet long at its greatest north-south dimension along Dent Branch and 1,600 feet wide at its greatest width just north of and parallel to Highway C. On the west the middle Bonneterre-Upper Sand contact forms the boundary.

The inferred north and south boundaries of the Central area are projected from observed contacts of coarse crystalline lower Bonneterre dolomite with lapilli tuff (fig. 12, section K-K') and with lapilli tuff and tuffaceous siltstone (fig. 13, section H-H'). These contacts are sharp but are exposed only under water in the creek and their attitude is not clear but is believed to be nearly vertical. A line between scattered outcrops of the dolomite and the pyroclastic rocks in section H-H' trends up the hillside at nearly right angles to the creek, and does not follow the hillside contours as it would if the contact were horizontal or nearly so. Large fragments of the dolomite are incorporated in the lapilli tuff near the contact. The ***in situ*** dolomite contains no pyroclastic material but it is strongly fractured and the fractures are filled with calcite. The sharp contacts



could be interpreted as the result of faulting. However, if faulting had occurred both sides of the fault plane would show evidence of movement and the pyroclastic rock side shows practically no disturbance. No evidence of faulting has been found along the projected contacts. The overlying Upper Sand beds on the hillside are undisturbed.

The eastern boundary of the Central area cannot be accurately delineated because of soil cover. A few scattered outcrops indicate that the boundary may be 300 to 400 feet east of Dent Branch in the vicinity of Highway C. South of this an area of over 1,000 feet in diameter has no outcrops. An intermittent stream cuts across the southern part of this area; it has an exposure of lapilli tuff about 1,000 feet east of Dent Branch. Outcrops of coarse crystalline Bonneterre dolomite along the foot of the Precambrian ridge indicate that a continuous band of lower Bonneterre beds separate the pyroclastic deposit from the Precambrian ridge.

The contact between the lower Bonneterre and the pyroclastic rocks is not exposed along the eastern boundary of the Central area. In the vicinity of

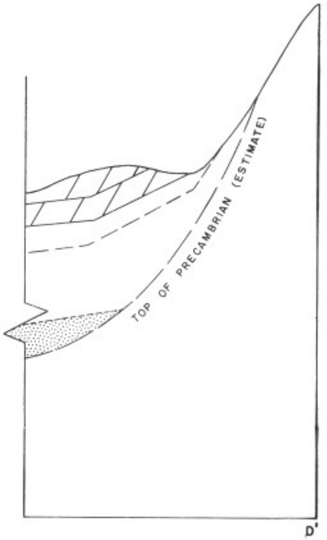


Figure 11. Stratigraphic cross section through the Dent Branch pyroclastic deposit, between the North Area and Central Area. See Plate 2 for line of section.

Highway C nearly horizontal, thick beds of slightly tuffaceous Lower Sand are exposed on a small hillside (fig. 14, section M-M'). A soil-covered interval separates these sand beds from horizontal beds of lower Bonneterre dolomite about 10 feet above the sandstone. When first noted the sandstone was considered to be the Lamotte because it is apparently overlain conformably by the lower Bonneterre. However, it is tuffaceous and is also conformably overlain by tuffaceous siltstone (fig. 14, section N-N') that is part of the pyroclastic deposit and postdates the lower Bonneterre rocks. More information is needed regarding the relationship of the pyroclastic rocks to both the lower Bonneterre and the Lower Sand before the deposit can be accurately delineated along the eastern boundary of the Central area.

SOUTH AREA

The South area has a length of about 1,000 feet along Dent Branch. It is separated from the Central area on the north by a distance of about 450 feet along which only the Upper Sand is exposed between dolomites of the lower

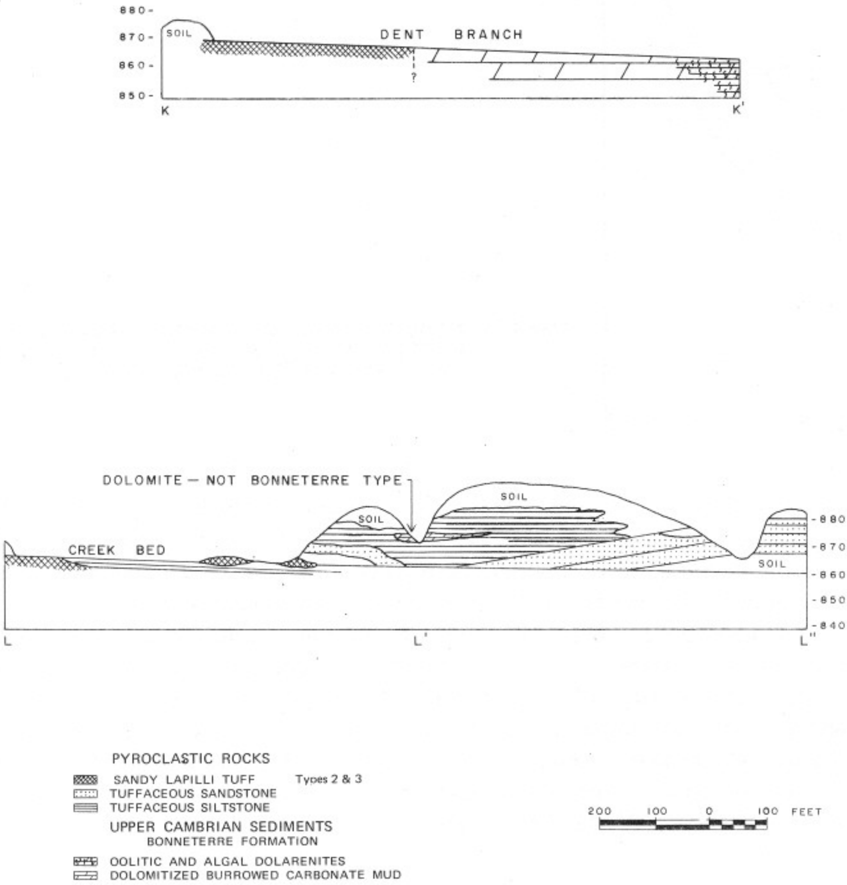


Figure 12

Stratigraphic cross sections through the Central Area. See Plate 2 for lines of section.

and middle Bonneterre. The South area is mostly soil covered and the only good outcrops are in the creek bed. An east-west arch of lower Bonneterre dolomite reflects the underlying westward extension of the Precambrian ridge, cuts off the outcrop of pyroclastic rocks, and forms the southern boundary of the area. The contact is not exposed.

The outcrop in the creek bed consists largely of tuffaceous siltstone. In the northern part of the area the Upper Sand is underlain by dark green lapilli tuff and tuffaceous siltstone (fig. 13, section J-J'). The Upper Sand is cut off by erosion about 300 feet south of this point but the lapilli tuff and siltstone continue to be exposed in the creek bed southward. The thickness of this pyroclastic section is probably not great as the creek bed must be quite close to the Precambrian surface. Because good contacts between the several rock types are not exposed, it is impossible to reach valid conclusions about this occurrence. However, the pyroclastic rock types are of the same character as those in the Central area.

NORTH AREA

A distance of about 800 feet separates the North area from the Central area. Mapping of the pyroclastic rocks along this distance is based entirely on the presence of float. Upper Sand float is present along the top of the ridge west of Dent Branch; lapilli tuff float occurs below the Upper Sand in several places. Scattered outcrops of lower Bonneterre dolomite occur on the hillside below the pyroclastic rock float.

The North area has a north-south dimension of about 1,200 feet and a maximum width of about 500 feet (pl. 2). The pyroclastic rocks are exposed from 100 to 400 feet west of Dent Branch in three separate outcrops. The southernmost of these outcrops is in an east-west gully where 20 feet of lapilli tuff is exposed between the Upper Sand and lower Bonneterre beds (fig. 15, section C-C'). The lapilli tuff contains blocks and lapilli of the underlying algal dolomite. The lower Bonneterre-lapilli tuff contact is not exposed. About 200 feet to the north the exposed section consists of 20 feet of tuffaceous sandstone and siltstone in the Upper Sand horizon (fig. 15, section B-B'). This is a significant exposure because it clearly shows the lower Bonneterre-Upper Sand contact. The Bonneterre beds below the contact correlate with the middle and lower sections of the exposed pyroclastic rocks. In the northern part of the area the pyroclastic section thickens (fig. 15, section A-A'). Here 20 feet of lapilli tuff is exposed below the Upper Sand but its contact with the underlying lower Bonneterre is not visible. Beyond this locality the Upper Sand extends northwesterly for a few hundred feet and is then cut off by erosion.

OUTLYING AREAS

The two additional outcrops of pyroclastic rocks near the Big River (pl. 1) have not been studied in detail. They are on the line of the general north-northeast trend of the main outcrop. Brief study indicates that these rocks are lapilli tuffs of the same character and of the same age as those in the main area. The Upper Sand was not found and the relationship of the pyroclastics to the Bonneterre is not known. Their outcrop is in an area of Bonneterre exposure. The farthest north exposure has a strike length of at least 1,200 feet and a bed thickness of at least 60 feet.

Two other occurrences of pyroclastic rocks in the general area should be mentioned. On the east side of the Precambrian ridge, about 700 feet north of Highway C and 4,500 feet east of the Central area, short sections of tuffaceous sandstone were encountered in a drill hole and were logged as tuffisite in 1955 by J. S. Brown, then chief geologist of St. Joseph Lead Company. These beds are very close to the surface, occur in the sandy Lamotte-Bonneterre transition zone and possibly in the upper part of the Lamotte Sandstone, and are in the same stratigraphic position as the Furnace Creek deposit. No surface exposures were found. Several other drill holes in the vicinity encountered small amounts of the same material. These cores were examined and thick sections of pyroclastic rocks similar to those in the Dent Branch deposit were found. Basal Bonneterre beds are not exposed in the Dent Branch area but indications are that these stratigraphically lower pyroclastic sections are confined to the east side of the Precambrian ridge and have no connection with the volcanic activity that produced the rocks at Dent Branch. A possible exception to this is the Lower Sand discussed on p. 71.

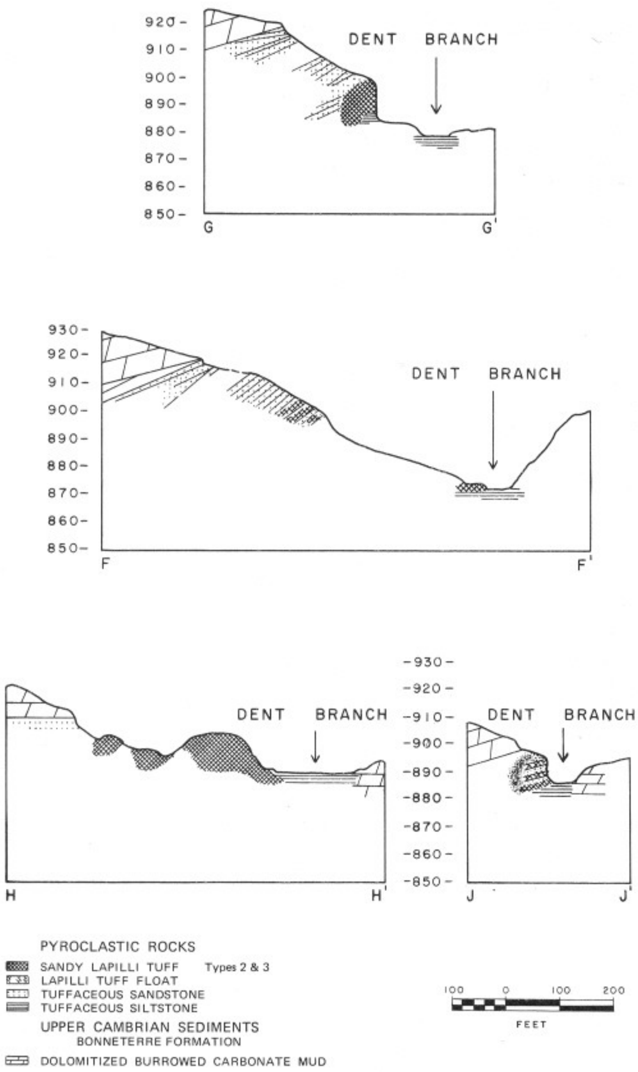


Figure 13

Stratigraphic cross sections through the Central Area (F-F'; G-G'; H-H') and South Area (J-J'). See Plate 2 for lines of section.

