REPORT OF INVESTIGATIONS NUMBER 46

ASH-FLOW TUFFS OF PRECAMBRIAN AGE

IN SOUTHEAST MISSOURI

CONTRIBUTION TO PRECAMBRIAN GEOLOGY NUMBER 2

BY R. ERNEST ANDERSON

APRIL 1970

MISSOURI GEOLOGICAL SURVEY & WATER RESOURCES

WILLIAM C. HAYES, STATE GEOLOGIST & DIRECTOR, BOX 250, ROLLA, MO. 65401

COVER: Well-bedded tuffaceous sedimentary rocks mapped with tuff and lava of Lake Springs are exposed east of Buck Mountain. Light blotches are lichens.

RIGHT: A panoramic view of Johnson Shut-ins looking west from Proffit Mountain across the valley of the East Fork Black River.

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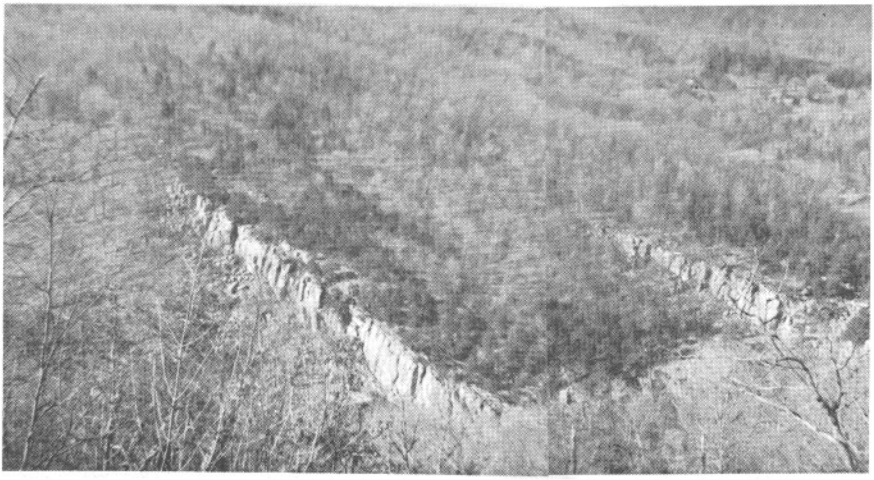

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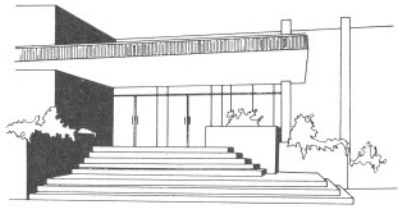

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FOREWORD

This is the second in a series of Contributions to Precambrian Geology of Missouri in the Survey's project "Operation Basement". The first, Report of Investigations 44 "Exposed Precambrian Rocks in Southeast Missouri" by Carl Tolman and Forbes Robertson, was published last year. One of the earliest comprehensive studies of the Missouri Precambrian, "Crystalline Rocks of Missouri" by Erasmus Haworth, was printed as a part of Volume VIII, 1st series, by the Missouri Geological Survey in 1895.

To meet the increasing academic and economic interest in the basement, the Survey plans to continue publication of this series of previously unpublished and current investigations of Missouri's Precambrian.

This report is a revision of R. Ernest Anderson's dissertation at Washington University, St. Louis, Mo. He is now a geologist in the Special Projects Branch of the U. S. Geological Survey in Denver, Colo.