About 3,500 feet northeast of the above location an occurrence of "conglomerate" with pebbles of porphyry, "marble", and sandstone in an arkosic matrix was described by Dake (1930, pp. 62-67). Porphyry pebbles range in size from tiny fragments to masses several inches in diameter and are mixed with sand grains. Dake found no outcrop of the "marble" or sandstone in the immediate vicinity from which the corresponding pebbles could have been derived. The associated rocks are described as "...basal Bonneterre, lapping against a very small porphyry knob..." Dake's description suggests that the material is similar to the lapilli tuffs of the Dent Branch area except that there is no mention of chloritic material. This occurrence was not examined as it is not pertinent to the present study. If these are pyroclastic rocks, they may be part of another deposit in the basal Bonneterre; there is no evidence of continuity between it and the Dent Branch deposit. Investigation of these isolated occurrences would have to be part of a broader study of all the post-Precambrian pyroclastic rocks in the region.

INTERRELATIONSHIP OF PYROCLASTIC ROCKS

The areal geology of the deposit is shown by an outcrop map (pl. 2). Stratigraphic relationships between the pyroclastic rocks and the host Bonneterre Formation are illustrated by a series of cross sections (figs. 11-15). These and a few additional cross sections are used to demonstrate the complicated and sometimes conflicting relationships of the pyroclastic rocks within the deposit. Relationships shown in figure 10 are not representative of any particular section but are generalized to show the stratigraphic position and hypothetical cross-section of the deposit.

One of the least complicated sequences is elongated in an east-west direction just north of and parallel to Highway C (fig. 16). It is the thickest exposed section of pyroclastic rocks in the entire Dent Branch area with a thickness of 75 to 80 feet. The outcrop is nearly continuous for a distance of 1,600 feet and is comprised of lapilli tuffs both of the massive (type 1) and porous (type 2) varieties. This large mass of lapilli tuff shows no bedding, only vague stratification that would result from settling of ejecta. Composition of the blocks and lapilli in the rock is variable, but sufficiently random to prevent classification of

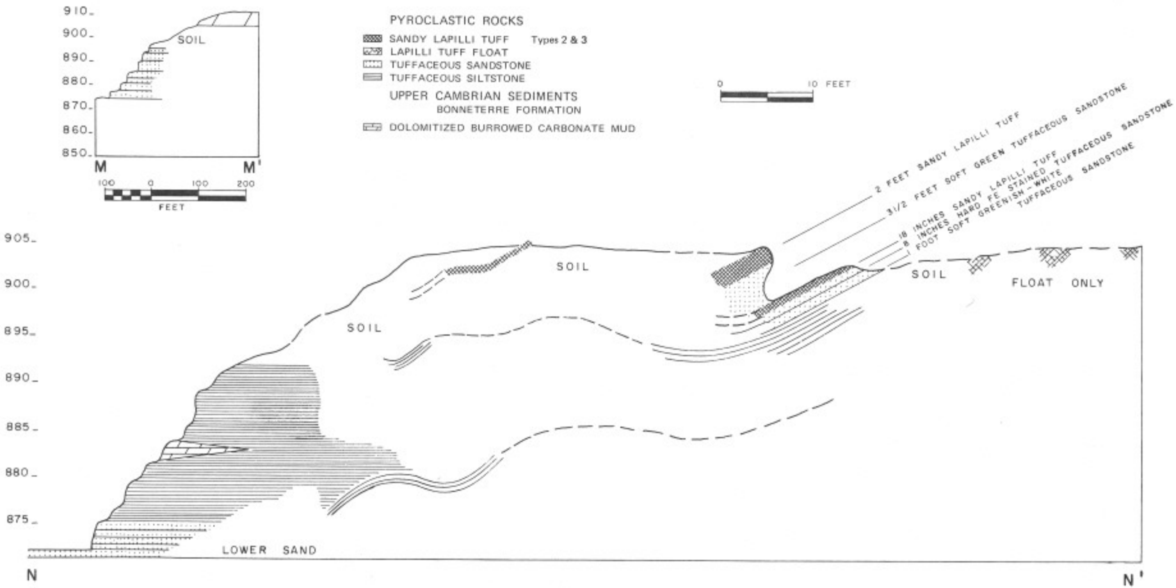


Figure 14. Stratigraphic cross sections through the Central Area. See Plate 2 for lines of section.

lithologic units on this basis. The degree of induration also changes along the outcrop; the massive types tend to occur in the area west of Dent Branch. However, these variations in stratification, composition, and degree of induration are not distinct enough to determine separate lithologic units and age relationships between them. The lapilli tuffs are overlain by the Upper Sand on the west.

A prominent series of well-bedded tuffaceous sandstones (Middle Sand beds) is exposed on the hillside south of Highway C (fig. 13, section F-F'). The outcrop is 150 feet wide, the beds dip 15 degrees to the northwest, and about 30 feet of sandstone is exposed. A soil-covered interval separates this exposure from the overlying Upper Sand and middle Bonneterre beds. It is probable that the Middle Sand is contiguous with the Upper Sand in this location but contains increasing amounts of lapilli and ash in the lower beds. It is important to note that the Middle Sand is absent in section E-E' (fig. 16) a few hundred feet to the north, and that the massive lapilli tuffs of that section are absent here although the surface elevation is the same.

South of section F-F' and about 100 feet west of Dent Branch a mound of ***in situ*** lapilli tuff (type 2) is exposed in a bluff about 10 feet high and 40 feet long (fig. 5 and fig. 13, section G-G'). The Middle Sand rests unconformably on the lapilli tuff and pinches out against it. On the north side of the bluff a horst of laminated tuffaceous siltstone extends a few feet into the lapilli tuff. Similar siltstone is exposed in the creek bed apparently both underlain and overlain by lapilli tuff. The apparent age relationships in ascending order are: lapilli tuff, siltstone, lapilli tuff, Middle Sand. However, the lower contact of the siltstone with the lapilli tuff is under water in the creek and the sequence of these rocks is uncertain.

Continuous exposures of pyroclastic rocks occur along Dent Branch south of Highway C for a distance of about 2,000 feet. Section L-L'-L'' in figure 12 illustrates some of the relationships observed. Siltstone and lapilli tuff are exposed in the creek bed (section L-L') and dip northeast to below creek level. Lower Sand is exposed near the base of a 30-foot high bluff on the east bank of the creek. It is overlain by a 20-foot section of gently dipping laminated siltstone that contains a 4-foot lens of dolomite. The latter has contorted laminae within thin beds and crackle breccia filled with calcite. The Lower Sand dips

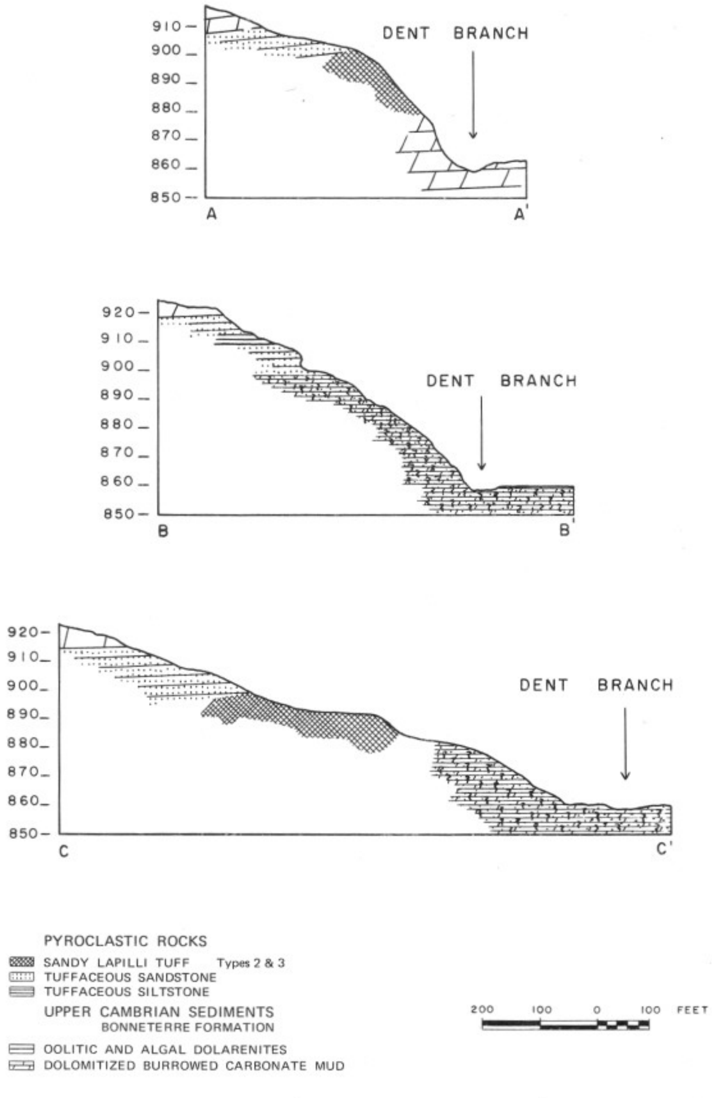


Figure 15

Stratigraphic cross section through the North Area. See Plate 2 for lines of section.

below creek level at this point but is exposed about 125 feet downstream and, in the vicinity of Highway C, a 20-foot section is exposed on the hillside.

The top of the siltstone bluff in section L'-L'' is soil covered, but farther east steeply dipping sandy lapilli tuffs and tuffaceous sandstones are exposed at a higher elevation (fig. 14, section N-N'). These beds dip 25 degrees to the northwest and if they continued downward at the same angle they would have to appear in the bluff face, but they do not. Their contact with the relatively flat-lying siltstone beds in the bluff face is not exposed. Possibly the siltstone had been deposited against the truncated ends of the dipping lapilli tuffs. However, outcrops in a dry gully about 50 feet southeast and parallel to section N-N' show crumpled and distorted beds of siltstone. Therefore, it appears more likely that the lapilli tuff was deposited on siltstone and they were subsequently folded. The dip of the lapilli tuff beds appears to decrease sharply toward the northwest; these beds are concealed in the soil-covered interval at the top of the bluff as indicated in the section.

On the basis of field observations, the following relationships seem well established:

1. The Lower Sand is the oldest exposed pyroclastic rock, but there is no information regarding underlying strata.

2. The Middle Sand probably constitutes the lower portion of the Upper Sand deposited in depressions between lapilli tuff mounds.

3. The Upper Sand is the youngest exposed pyroclastic rock.

4. All sandstones represent transported and sorted material derived from adjacent lapilli tuff deposits.

5. Assuming that the expulsion of ejecta took place intermittently and alternated with quiet periods, all the lapilli tuffs are not of the same age.

6. Any individual sandstone bed therefore is only younger than the particular lapilli tuff deposit from which it was derived and may be older than another

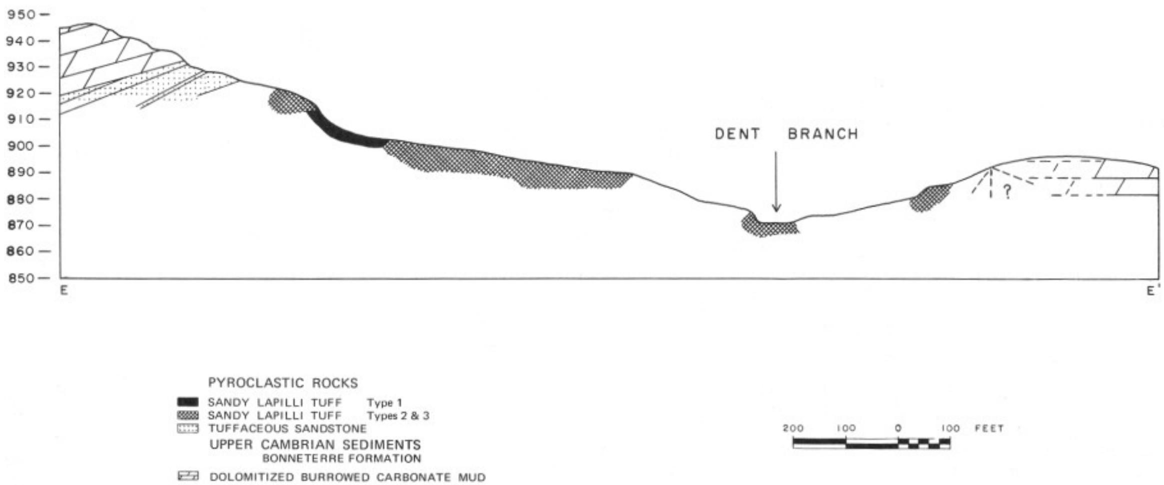


Figure 16. Stratigraphic cross section through the Central Area. See Plate 2 for line of section.

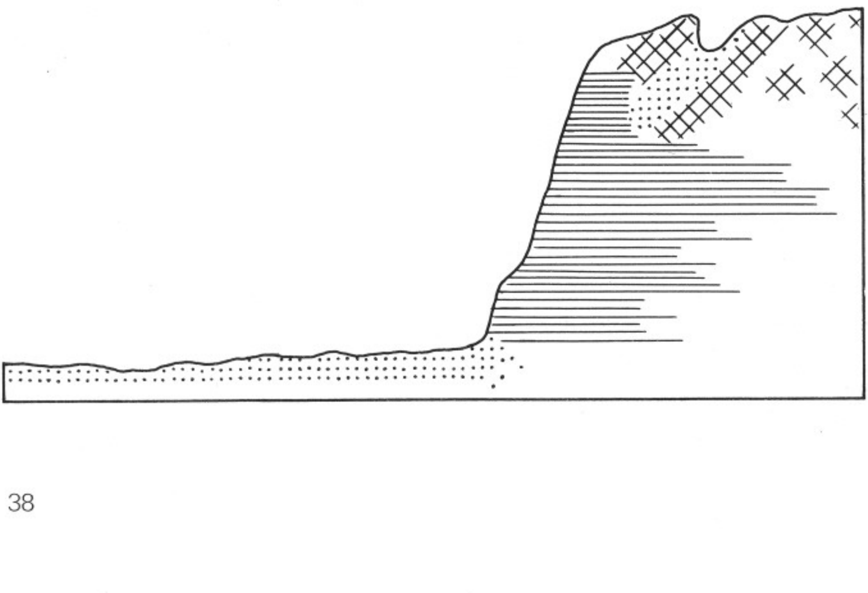
lapilli tuff deposit.

7. All exposed contacts between lapilli tuffs and either the Upper or the Middle Sand indicate that these sandstones are younger than the lapilli tuffs they are in contact with.

8. Tuffaceous siltstones were deposited at different times during the span of volcanic activity. In the Central area they are in the lower part of the exposed section; in the South area they are near the Upper Sand horizon; in the North area they are in the Upper Sand. However, the amount of siltstone in a vertical section is small compared to that of the lapilli tuffs and tuffaceous sandstones.

9. Displacement of the beds subsequent to their deposition is indicated by abrupt changes in attitudes within short distances. This factor combined with the reworking of the ejecta must be primarily responsible for developing the complicated relationships between the pyroclastic rocks.

Interpretation of the relationships between various rock units within the deposit is based primarily on the limited number of outcrops and well-exposed contacts. Important relationships may be hidden under the cover of soil and younger sediments. Additional surface and subsurface information will be necessary to make a more definite description of the deposit.



PETROGRAPHY OF THE PYROCLASTIC ROCKS

The description of pyroclastic rocks is based on examination of collected samples by the binocular microscope and study of 28 thin sections of representative samples by the petrographic microscope. Locations of those referred to in the text are shown on plate 2 by number.

LAPILLI TUFFS

The lapilli tuffs are coarse-grained rocks and consist of up to 80 percent pyroclastic ejecta unsorted both as to size and composition in a tuffaceous carbonate mesostasis. At least 50 percent of the ejecta are lapilli size and the remainder generally fall in the smaller size ranges. Occasionally blocks are also incorporated, usually limestone and dolomite from the Bonneterre Formation; Precambrian blocks are also present. Blocks are angular to subangular and subrounded and frequently weather out as large boulders sealed in fine grained tuffaceous material. Most of the carbonate blocks have centers of coarse crystalline calcite.

Essential lapilli and ash comprise between 20 and 50 percent by volume; the amount is not consistent but varies from outcrop to outcrop. These lapilli occur as green, round, and irregular-shaped chloritic pellets that often weather out and leave a pockmarked surface. In reworked and bedded lapilli tuffs they alter to dark gray montmorillonite-illite clay that has a waxy luster and resembles bentonite. A small proportion of the essential material is represented by phlogopite and other ferromagnesian minerals, usually less than 4 mm in size. Essential lapilli often incorporate accidental sand grains and small crystal and lithic fragments that may either form the nucleus, are arranged concentrically within them, or have no apparent relationship to the shape of the lapilli.

Accidental ejecta may comprise as much as 50 percent of any given lapilli tuff. These include Precambrian devitrified welded tuffs of rhyolitic composition and rhyolite porphyries, limestone and dolomite of the Bonneterre Formation, and occasionally fragments of Lamotte sandstone. These accidental lithic fragments range from lapilli size to less than 4mm in diameter, are typically angular, unaltered, and are often surrounded by a thin shell of fine tuffaceous material. Lamotte sand grains comprise about 25 percent of the lapilli tuffs and are distributed with the finer ejecta throughout the mesostasis, giving the rocks a distinctly sandy aspect.

ESSENTIAL COMPONENTS

Essential components consist of crystal, vitric, and crystal-vitric ejecta. Crystals are phlogopite, magnetite-hematite, and altered olivine and pyroxene (?). In hand specimen only the phlogopite and the iron minerals can be recognized. Vitric ejecta consist of chloritized sideromelane vitrophyre which alters to ferruginous clay. Crystal-vitric material consists of phenocrysts of the above minerals plus apatite and zircon in vitric groundmass.

Size of the crystals ranges up to 2 mm. Vitric components range from fine dust in the mesostasis to individual fragments of ash (up to 4 mm) to lapilli size (up to 25 mm rarely). The larger lapilli tend to be composite crystal-vitric material and are mostly altered to clay. They also tend to incorporate accidental crystal fragments and sand large enough to be recognized in hand specimen.

Crystal

Phlogopite occurs as fine grained scaly aggregates of red-brown color and as flakes that average about 0.1 mm but range up to 2 mm in size. In hand specimen it is silver colored and has a pearly luster that distinguishes it from accidental biotite and chlorite. Phlogopite flakes are weakly pleochroic from colorless to light brown, have ragged outlines and sometimes a blistered surface. They occur both in the tuffaceous carbonate mesostasis and as phenocrysts in the chloritized vitric groundmass of essential lapilli and ash. The red-brown scaly aggregates of phlogopite are restricted to the mesostasis of type 1 lapilli tuffs where they occur with calcite. Phlogopite is fresh in the well indurated lapilli tuffs but alters to a brown, nearly opaque micaceous substance in reworked material where it may be partially replaced by calcite (fig. 17).

Primary essential magnetite occurs as individual angular to rounded grains less than 0.1 mm in size. They are most common in the tuffaceous carbonate mesostasis. They alter to hematite. Minute grains of apatite and zircon are preserved in some of the chloritized crystal-vitric ejecta.

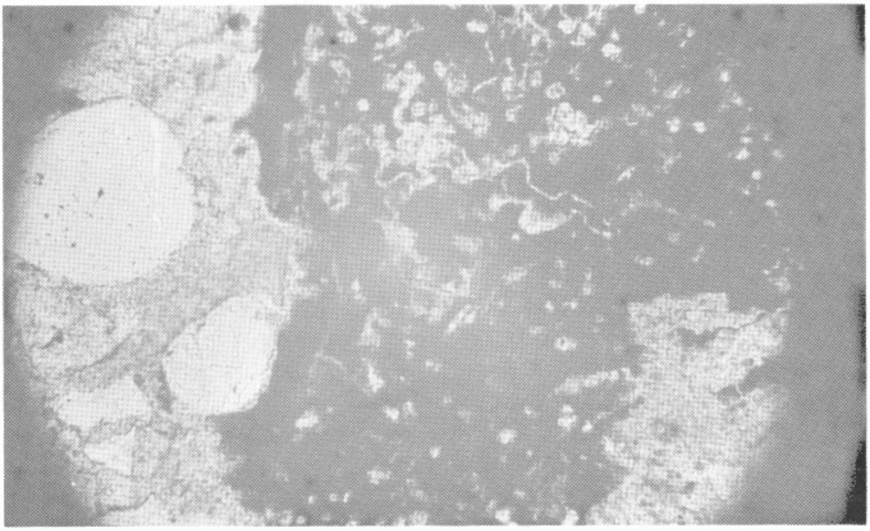


Figure 17

Photomicrograph of phlogopite partially replaced by carbonate in reworked lapilli tuff. Sand grains visible on the left. Parallel nicols, 50X.

Aside from the above minerals no other primary essential crystals can be identified with certainty in the lapilli tuffs. They are generally altered to such an extent that the less stable minerals are completely destroyed. Some of these minerals preserved their original euhedral crystal form, and these can be readily observed in the chloritized lapilli. The euhedra are four- and six-sided, of short prismatic habit, suggestive of both olivine and pyroxene. They occur in two size ranges: less than 0.05 mm and 2 to 3 mm. The smaller ones are sharply euhedral, occur exclusively as phenocrysts in crystal-vitric ejecta, and are replaced by fine-grained fibrous chlorite, rarely by calcite. The chlorite replacing these euhedra is clear in contrast to the highly iron-stained chloritic groundmass around them with the result that the ghost crystals are readily distinguished with both parallel and crossed nicols under the microscope.

Crystals in the 2 to 3 mm size range have somewhat resorbed and rounded outlines and are invariably replaced by calcite. Cross fractures characteristic of olivine are frequent and are filled with magnetite (fig. 18). Larger crystals are less common than the smaller generation, occurring one to a chloritic fragment in contrast to the numerous smaller phenocrysts. They are also present in the

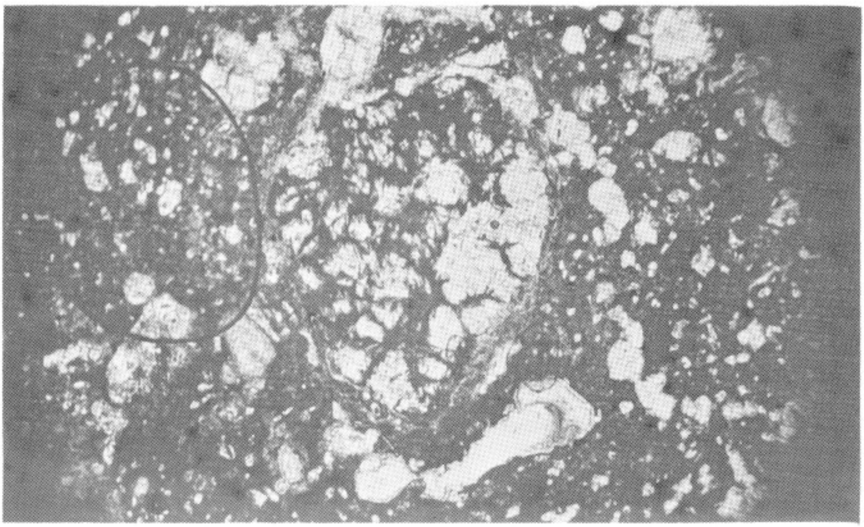


Figure 18

Photomicrograph of ghost crystal of olivine in lapillus of sideromelane vitrophyre, now altered to ferruginous clay. White areas are calcite and black areas in cross fractures are magnetite. Parallel nicols, 22X.

tuffaceous carbonate mesostasis of the lapilli tuffs where their outline is indicated only by vague and diffuse iron oxide rims, and their recognition is more difficult.

Vitric

Although the original glass content of these rocks is now devitrified and has been replaced, terms indicating the original glass content are used. In hand specimen the vitric fragments appear as green clasts and pellets ranging in size from a few to rarely 25 mm. The larger lapilli are usually rounded but the smaller ones are angular to subangular or flattened and squeezed. In bedded lapilli tuffs they tend to be aligned with their long axes parallel to the bedding. In reworked lapilli tuffs and in the tuffaceous sandstones they are more rounded and are altered to a soft, plastic, green or gray clay. A moderate swelling is observed when these clay pellets become saturated with water.

The green lapilli were identified under the petrographic microscope as chloritized sideromelane vitrophyre. Although devitrified and chloritized, their primary texture is excellently preserved. Two types of textures are recognized: a) vesicular vitric devoid of phenocrysts, and b) porphyritic, the former being the more abundant. Both types may enclose accidental crystal and lithic fragments as well as whole and comminuted quartz sand grains.

The shape of the vitric lapilli and ash is typically shard-like under the microscope, although distinctly different from that observed in acidic

Figure 19

Chloritized sideromelane vitrophyre fragments in massive lapilli tuff.

lavas. Sharply concave outlines are recognized in unreworked lapilli tuffs. Plasticity is indicated by the squeezed and flattened aspect that is especially evident in the vesicular fragments (figs. 19 and 20). The vesicles appear as small, drawn-out ovoids with their long axes roughly parallel to fragment outlines.

The vitric ejecta of the lapilli tuffs consist dominantly of fine fibrous chlorite and diffuse iron oxides. In relatively fresh samples they are dominantly green in plane-polarized light with irregular black patches of iron oxides. In altered and reworked material they are nearly black and almost completely opaque; only the vesicles and the phenocrysts remain transparent. These would still appear green in hand specimen.