William C. Hayes
State Geologist & Director

ASH-FLOW TUFFS OF PRECAMBRIAN AGE IN SOUTHEAST MISSOURI

(Contribution to Precambrian Geology No. 2)

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(Contribution to Precambrian Geology No. 2)

ABSTRACT

Supracrustal igneous rocks of Precambrian age were mapped at a scale of 1:62,500 over an area of about 150 square miles in the west-central St. Francois Mountains, southeastern Missouri. The St. Francois Mountains are centrally located in the midcontinent region of the craton where they form the structural apex of the Ozark uplift — a broad warp in the craton. Most of the mapped rocks are rhyolitic ash-flow tuffs interstratified with minor-bedded tuff. Minor amounts of felsitic rhyolite and trachyandesite of uncertain origin occur low in the stratigraphic section. The volcanic strata accumulated to a thickness of about 1 mile in what is inferred to be an extracaldera environment. They are divided into 10 major cartographic units and locally some of these are subdivided. The sequence includes at least 11 cooling units ranging in thickness from 50 to 2,500 (?) feet separated by thin deposits of bedded tuff. The prevolcanic surface onto which these volcanics flowed has not been observed nor have lithic fragments of prevolcanic rocks been identified in the volcanic strata.

The volcanic strata form a broad depression, the Taum Sauk depression, with flanks that dip about 25^{o} toward a center near the middle of the mapped area. Within the depression the volcanic rocks are cut by dikes and plugs of rhyolite, granite porphyry, and mafic rocks. These are part of a regional system of postvolcanic intrusives and are interpreted as hypabyssal extensions of a broad batholith inferred in the shallow subsurface. The depression is viewed as a downwarped roof segment of a batholithic mass of regional proportions. The volcanic rocks are similar in age and generally similar in chemical composition to

at least three granitic masses of combined batholithic proportions that lie east of the mapped area. The plutonic and volcanic rocks may be cogenetic. Contacts between intrusive and extrusive rocks are sharp and lack any evidence of deep-seated syntectonic emplacement of even the largest granitic masses. The batholith appears to have been emplaced at a shallow level, possibly into earlier cogenetic ejecta or its own skin.

The intrusive activity was accompanied by pervasive hydrothermal alteration of the volcanic and rhyolitic intrusive rocks. Alteration effects include silicification, sericitization, propylitization, potassium metasomatism, albitization, and replacement by hematite of the volcanic rocks. Noncommercial iron ore deposits in the mapped area and important commercial deposits in the surrounding region of Precambrian rocks were probably formed during this period of widespread alteration and replacement. Despite their pervasively altered condition some of the volcanic rocks yield chemical analyses that appear to reflect rather closely the original rock composition. For the bulk of the volcanic pile the original rocks appear to have been rhyolitic with peralkaline affinities. This conclusion is supported by field and petrographic data. The widespread effects of alteration preclude interpretation of presently available chemical or petrographic data in terms of modern concepts that relate zonal variations in ash-flow tuffs to processes in the source magmas.

INTRODUCTION

The area described in this report covers about 150 square miles in the western part of the St. Francois Mountains in Iron and Reynolds Counties, Missouri (fig. 1). It has a roughly triangular shape and is situated between the towns of Ironton on the northeast, Edgehill on the northwest, and Lesterville on the south (pl. 1). The St. Francois Mountains form hilly and low mountainous terrane within the region commonly referred to as the Ozarks. Elevations range from 675 feet in the south on Mill Creek to 1,772 feet on Taum Sauk Mountain which is the highest point in Missouri.

Reconnaissance geologic studies of Precambrian volcanic and intrusive rocks were conducted throughout the St. Francois Mountains during 1959 and 1960. It was noted that ash-flow tuffs are thick in the western mountain area. A part of the western area (northern part of pl. 1) was mapped in detail during 1961 and early 1962 in an attempt to establish a stratigraphic framework for future studies in the region. The area was revisited in November 1965 during which time field checks were made in the eastern part of the original map area and additional mapping was done to the south. During this revisit the writer was "armed" with 3 years of experience mapping Tertiary volcanic and intrusive rocks in the Great Basin. Time did not permit field checking of the central and northwestern parts of the area (pl. 1); that part of the map should be considered less reliable than the rest.