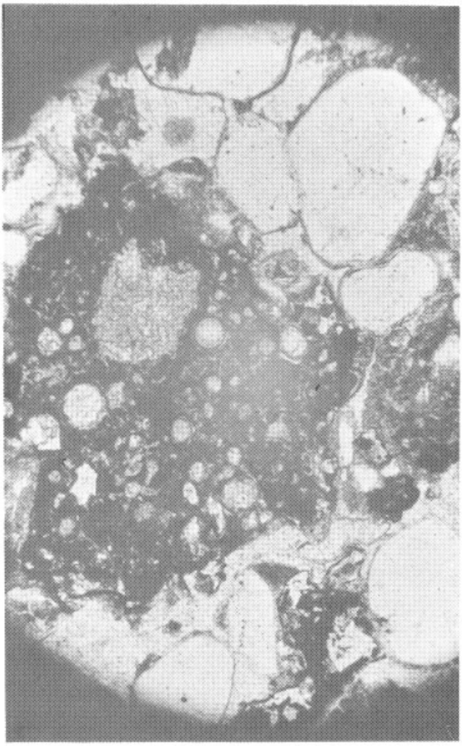


Figure 20

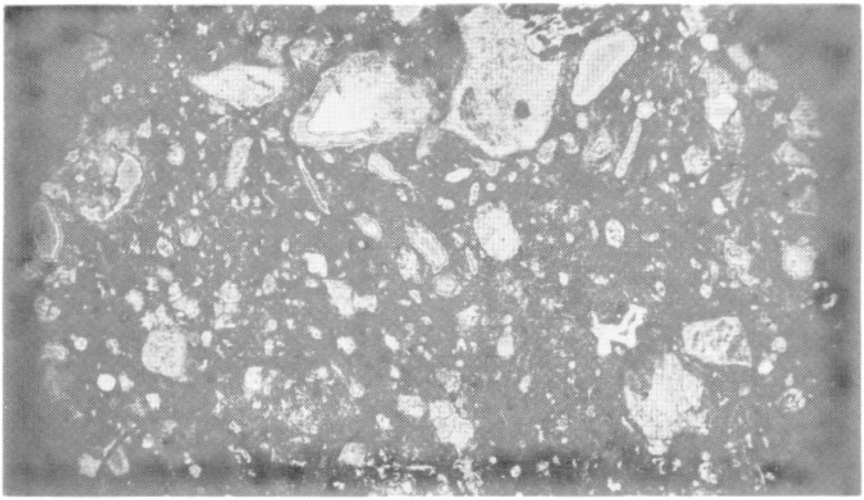
Photomicrograph showing vesicular texture in chloritized sideromelane vitrophyre. Vesicles are filled with fibrous chlorite. Parallel nicols, 50X.

It is of considerable interest that the altered and reworked soft green and gray clay pellets in both the lapilli tuffs and the tuffaceous sandstones retain the characteristic vitrophyric and vesicular texture of the fresh "green lapilli and ash", although the chloritic substance is broken down to a dark, highly ferruginous microcrystalline aggregate of clay (fig. 21). This clay cannot be determined under the microscope but X-ray diffraction analysis indicated it to be a mixed layer illite-montmorillonite.

Because of this remarkable persistence of textural features it is possible to identify even indistinct dark smudges in altered lapilli tuffs and tuffaceous sandstones as essential vitric material. In fact, by careful selection of thin sections it is possible to follow the gradual change from the green chloritized sideromelane vitrophyre to dark gray ferruginous clay. In the latter only accidental crystal fragments and phlogopite are preserved. The phlogopite is quite resistant to alteration compared to the vitric material; flakes of it can be identified even in completely altered vitric material.

In the vesicular vitric fragments the vesicles are filled with either chlorite or calcite or both. The chlorite is fibrous and has spherulitic extinction. The walls of chlorite-filled vesicles are usually marked by a thin rim of diffuse iron oxide. Where both chlorite and calcite are present in the same vesicle an interesting relationship is observed between the two minerals. Either, (a) calcite lines the vesicle with fibrous spherulitic chlorite filling the void, or (b) chlorite lines the wall and calcite forms the filling. In rare cases calcite lines the wall, is followed by a layer of chlorite, and the center of the void is filled by calcite. In other vesicles the replacement of chlorite by calcite is observed.

Figure 21
Photomicrograph showing vesicular texture in composite crystal vitric lapillus in reworked lapilli tuff. Dark-colored groundmass consists of ferruginous clay. Vesicles are filled with fibrous chlorite. A rhyolite fragment is seen in the upper right. Parallel nicols, 22X.



Although calcite-filled vesicles are fairly common, replacement of the vitrophyre by calcite is rare. When observed, it appears to progress along tiny cracks from the tuffaceous carbonate mesostasis toward the interior of the fragment.

Crystal, vitric, and crystal-vitric fragments from ash to lapilli size can be detected under the microscope with ease. These are most abundant in the discovery area just to the north of Highway C, namely in samples 19, 40, and 41 (pl. 2), and in sample 35 (south of the highway) where they comprise up to 50 percent of the rock. The fine dust in the tuffaceous carbonate mesostasis is more difficult to recognize and will be discussed later.

ACCIDENTAL COMPONENTS

Accidental components of the lapilli tuffs consist of fragments of Precambrian rocks, Lamotte sandstone, and limestone and dolomite of the Bonneterre Formation.

Precambrian Ejecta

These include both lithic and crystal fragments. The former range from about 2 mm to blocks 40 cm in diameter. They are angular to subangular and fresh in lapilli tuffs, but tend to be more rounded and altered in reworked rocks. A majority of the Precambrian lithic fragments are rhyolitic in composition, but a number of textural varieties are observed:

1. ***Microcrystalline granular with no phenocrysts.*** Grain size is less than 0.01 mm. It is composed of quartz and potash feldspar. Replacement by calcite is patchy and progresses from several centers in a fragment. It is identified as devitrified rhyolite.

2. ***Porphyritic.*** Orthoclase and quartz phenocrysts (0.1 to 2 mm) in microcrystalline granular quartz-feldspar matrix. The orthoclase is often cloudy and more or less altered, but there is no prominent alteration in the groundmass.

Quartz phenocrysts frequently have resorbed outlines. Irregular patches of black iron oxide probably represent former ferromagnesian minerals. Identified as rhyolite porphyry.

3. ***Cataclastic.*** Cataclastic quartz phenocrysts (0.5 to 1 mm) in granulated quartz-feldspar matrix.

4. ***Vitroclastic.*** Angular quartz and orthoclase micropherthite phenocrysts (1 to 2 mm) in microcrystalline groundmass of quartz-feldspar (0.1 mm) that has "snowflake" texture. Flow lines and glass shards evident in plane polarized light, usually indicated by the distribution of fine iron oxide dust. Identified as devitrified welded tuff.

5. ***Spherulitic.*** Phenocrysts of orthoclase and quartz in groundmass that consists of small spherules of orthoclase and microcrystalline quartz. Plagioclase laths, biotite flakes, and magnetite are present in small amounts.

Replacement by calcite is most prominent in the first variety where up to 90 percent of the rhyolite may be replaced. Sericitic alteration is rare. All rhyolite fragments appear somewhat iron stained in plane polarized light, but with the exception of the calcite replacement mentioned above, they are remarkably fresh. Orthoclase phenocrysts tend to be more altered than the groundmass. Ferromagnesian minerals are completely altered, but their percentage must have been quite small as indicated by the minor amount that was observed in only a few fragments. Most fragments are completely devoid of mafics. Accessory magnetite is present as small (less than 0.05 mm) euhedral grains in most varieties. In rare cases magnetite is observed as narrow veinlets in rhyolite. These lithic fragments are frequently enclosed in a thin shell of fine tuffaceous material.

Only a few granite fragments were observed among the ejecta The granite is salmon colored, medium crystalline, and consists dominantly of feldspars with minor quartz and biotite.

Individual crystal fragments derived from Precambrian rocks include quartz, orthoclase, orthoclase micropherthite. microcline, oligoclase, and flakes of biotite and chlorite. Of the feldspars, orthoclase is most abundant with perthite, microcline, and oligoclase following in that order. The feldspar fragments exhibit a wide range in size from less than 0.1mm to 3mm. Typically they are sharply angular, monomineralic, and fresh; orthoclase being the only one that shows moderate alteration to clay minerals and rarely to sericite. The orthoclase microperthite is of the string-perthite variety, and its albitic component is often selectively replaced by calcite. Some of the feldspars that fractured along the (010) cleavage appear more euhedral than others that are irregularly fractured.

Igneous quartz is difficult to distinguish from comminuted quartz sand, especially in the lower size ranges where the rounded outer portions of the sand grains are absent. Thus, there are abundant angular quartz grains in the less than 0.1 mm range that may have been derived from either the Lamotte or Precambrian rocks. These, together with other small crystal fragments, are embedded in the tuffaceous microbreccia of the mesostasis that is discussed on page 51.

Biotite occurs in small distinct flakes that are strongly pleochroic from green to brown. They are frequently altered to chlorite. Crystal fragments are often included in the chloritized sideromelane vitrophyre lapilli and in such cases the partial replacement of orthoclase by chlorite may be observed. In the tuffaceous carbonate mesostasis, calcite replaces either partially or completely a small percentage of the feldspars.

The above assemblage of crystal fragments represents the characteristic mineral suite of a granite. It is unlikely that these crystals should be liberated phenocrysts of the rhyolitic rocks discussed above, for none of them were observed in rhyolitic groundmass. They are dominantly monomineralic but a few of the larger fragments are made of more than one crystal unit. Commonly these are intergrowths of orthoclase or sometimes of orthoclase and quartz. The crystal fragments, therefore, suggest a medium to coarse crystalline granite at depth which was fragmented and brought up by the force of the explosions. Fragments of granite, however, are very rarely found in outcrop.

Lamotte Sandstone

Fragments of sandstone are relatively rare in the lapilli tuffs but several small blocks, some up to 20 cm in diameter, were observed. The interior of sandstone blocks consists of sand grains in a buff-colored cement of clay, but their margins show some recrystallization; sand grains break across and are embedded in a hard, siliceous cement.

Whole and comminuted quartz sand grains derived from the Lamotte make up about 15 to 25 percent of the lapilli tuffs. Unbroken sand grains, generally measuring 0.5 to 1.5 mm, are visible in hand specimen. Broken sand grains have a much wider size range, from about 1 mm down to silt size (less than 0.05 mm).

Part of the quartz sand and silt occurs as inclusions in chloritized sideromelane vitrophyre lapilli and ash; the silt-size fraction is most common in the tuffaceous microbreccia phase of the mesostasis; the majority occurs in the tuffaceous carbonate mesostasis together with the other clastic constituents. These latter quartz grains frequently show minor initial carbonate replacement along grain boundaries that results in a thin corroded rim.

Figure 22

Calcite replacement in blocks of dolomite in sandy lapilli tuff located in central area.

The unbroken sand grains are well rounded to subrounded. Some show strain by undulatory extinction and some are fractured. Inclusions of green biotite, apatite, rutile needles, and zircon have been observed as well as planar sets of inclusions that cannot be resolved under the microscope.

The broken sand grains have sharply angular, splintery, and slivery shapes. Larger ones can be clearly seen as halved or quartered sand grains, retaining one rounded side.

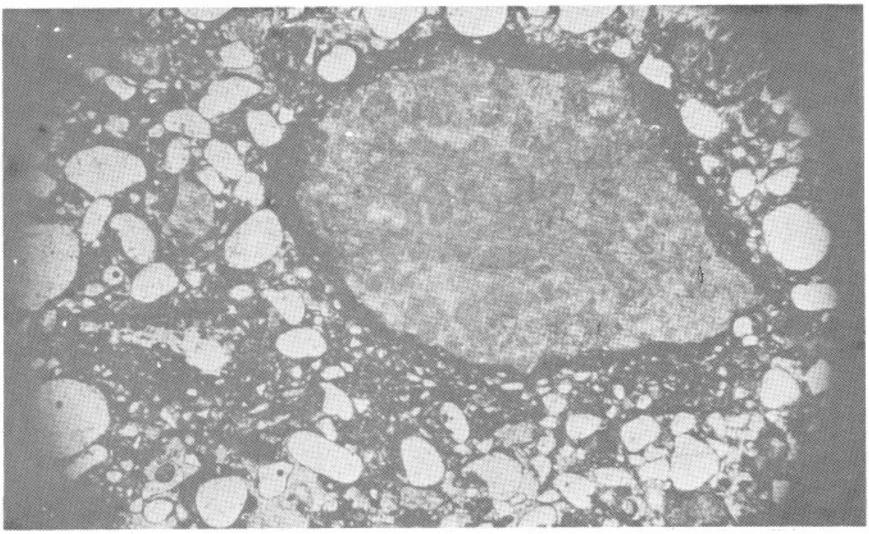


Figure 23

Photomicrograph of limestone fragment rimmed by tuffaceous microbreccia in lapilli tuff. Mesostasis consists dominantly of tuffaceous microbreccia and contains sand grains. Parallel nicols, 22X.

Bonneterre Limestone and Dolomite

Angular blocks and lapilli of limestone and dolomite are common in the lapilli tuffs. In hand specimen they can be recognized as desne, pink and white limestone; red dolomitic limestone; and algal and tan dolomite characteristic of the lower Bonneterre. One of the most striking features of the carbonate blocks is the replacement of their interiors by coarse crystalline calcite (fig. 22).

The limestone consists of extremely fine-grained (less than 0.01 mm) interlocking anhedral calcite. It has pseudo-oolitic or pelletal texture and contains fossil debris. The red dolomitic limestone fragments typically have a narrow recrystallized dolomite rim, while their core consists of both calcite and dolomite with indistinct iron oxide impurities. The tan dolomite is coarser grained than the limestone with grains averaging 0.1 mm. Dolomite crystals are subhedral to rarely euhedral. Carbonate rock fragments are usually enclosed in a thin shell of fine tuffaceous material annealing to their surface (fig. 23).

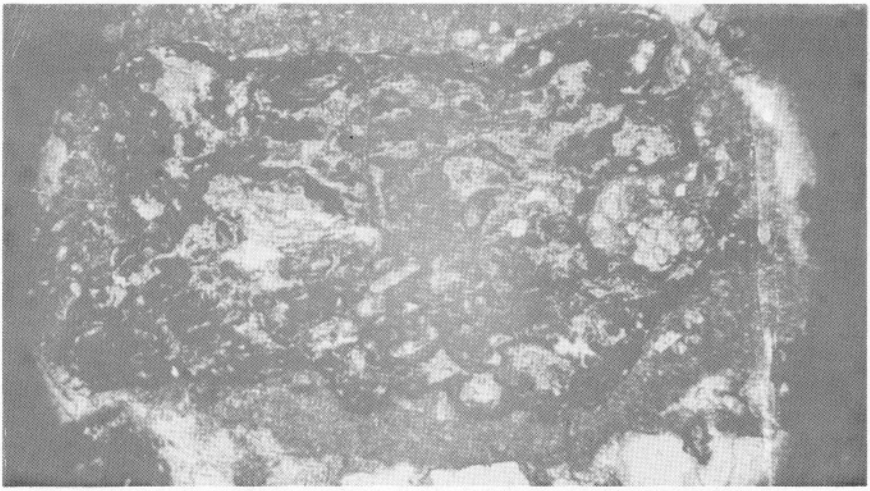
THE MESOSTASIS

The mesostasis makes up about 20-25 percent of the well indurated lapilli tuffs, but its proportion increases in reworked tuffs and in the tuffaceous sandstones. It consists of two distinct phases referred to as tuffaceous microbreccia and carbonate.

Tuffaceous Microbreccia

The tuffaceous microbreccia consists predominantly of anhedral granular epidote or pumpellyite of extremely fine-grain size (less than 0.001 mm). Embedded in it are angular fragments of quartz and feldspar, flakes of chlorite and biotite, grains of iron oxide, and (rarely) euhedral crystals of dolomite. These minerals usually fall in the 0.1- to 0.01-mm size range. Presence of angular feldspar and quartz suggested the term microbreccia, as these are clearly brecciated fragments of accidental ejecta of very fine grain size. These fragments are typically elongate and those of quartz are often curved reflecting its conchoidal fracture.

The microbreccia is most abundant in the well-indurated rocks including both lapilli tuffs and tuffaceous sandstones. In hand specimen it imparts a dark grayish-green color to the mesostasis, is very hard (about 7 on the Mohs scale).



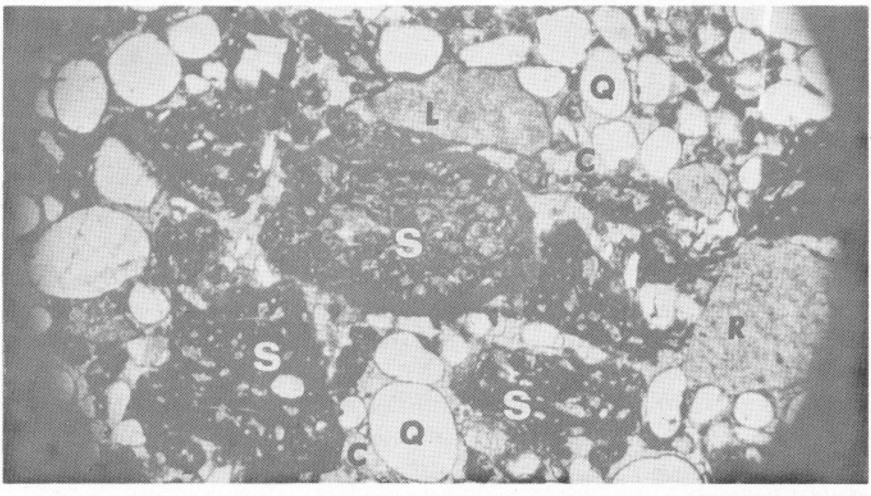


Figure 24 and 25

(Top) Photomicrograph of chloritized sideromelane vitrophyre shard rimmed by tuffaceous microbreccia in massive lapilli tuff. Parallel nicols, 50X. (Bottom) Photomicrograph of fragments of chloritized sideromelane vitrophyre (S), limestone (L), and rhyolite (R) with sand grains (Q) in lapilli tuff. Note the dark tuffaceous microbreccia rim around the central vitrophyre fragment and the intergranular calcite (C). Parallel nicols, 22X.

and is resistant to weathering. In fact, the preservation of the microbreccia appears to be the very reason for the well-cemented, indurated aspect of the massive lapilli tuffs just north of Highway C (pl. 2). Where the microbreccia is subordinate because of carbonate replacement or removal by reworking, the mesostasis tends to be leached, porous, and much more subject to weathering. These rocks, therefore, do not appear to be as "well-cemented" even if they contain a high amount of essential ejecta. An example is the lapilli tuff south of Highway C (sample 35) which contains a high percentage of essential ejecta but its mesostasis has almost completely been replaced by dolomite. Consequently, the rock is soft, porous, and friable, and weathers easily.

Under the microscope the most prominent feature of the microbreccia is that it occurs as a shell or coating around all types of ejecta, although not necessarily all of the ejecta (figs. 24 and 25). The thickness of this shell is usually about 1 mm, sometimes more. It is annealed to the surface of the ejecta regardless of irregularity of outline, and the contact between them is very sharp. Elongate grains, where present in the microbreccia, tend to have their long axes parallel to the ejecta outlines and impart a slightly foliated aspect to the shell. The microbreccia appears to have been wrapped around the ejecta before ejecta emplacement. It also appears to have formed protective shells around the ejecta fragments for those surrounded by it are much less affected by secondary alteration processes than those that lack the microbreccia rim. Pelletal limestone fragments show no trace of recrystallization or replacement by dolomite. Fragments of red dolomitic limestone have a narrow zone of recrystallized dolomite that separates the interior of the fragment from the microbreccia rim, but its contact with the latter is sharp.

Occasionally, the microbreccia forms individual rounded lapilli. Commonly, however, it forms a mesostasis around a group of assorted ejecta, including several sand grains, crystals, and lithic fragments. Where predominant in the mesostasis of the lapilli tuffs, the microbreccia fragments are aligned almost parallel to megascopically observable bedding planes. Graded bedding on a microscopic scale is evident in sample 19 (pl. 2) with lapilli and microbreccia alternating with each other.

The microbreccia is interpreted as the finest fraction of ejected essential and accidental pyroclastic material, i.e. very fine ash and dust that (a) were annealed to the surface of coarser ash and lapilli before their emplacement and (b) accumulated in distinct layers over the coarser ejecta. Conceivably it has also

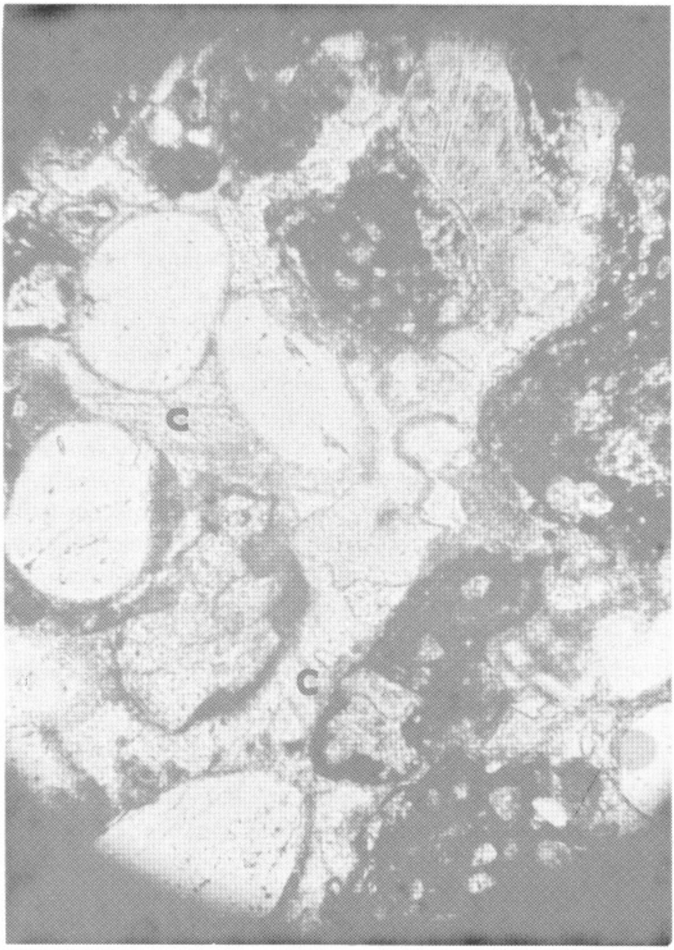


Figure 26

Photomicrograph of calcite (C) in mesostasis of massive lapilli tuff. Parallel nicols, 66X.

formed composite lapilli, incorporating several vitric, crystal, and lithic fragments in the ascending mixture of hot solid-gas phases. These are seen to be largely disintegrated in the lapilli tuffs and the microbreccia partially replaced by carbonate. The essential component of the microbreccia has been altered to epidote or pumpellyite.

Carbonate

Carbonate of the mesostasis in the lapilli tuffs consists of both calcite and dolomite. In the massive lapilli tuffs, calcite predominates but is partially or wholly replaced by dolomite in the reworked types.

Calcite occurs in anhedral to subhedral grains most of which are between 0.1 and 1 mm in size. Undulatory extinction and twinned crystals are fairly common. Where abundant, calcite forms a matrix in which essential and accidental lapilli and ash are embedded (fig. 26). Sometimes it is poikilitic with anhedral grains completely enclosing smaller fragments of other minerals or forming optically continuous webs between closely-spaced smaller ejecta. Calcite in the vesicles often has radial extinction; a similar pattern is also observed around vitrophyre fragments.

Replacement of the vitrophyre by calcite is less common in the lapilli tuffs than in the tuffaceous sandstones. Where observed, radiating clusters of calcite contain some intergranular chlorite, apparently representing the recrystallized remains of the original iron-rich vitrophyre. Much of the calcite, however, apparently has not originated by replacement.

Dolomite occurs as euhedral to subhedral crystalline aggregates of irregular outline. Grain size ranges up to 1 mm, but is generally about 0.5 mm. Euhedral crystals are often zoned. Relationship of the dolomite to the clastic components of the lapilli tuffs is best observed in sample 35 (pl. 2) where it has replaced about 90 percent of the mesostasis. Quartz, feldspar, and rhyolite fragments are only slightly affected by dolomite replacement, manifested by a somewhat corroded outline in the case of the quartz sand grains. The microbreccia rim around rhyolite fragments has been replaced completely, and incipient dolomitization in the interior of some of these fragments was observed (fig. 27). Chloritized vitrophyre fragments are more extensively replaced by dolomite. Large euhedral dolomite crystals replace the calcite filling of the vesicles extending into the vitrophyre itself. Gradual encroachment of dolomite from the mesostasis along the exterior of the fragments is obvious.

TUFFACEOUS SANDSTONES

Approximately 80 percent of the clastic components of the tuffaceous sandstones consists of quartz sand grains and fragments. They are usually less than 1 mm in size; a small percentage are in the silt-size range. Their morphology and inclusions are the same as those of the lapilli tuffs.

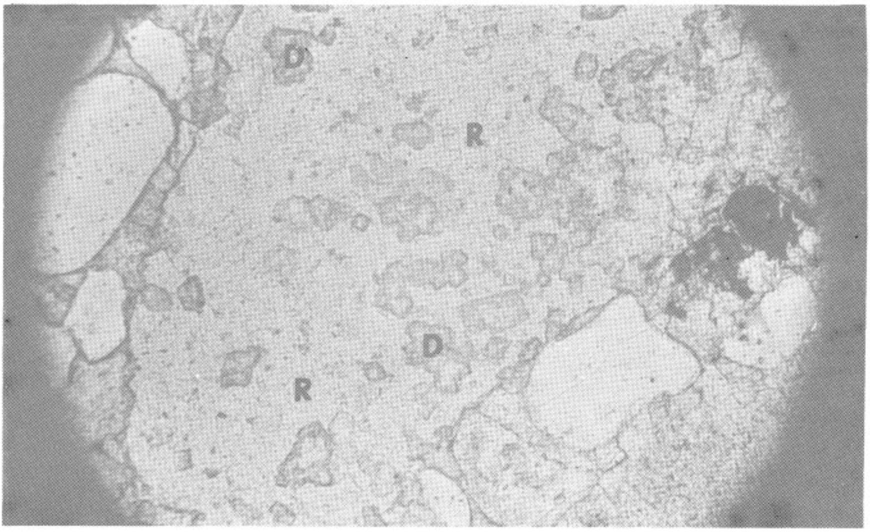


Figure 27

Photomicrograph of replacement of rhyolite (R) by dolomite (D) in reworked lapilli tuff. Parallel nicols, 50X.

Accidental constituents of the lapilli tuffs, namely fragments of rhyolite, limestone, dolomite, orthoclase, microcline, and plagioclase are all present in the tuffaceous sandstones. Together these comprise about 15 percent of the clastic constituents. Most frequently they are less than 2 mm in size, but the lithic fragments also occur in lapilli size. Both lithic and crystal fragments retain the irregular angular shape characteristic to them in the lapilli tuffs. However, the larger orthoclase fragments appear to be somewhat more rounded.

The degree of alteration of the rhyolitic fragments is generally the same in the tuffaceous sandstones as it is in the lapilli tuffs. Fresh rhyolite fragments are common, and post-diagenetic alteration is restricted to moderate sericitization of the phenocrysts in the porphyritic varieties. As in the lapilli tuffs,replacement by fine-grained calcite is most prominent in the microcrystalline granular textural varieties. Microcline and plagioclase fragments are invariably fresh, while orthoclase is usually cloudy and sericitized to various degrees.

Essential ejecta comprise about 5 percent of the clastic components. A brown, non-pleochroic mica with ragged outlines is sparsely distributed in the mesostasis along with euhedral and rounded grains of magnetite. The latter invariably shows alteration to hematite along grain boundaries.

Chloritized sideromelane vitrophyre of the lapilli tuffs is altered to a dark green to gray ferruginous clay in the tuffaceous sandstones. Their shape is usually somewhat more rounded than in the lapilli tuffs, although quite frequently their concave, angular, shard-like shape is retained. Smaller fragments of quartz, feldspar, and (occasionally) even sand grains adhere to and are partially embedded in the surface of the rounded clay pellets. Under the microscope the clay appears as irregular patches and smudges of extremely fine-grained semi-opaque material. The characteristic vesicular texture is preserved to a degree sufficient to relate to the vitrophyre. Accidental inclusions are also preserved in them as well as grains of magnetite-hematite. In rare instances remnants of fine-grained chlorite are also recognized in the clay.

Replacement of the altered vitrophyre by carbonates is much more prominent in the tuffaceous sandstones than in the lapilli tuffs. Replacement by calcite progresses from the center of the fragment toward its outer margins. In some cases as much as 90 percent of the fragment may be replaced, with calcite forming the irregular nucleus surrounded by a narrow rim of black opaque material consisting largely of the expelled iron oxides. In such cases the calcite is usually a single anhedral cyrstal (up to 2 mm in size) or is made up of two or three smaller individuals with interlocking and somewhat sutured boundaries. It frequently shows both strained and radial extinction.

Replacement by dolomite progresses from the mesostasis toward the interior of the altered vitrophyre fragments. The dolomite is euhedral (fairly uniformly 0.1 mm in size) and is decidedly zoned with dark-brown iron oxides. Dolomite replacement is never as complete in the interior of the fragments as it is in the case of calcite; between the zoned and euhedral dolomite crystals, the black iron-rich remnants of the altered vitrophyre can always be recognized. Interestingly enough, such fragments that have been partially replaced by calcite are not affected by dolomite replacement.

TUFFACEOUS SILTSTONES

The clastic components of the siltstones are less than 0.05 mm in size and make up approximately 30 percent of the rock by volume. They consist dominantly of sharply angular slivers and fragments of quartz believed to have been derived from the Lamotte Sandstone. Elongate grains lie with their long axes parallel to planes of lamination in sections cut perpendicular to the lamination. Most of the quartz grains are clear, but minute inclusions resembling rutile are observed occasionally. Some fragments are composed of microcrystalline aggregates of quartz.

Fragments of feldspar and rhyolite are less abundant than those of quartz and make up about 5 percent of the clastic components. Feldspars are generally cloudy and contain minute inclusions that cannot be resolved under the microscope. Orthoclase and plagioclase are present in almost equal amounts; a trace of clear microcline and a few rhyolite fragments were also observed. Flakes of sericite and euhedral and rounded grains of zircon, magnetite, and pyrite occur as accessory minerals.

Impure dolomitic matrix comprises about 70 percent of the siltstones. Dolomite only makes up about 50 percent of the rock as indicated by the amount of insoluble residues. The dolomite occurs in very fine-grained anhedral aggregates; it is cloudy throughout, contains indistinct inclusions, and has black opaque spots. The dark-gray color banding observed in hand specimen is caused by brown iron oxide that stains the siltstone matrix. These color bands, which range from 1 to 2 mm in thickness, alternate with bands of unstained matrix of about equal thickness.

All dolomite in the tuffaceous siltstones occurs as late diagenetic replacement of an earlier very fine grained matrix which is preserved only in the form of the impurities in the dolomite. Replacement by dolomite is indicated in the clastic quartz and feldspar grains; sometimes it is almost complete. Some replacement is usually shown along grain boundaries.

Impurities in the dolomite matrix could not be resolved under the microscope. In an attempt to identify them insoluble residues obtained by the digestion of a siltstone sample in hydrochloric acid were carefully examined. Aside from the clastic constituents, the residue consisted of extremely fine grained, porous, slightly gritty clayey material that retains the fine rhythmic banding of the siltstone. Using the Becke method, the refractive index of the fine clayey reisdue was determined to lie between 1.520 and 1.525. It has very low birefringence and is white in reflected light. An X-ray diffractogramm of the residue indicated indistinct and very weak clay peaks that were not definite enough to be used for identification.

Essential components as described in the lapilli tuffs and the tuffaceous sandstones were not recognized in the tuffaceous siltstones. The quartz, feldspar, and rhyolite grains resemble the finest fragments observed in the tuffaceous microbreccia of the lapilli tuffs in every aspect and are interpreted as accidental components indirectly derived from the Lamotte Sandstone and Precambrian igneous rocks. These accidental components provide the basis for classifying the siltstones as tuffaceous rocks and as members of the sequence of pyroclastic sediments in the Dent Branch area. It is assumed that the original matrix of the siltstones consisted of fine essential ash and dust that were subsequently almost completely replaced by dolomite and were preserved in the rocks only as the clayey impurities in the dolomite.

HISTORY AND ORIGIN

The stratigraphic position of outcrop of the pyroclastic rocks is in the upper part of the lower third of the Bonneterre Formation. During the deposition of this horizon the only land masses extending above the Cambrian sea within an area of 20 to 30 miles in diameter were the Precambrian felsite ridge and the associated island chain extending southwestward (pl. 1). These rocks could have provided an arkosic debris to be incorporated in the sediments. Exposures of granite, however, are not known for about 10 to 15 miles to the east and southeast and, according to limited drillhole data available in the immediate area, are not present in the top of the buried Precambrian basement. The dominantly fresh and angular feldspars and the few observed granite fragments could not have been derived from a distant source by normal geologic processes. Granitic intrusives are present over a considerable part of the St. Francois Mountain area and have often been encountered by drilling beneath the felsite flows. It is quite likely that granite would be encountered at depth in the Dent Branch area.

At the time of deposition of the lapilli tuffs, the Lamotte Sandstone had been covered by lower Bonneterre beds. The possibility exists that sandstone fragments and sand grains were derived as arkosic debris from areas elevated by faulting in early Bonneterre time. Present knowledge of the subsurface in the area, however, does not warrant the assumption that such elevated areas existed. Similar considerations apply to the incorporated lower Bonneterre limestone and dolomite fragments. Lapilli tuffs show a sharp localization into relatively small distinct bodies of considerable vertical extent and are separated from each other in the same horizon by normal Bonneterre beds. There is no mixing of the two where they are adjacent to each other.

The tuffaceous microbreccia rim coating all observed types of fragments ties these ejecta genetically to the same manner of origin. By whatever manner these were derived, the tuffaceous shell was formed before they were emplaced in their sedimentary environment. These fragments represent rocks far apart from each other in time and, consequently, in their place in the stratigraphic column. Any theory on the origin of these rocks has to account for the presence of the tuffaceous microbreccia that coats the otherwise unrelated accidental components. Accordingly, they could only have been emplaced under conditions that acted simultaneously and rapidly upon the various rock types. The tuffaceous material could not be derived from any known pre-existing rocks in the area and, therefore, it is a genetic factor to be reckoned with.

One of the frustrating aspects of the Dent Branch rocks is their relatively small content of essential volcanic material. No flows or comparable extrusive rocks have been recognized that might indicate a normal upwelling of lava through established channels, and there is no suggestion of a buried "volcano" in the usual sense of the word. What essential material there is (about 10 to 15 percent in terms of the total volume of exposed pyroclastic rocks), has been considerably altered and is recognized largely on textural criteria. The lapilli and coarse ash fragments of the essential vitric material are coated by the same tuffaceous microbreccia that surrounds the accidental ejecta, which establishes a genetic link between essential and accidental components.

By what manner of origin then could the clastic components of the Dent Branch rocks have been derived? In the authors' opinion explosive brecciation and fluidization could have produced the angular unsorted fragments of pre-existing rocks and brought them up high above their normal stratigraphic horizon. The resultant structure then would essentially be that of a diatreme.

PETROLOGIC CONSIDERATIONS

In the relatively stable continental platform of the Midcontinent, volcanism (such as is connected with orogeny in tectonically active areas in other parts of North America) has not occurred since the close of Precambrian time. In this vast expanse of continent, igneous rocks of any kind are few and far between. Yet, recurrent breakthroughs through Paleozoic and Mesozoic sediments have been recorded in widely-scattered localities.

Explosive igneous activity, ranging in age from Late Cambrian to Devonian, along an east-west axis has been described by Snyder and Gerdemann (1965). This includes the Avon diatremes and associated intrusives in Ste. Genevieve County, Missouri, described earlier in detail by Kidwell (1947), and the Furnace Creek volcanics. Ultramafic intrusions of Cretaceous age, identified as kimberlites, and brecciated pipes with kimberlite zenoliths have been described from Riley County, Kans., by Brookins (1966). Igneous rocks of Mesozoic age, known from several drillholes in the northern Gulf Coastal Plain include a variety of alkalic and ultramafic intrusives, extrusives, and associated pyroclastics (Moody, 1949, and Kidwell,(1951).

The alkalic intrusive complexes at Magnet Cove and Little Rock, Arkansas, have been described by several authors, and their radiometric age has recently been determined as Late Cretaceous (Zartman et al., 1967). The well-known diamond-bearing peridotite from Murfreesboro, Arkansas, that forms a pipe-like intrusive (Miser and Ross, 1923) has more recently been referred to as kimberlite, kimberlite breccia and tuff by Watson (1967). Its age is also Late Cretaceous. Water-laid volcanic rocks of Late Cretaceous age are known to crop out in adjacent parts of Arkansas, Oklahoma, and Texas (Ross, Miser, and Stephenson, 1929).

The igneous rocks represented at these various localities are dominantly alkalic and according to Zartman et al. (1967) together with similar occurrences in the Eastern United States, constitute a petrologic province. They occur as stocks, plugs, sills, dikes, and diatremes that occupy deep-seated fractures and pipes that penetrate the continental platform. Many of the intrusions possess characteristics that are similar to those observed in the Dent Branch rocks, and these similarities provide a clue for the proposed manner of origin for the latter. In fact, certain similarities can be extended to worldwide occurrences of alkalic ultrabasic complexes, and the Dent Branch pyroclastics can be fitted into the overall framework of closely related processes. Some of the similarities that are considered to have a bearing on the genesis of the Dent Branch deposit are discussed briefly.

TECTONIC SETTING

The gross tectonic environment of the Dent Branch deposit corresponds to that of other alkalic intrusive and extrusive complexes in the central stable region of the Midcontinent. Here tectonic movements since Precambrian time have largely been vertical, namely block faulting, slow subsidence of interior basins, arching, vertical uplift and doming. These movements were generally accompanied by the development of tension fractures and joints.

On a more local scale the Dent Branch deposit is situated near the intersection of two major fault systems on the flank of the uplifted Precambrian core of the Ozark dome. Its position on the northwest flank of the exposed Precambrian high is considered to be especially significant because the Furnace Creek volcanics, the Avon diatremes, and the Bee Fork pyroclastics also occupy positions peripheral to the main exposed area of Precambrian rocks in southeast Missouri. The central core of the Ozark dome has been a tectonically positive area throughout geologic time. Some downwarping and faulting of differentially less-rapidly rising peripheral areas was associated with its gradual uplift. Crustal instability in this general area could, at times, have been sufficient to tap deep-seated reservoirs of magmatic material and provide periodic release of pressure and escape of gases.

That the pyroclastic rocks do not occur along a known fracture system does not appear to be significant. Any movement in late Lamotte or early Bonneterre time in zones of weakness would now be obscured by subsequently deposited strata. It is well known that movement in the Precambrian basement often is not translated directly into the overlying sediments but may shift position laterally. With the passage of time the loci of areas of greatest pressure from the underlying magma would change, and the fracturing would become more dominant in other parts of the periphery of the core.

TEMPERATURE OF INTRUSION

Corresponding to worldwide occurrences of diatremes, the Dent Branch rocks are characterized by the virtual absence of thermal metamorphic effects on their enclosed accidental ejecta. This is especially true for the smaller lapilli and ash fragments that show no effects of recrystallization, even in the very fine grained limestone fragments. Some of the larger blocks on the other hand, tightly wrapped in tuffaceous material, do exhibit slightly recrystallized margins. These include the fragments of sandstone and those of the dolomitic limestone. The presence of blocks of limestone and dolomite with coarse crystalline calcite centers could not be adequately explained by the methods of our present investigation.

A certain amount of heat is indicated, but the prominent feature appears to be that of relatively low temperatures. This is in accordance with investigations that show that the temperature of intrusions of alkalic ultrabasic dikes and sills in non-orogenic regions was generally less than 600 degrees C and could have been as low as 340 degrees C (Watson, 1967). Recent investigations by Brookins (1969) indicate that the kimberlite pipes in Riley County, Kans. were emplaced at low temperatures, possibly as low as 100 to 200 degrees C.

EXPLOSIVE BRECCIATION AND FLUIDIZATION

Brecciation of accidental components is one of the most prominent features of the Dent Branch rocks. These fragments were clearly brecciated before their emplacement. The mechanism of brecciation has been interpreted by the authors as explosions of a magma that was intruding slowly along a system of deep-seated tension fractures. The process is described in detail by Dawson (1967). At certain points, probably strongly influenced or controlled by structural factors where access to the surface is easiest, explosive breakthroughs may occur. Where the ascending magma encounters porous, water-saturated clastic sediments, such as the Lamotte Sandstone in the case of Dent Branch, the rate of explosions may be increased to a considerable degree because of the added pressure of water vapor. Rapid vesiculation of magma accompanies the explosions with continuous escape of gases. Under high velocity gas flow the overlying column of rocks tends to expand, shatter, and rotate, creating a complex fluidized system consisting dominantly of a two-phase gas-solid mixture. Very little liquid magmatic material may actually reach the surface; this explains the scarcity of essential ejecta in the Dent Branch rocks which represent the surface level of such an explosive vent. The process also accounts for the preponderance of Lamotte sand grains in the rocks, as this formation must have been especially prone to fluidization and sand from it may actually have been siphoned out from areas immediately surrounding the vent. This may have been accompanied by collapse of overlying formations, developing the complicated relationships that are now observed on the surface.

According to Dawson (1967), in the later stages of the formation of a diatreme, gas surges may emplace columns of tuff or tuffisite veins, and cavities in the vent may be infilled with quietly upwelling magma that consolidates the rocks into a massive breccia. If it were possible to determine the exact location of the vent or vents in the Dent Branch area, drilling would most likely encounter true diatreme material with higher proportions of essential constituents, possibly even intrusive offshoots of the parent magma.

In summary, the prominent features of the Dent Branch deposit that relate it to worldwide occurrences of diatremes are the following: tectonic setting, absence of thermal metamorphism, nature of brecciation, and minor amount of liquid magma phase.

CHEMISTRY OF THE MAGMA

To establish the composition of the magma that triggered the explosive activity at Dent Branch, it would be necessary to identify its essential mineral suite. Unfortunately the subordinate amount of primary magmatic material and the extreme alteration of this material prevent such an identification.

The liquid magmatic material that reached the surface at Dent Branch consisted predominantly of glass and has been identified as chloritized sideromelane vitrophyre. At the time of their ejection from the vent these vitrophyre fragments cooled enough so that they did not shatter upon contact with the sea water. There is no evidence that these ejecta were fragmented, granulated, or brecciated subsequent to their deposition. On the other hand, they must have been sufficiently plastic to be squeezed and flattened under the load of other ejecta after they had fallen back into the water. In this respect they differ from typical shards, as the latter are usually defined as broken walls of gas filled bubbles, and their fragmentation occurred during viscous flow or after ejection from a vent, either in subaereal or subaquaeous conditions.

The fragmentation of the sideromelane in the Dent Branch event occurred in the vent as part of the explosive brecciation and fluidization of all other components that were involved in the event. Incipient crystallization of early-formed minerals in the liquid magma phase is indicated by the presence of porphyritic sideromelane fragments; however, these are subordinate in amount to the vesicular vitric fragments. It should be stressed here that no essential feldspars or feldspathoids were recognized in the sideromelane.

The essential crystal fragments also indicate some degree of crystallization in the magma. It is assumed that these were ejected from deeper levels of the liquid magma phase than the sideromelane fragments. Although no fresh olivine or pyroxene were recognized, they are indicated by crystal outlines. Davidson (1967) describes some breccia pipes in the U.S.S.R. that cut Cambrian strata and notes that these too are very heavily altered and are devoid of fresh olivine.

The phlogopite was identified on the basis of optical properties. Phlogopite is a characteristic mineral of diatremes and is an essential mineral of micaceous kimberlites and related ultramafic rocks. Its associated minerals include olivine, garnets, pyroxenes, amphiboles, picro-ilmenite, magnetite, perovskite, and a host of secondary minerals. Von Eckermann (1967) notes that in the classic area of Alnö Island in Sweden, where ultramafic rocks are associated with kimberlites and carbonatites, the phlogopite is often substituted by a more biotitic mica.

From the scanty evidence of phlogopite, magnetite, and altered olivine and pyroxene (?) it is impossible to reconstruct the precise chemical composition of the Dent Branch magma. Essential lapilli in the Avon diatremes contain abundant crystals of melilite in a chloritized groundmass, but no melilite was recognized at Dent Branch. This may indicate the more mafic or ultramafic composition of the latter.

Trace element analysis of the essential lapilli may provide some answers to many interesting and as yet unanswered questions relative to the petrology of these rocks.

ORIGIN OF THE CARBONATE

The carbonate of the mesostasis in the massive lapilli tuffs is entirely calcite. It was originally assumed that this carbonate represented the sedimentary matrix because the explosive event occurred in subaqueous environment under conditions of carbonate sedimentation.

At this point the origin of the calcite is not completely understood. Petrographic evidence suggests that it was introduced as a liquid, rather than as a primary precipitate. It cannot be a product of weathering, as it is most abundant in the least-weathered rocks. As suggested by the textural relationship, it was introduced shortly after the clastic components and definitely before complete consolidation of the rocks. Some of it can be recognized as deuteric, notably the calcite that forms pseudomorphs of olivine and pyroxene (?). Most of it, however, is evidently a late crystallizing primary mineral.

The calcite may have been derived from hydrothermal solutions escaping through the breccia-filled vent in the late stages of the magmatic activity, after explosions and brecciation ceased. If so, it must have filled voids and open pores in the clastic rocks as there is little evidence of replacement in the mesostasis. Hydrothermal activity would also undoubtedly have intensified thermal conditions and under such circumstances it is surprising that accidental limestone fragments should have remained stable and that feldspars should also have been unaffected.

The calcite may also have been derived from lower Bonneterre carbonate rocks penetrated by the vent through reaction of the liquid magma phase with the calcareous beds. Such a reaction, however, usually produces a number of characteristic skarn minerals, such as grossularite, hedenbergite, wollastonite, scapolite, etc. Although they may be present at a deeper level of the deposit, none were found in the Dent Branch rocks.

The possibility must also be considered that the calcite is a product of the magma itself and represents its immiscible carbonate-rich phase. Carbonatites are associated with several known alkalic ultrabasic complexes throughout the world. According to Watson (1967) the presence of primary carbonate could explain the emplacement of ultrabasic magma as a highly fluid material at relatively low temperatures.

The authors have reached no definite conclusions about the origin of the carbonate in the Dent Branch rocks but considered all of the above possibilities. It would be a worthwhile effort to study this aspect of the deposit further, which is only one of the many other unsolved problems relating to it.

SECONDARY MINERALS AND ALTERATION

On the basis of the stratigraphic evidence, the Dent Branch event has been dated as Late Cambrian in age. Subsequent to the formation of the deposit and the subaqueous reworking of the lapilli tuffs the entire complex was buried under Cambrian, Ordovician, and possibly even younger formations whose combined thickness may have reached several thousand feet. The combined effects of uplift and erosion have subsequently removed most of these overlying strata and partially exhumed the buried deposit to reveal essentially the same level at the surface today that represented the surface at the time of the volcanic activity. These factors of age, long burial, and erosion must be considered to have left their mark on the rocks and are bound to complicate a reasonable interpretation of their history.

Some of the alteration must have been contemporaneous with the volcanic activity. This almost certainly would have involved the palagonitization of the sideromelane soon after it was emplaced in the sea water. Peacock (1926) describes palagonitization as the hydration of sideromelane by immersion in sea water. The palagonite tuffs of Iceland are a classic example. There, this process was accompanied by extensive oxidation of the iron component and some loss of lime and soda, and the brittle sideromelane was converted to relatively soft gel-palagonite and fibro-palagonite. According to Peacock, palagonite alters to chlorite and zeolites, and he suggested that some of the obscurely fibrous, weakly birefringent material in fibro-palagonite may represent incipient separation of limonite and chlorite.

Palagonite is an unstable mineraloid and, accordingly, it cannot be expected to have been preserved in the Dent Branch rocks. There are certain indications, however, that the process of palagonitization has affected them. The freshly fallen ejecta were subject to almost immediate agitation and some reworking by submarine currents, yet there is no evidence that the brittle sideromelane was further fragmented or borken in the process. Instead, they appear to have become less angular, even rounded in the tuffaceous sandstones, and it is probable that at this stage of their history they had already been converted to palagonite. Their subsequent chloritization was very likely a diagenetic process, and their alteration to ferruginous clay appears to be a product of weathering.

The alteration of the finest tuffaceous material to epidote or pumpellyite is not as well understood. Some of this fine dust was evidently attracted to the surface of larger ejecta in the ascending mixture of solid and gas, either in the vent, or during the short period of ejection through water and probably air. It was also expelled as a dust cloud that presumably remained in suspension in the water longer than the larger ejecta and upon deposition produced the graded bedding that is observable in some of the massive lapilli tuffs. It can be assumed that this fine tuffaceous material became saturated with sea water which must have been heated up considerably during the volcanic periods, and that some reaction between the dust and water took place resulting in an exchange of calcium and the formation of the epidote or pumpellyite.

Replacement by dolomite is a relatively recent process in the history of the pyroclastic rocks and may have been connected with the regional dolomitization of Cambrian sediments in the area. The process intensely affected the mesostasis of the pyroclastic rocks, sparing the massive lapilli tuffs. The problems of dolomitization in the Dent Branch rocks should be the subject of another study.

EMPLACEMENT HYPOTHESES

The time and approximate duration of the Dent Branch volcanic event are established by stratigraphic evidence. Lower Bonneterre beds are exposed in the same horizon with the pyroclastic rocks of the Central area. There is no interfingering of these rock types as would be the case if volcanism had occurred during the deposition of the dolomite. The accidental fragments derived from preexisting formations and incorporated in the pyroclastic rocks indicate that both the Lamotte Sandstone and the lower part of the Bonneterre Formation had already been deposited at the time of the first breakthrough. It has been estimated that the lower 100 to 110 feet of the Bonneterre Formation was involved. The tuffaceous sandstone designated as the Upper Sand represents the highest rock unit in the pyroclastic sequence and is overlain by middle Bonneterre dolomite. Drill holes indicate that the Upper Sand is always in the same horizon in the Bonneterre section, its lower contact with the dolomite is always sharp, and its upper contact with the dolomite is often gradational. The position of the Upper Sand in the Bonneterre section therefore fixes the time and its thickness approximately represents the duration of the Dent Branch volcanic event.

Some of the important aspects of the mode of emplacement of the pyroclastic rocks will be discussed in the following sections.

LOCATION OF THE VENT OR VENTS

Although the conditions and mechanism of the origin of the pyroclastic rocks have been established, the exact location of the vent through which the ejecta were expelled could not be determined with certainty. It is also uncertain whether there are one or more vents within the Dent Branch area.

The lapilli tuff-lower Bonneterre dolomite contacts exposed in Dent Branch along the north and south boundaries of the Central area are believed to be parts of the north and south walls, respectively, of the main vent through which the bulk of the pyroclastic material was ejected. This is indicated by the apparently vertical attitude of the contacts, the large size and quantity of dolomite blocks in the lapilli tuff adjacent to the contacts, fracturing of the dolomite, and the abundance of calcite in both the dolomite walls and the dolomite blocks in the lapilli tuff. The east and west walls of the postulated main vent may be soil covered and/or overlain by middle Bonneterre dolomite.

It is not known whether the lapilli tuffs in the South and North areas were derived from the main vent in the Central area or whether secondary centers provided the ejecta for these deposits. As outcrops of pyroclastic rocks extend in a southwest-northeast direction it is conceivable that both the South and North areas represent the location of secondary vents from fissures along a line of basement weakness. However, all activity in the Dent Branch area must have been contemporaneous as indicated by the stratigraphic position and identical composition of the deposits.

The shape of the vent or vents may have been circular and crater-like, or elongate reflecting the southwest-northeast direction of the postulated basement weakness. The coarse unsorted lapilli tuffs must have accumulated nearest to the vent areas in mounds and probably have built rims around the vents that at times may have risen above sea level. Their subsequent reworking and the deposition of tuffaceous sandstones within the crater obscured the relationships that could possibly have helped to locate the vents. Both field and petrographic evidence are inconclusive regarding this very important aspect of the Dent Branch deposit, but they do indicate that the primary source of pyroclastic material is within the immediate area. Geophysical and drill hole data would be required to confirm the more accurate location of the vent or vents.

THE LOWER SAND

The origin of the Lower Sand and its relationship to the other pyroclastic rocks is not understood at present. It involves the question of whether there were one or more major periods of volcanic activity that formed the deposit. There is little doubt that the Upper and Middle Sand, the lapilli tuffs, and tuffaceous siltstones are part of one major period of activity, regardless of whether their constituents were expelled through one or several centers. It is possible that the Lower Sand belongs to an earlier volcanic episode and was covered by lower Bonneterre sediments as suggested by the relationships observed in section

M-M' (fig. 14). Some support is given to this idea by the presence of a considerable thickness of pyroclastic rocks in the Lamotte-Bonneterre transition zone and probably in the upper Lamotte horizon east of the Precambrian ridge.

Evidence to the contrary is also fairly convincing. If the Lower Sand was associated with an earlier volcanic episode it would closely coincide in time and in stratigraphic position with the pyroclastic rocks at Furnace Creek, located about 4 miles to the north-northeast. The Furnace Creek activity ended after the deposition of the Lamotte-Bonneterre transition beds; outwash from that deposit is present in the form of tuffaceous beds within the transition zone for miles in all directions and has been projected to extend into the Dent Branch area (Snyder and Gerdemann, 1965, p. 476, fig. 4). However, these tuffaceous beds gradually decrease in thickness southward and are absent in drill holes south of Dent Branch. It is evident that the source of the tuffaceous material in these beds is not along Dent Branch but toward the northeast or possibly to the east of the Precambrian ridge. These tuffaceous beds represent the only pyroclastic material in the transition zone in the area immediately adjacent to Dent Branch. Therefore, there evidently was no volcanic activity in the Dent Branch area prior to that initiated after the deposition of lower Bonneterre beds, and the Lower Sand could not have been deposited as part of such activity.

It is possible that the Lower Sand is Lamotte Sandstone deposited over a Precambrian high and has become exposed because of its elevation. The fine pyroclastic material of the Lower Sand might have been washed into the area through a low gap in the Precambrian ridge from the east where a thick section of pyroclastic rocks in the upper Lamotte horizon may indicate another center of volcanic activity. The elevation of the gap along Highway C relative to that of the deposits east of the ridge allows this possibility. However, this explanation raises other problems in regard to the relationship of the Lower Sand and the other pyroclastic rocks of the Dent Branch deposit. The only exposed contact between them is the one with the overlying siltstone; conditions at the base of the Lower sand are not known. More information would be necessary to understand the place of these beds in the history of the deposit.

EVIDENCE FOR INTERMITTENT ACTIVITY

With the possible exception of the Lower Sand, the Dent Branch deposit is probably the result of one major period of volcanic activity. However, periods of prolonged inactivity are indicated by the deposition of the tuffaceous siltstone containing thin lesnses of dolomite between lapilli tuffs, and by the presence of thin layers of sandy dolomite in the Upper Sand.

It is believed that the tuffaceous siltstones were deposited in areas that were protected from the current and wave activity of the surrounding sea during quiet periods. Lapilli tuff rims around the vent or vents would provide such protected sites of deposition within their boundaries. The fine essential and accidental ash content of the siltstones could be derived from the inner walls of the rim deposits under conditions of mild wave activity and the environment would probably be subject to carbonate deposition also. If this is true, the 20-foot section of siltstone in the bluff along Dent Branch represents either a considerable period of time or unusually rapid sedimentation.

The thin layers of sandy coarse crystalline dolomite in the Upper Sand are interpreted as the result of carbonate deposition over the pyroclastic deposits during prolonged periods of no activity. This condition could arise at times when adjacent lapilli tuff mounds had been worked down to below wave base and ceased to provide additional pyroclastic debris. Renewal of activity would remedy this situation and more tuffaceous layers could be deposited over the sandy dolomite. The location of these carbonate sediments on the southwest flank of the deposit lends support to this idea. Peripheral deposits of similar character farther north may be hidden under the cover of overlying Bonneterre beds.

Sufficient inactive intervals are indicated by the graded bedding observed in the ***in situ*** lapilli tuffs. During these intervals the finest fraction of the ejecta that remained in suspension settled over the coarser fraction. On the other hand, the thickest exposed lapilli tuff section (fig. 16) indicates that the duration of quiet periods was insufficient to allow the deposition of non-pyroclastic sediments.

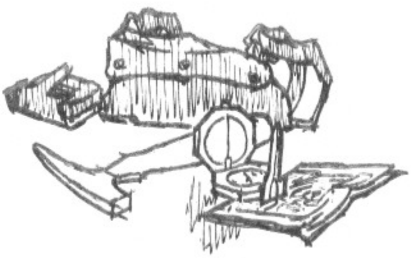
The stratigraphic evidence therefore suggests not only that the volcanic event was confined to a definite time interval during the deposition of the lower part of the Bonneterre Formation, but it also establishes that the activity was intermittent and consisted of alternating active and quiet periods. During the initial stage of volcanism emissions were probably fairly continuous and lapilli tuff deposits were built up above sea level to be subjected to constant attack by wave and current action. Later, with the gradual release of pressure from beneath the quiet periods between emissions became more frequent and of longer duration. Lapilli tuff mounds were more thoroughly reworked into tuffaceous sandstones. The Upper Sand was spread out to some distance over the lower Bonneterre beds and into the interior of the vent itself. With the reduced level of activity it is probable that emissions no longer took place over the entire diameter of the vent area but were localized in fissures in the vent floor, much as small cones are built up in the crater of modern volcanoes. After a final period of mild activity the reworking of the upper portion of the deposit was completed and middle Bonneterre dolomite was deposited over the Upper Sand.

POSTDEPOSITIONAL DISPLACEMENT

Abrupt changes in the attitudes of both lapilli tuff and sandstone beds within short distances indicate that at least some of the pyroclastic rocks are not in their original position. It is suggested that subsidence and/or collapse in the vent areas were primarily responsible for these changes. The downward movement would be similar to that described by Hearn (1968), but of minor magnitude.

Subsidence of the deposits in the conduit may have taken place several times and certainly must have affected the attitudes and relationships of the rocks within the vent area. The tilting of both siltstone and lapilli tuff beds at the top of the bluff on Dent Branch indicates that at least part of the subsidence took place after the deposition of the lapilli tuff. The crumpling and distortion of the siltstone appear to have been caused by compressive forces before complete lithification had occurred. It may also have been the result of subsidence in the underlying vent conduit.

Collapse of the vent walls is considered to have been a factor in the development of the erratic relationship of the pyroclastic rocks. It may have contributed to the progressive enlargement of the diameter of the vent. The preponderance of sand grains in both the lapilli tuffs and tuffaceous sandstones strongly suggests that the underlying Lamotte Sandstone was laterally and vertically affected during the active periods, and that the vent walls were not sufficiently stable to support open pipes during the time necessary for incremental filling. Different sections of the walls may have collapsed during successive active periods which explains the zones dominated by different types of accidental ejecta in the lapilli tuffs.



SUMMARY

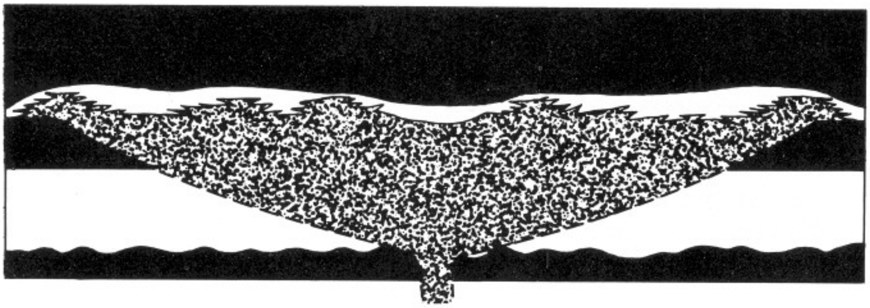
The evidence developed by this study has shown conclusively that the deposit is not an arkosic conglomerate derived from neighboring high Precambrian areas.

Explosive volcanic activity interrupted the process of normal Bonneterre carbonate sedimentation in the Dent Branch area subsequent to the deposition of approximately one third or about 100 to 110 feet of the Bonneterre Formation and produced a deposit of mixed pyroclastic sediments in the Late Camrian sea. The exposed section of the deposit which is the subject of the study has a maximum known thickness of 80 feet and consists of lapilli tuffs, tuffaceous sandstones, and tuffaceous siltstones that represent brecciated essential and accidental material ejected through a vent or vents, deposited in marine environment in the immediate vicinity of the vent or vents, and partially reworked subsequent to deposition by marine currents. Following termination of the period of volcanism the pyroclastic rocks were buried by additional thicknesses of Bonneterre and younger carbonate sediments. The pyroclastic rocks, therefore, represent a distinct facies within the Bonneterre Formation. The areal distribution of this facies has been determined by the extent to which the volcanic ejecta were transported from their source. Its stratigraphic distribution has been determined by the available supply of ejecta to be reworked and incorporated in the sediments, and is thus indicative of the time and duration of the period of volcanism.

Petrographic and petrologic criteria relate the pyroclastic rocks to those found associated with diatremes. They are indeed the surface expression of a diatreme modified by sedimentary processes but the location of the underlying pipe was not positively determined. Accordingly, this study was primarily oriented toward a description of the deposit and the pyroclastic rocks. The

north-northeast trend of the outcrop may indicate a line of structural instability in the underlying Precambrian basement between the Dent Branch deposit and the Furnace Creek volcanic structure along which explosive breakthroughs of magmatic material had occurred at different times.

The magma involved in the formation of the pyroclastic rocks is assumed to have been basic to ultrabasic in composition, possibly with alkalic affinities. The mode of origin and the composition of the lapilli tuffs are characteristic of alkalic ultrabasic complexes in tectonically stable continental areas in other parts of the world.



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LAPILLI TUFFS AND ASSOCIATED PYROCLASTIC SEDIMENTS

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