At the time of this study, only 15′ topographic maps of the Ironton and Edgehill quadrangles were available. For this reason, geologic mapping was done on 1:24,000 scale aerial photographs. The planimetric base for most of plate 1

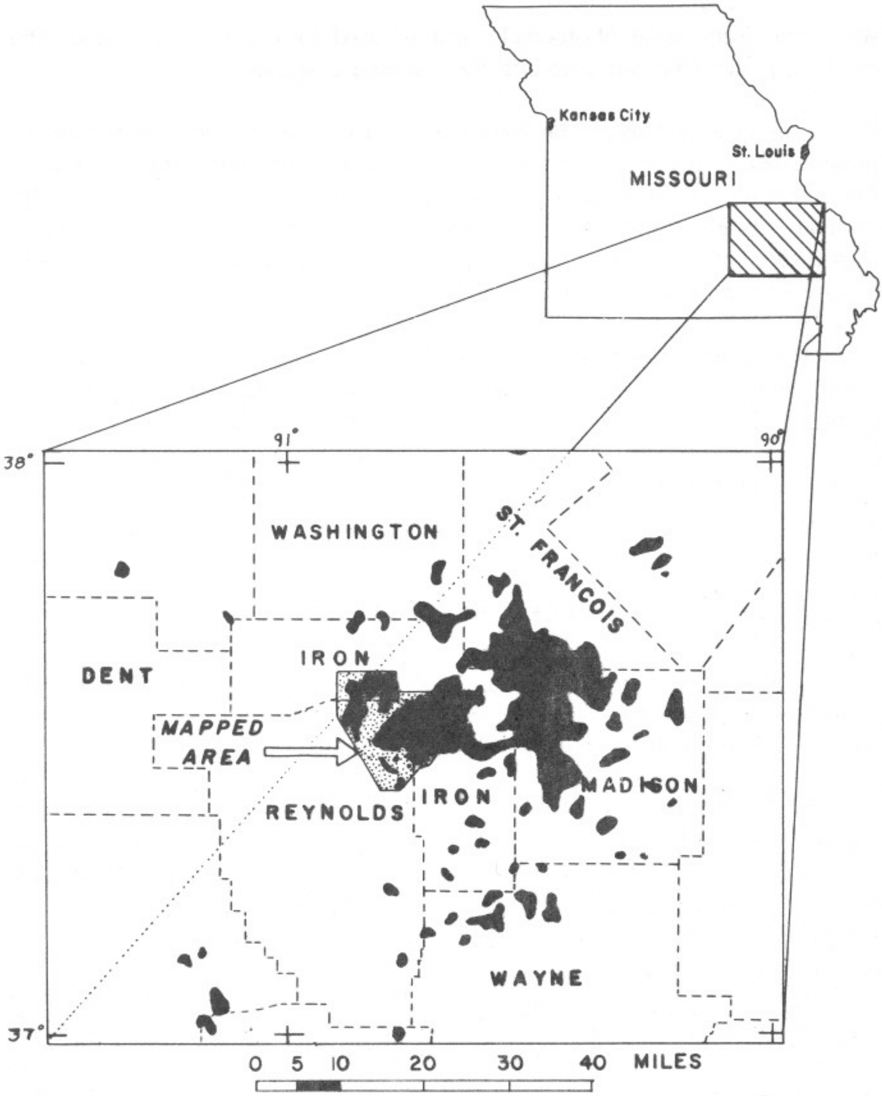


Figure 1

Index map showing area of this report (stippled) and area of exposed Precambrian rocks (black) in southeastern Missouri.

was made from aerial photographs and reduced to a scale of 1:62,500. The resulting planimetry was adequate for mapping purposes.

The areal geology of the Precambrian rocks near the area covered by the present report was studied by several graduate students under the direction of Carl Tolman at Washington University (Meyers, 1939; Robertson, 1940; Bonham, 1948). The most comprehensive recent reports are by Hayes (1961b) in the form of a quidebook to the geology of the St. Francois Mountain area; and by Tolman and Robertson (1969).

The investigation was conducted for the purpose of acquiring geologic information necessary to interpret paleomagnetic data that were assembled concurrently. Some of the paleomagnetic results are published (Hays and Scharon, 1966; Hsu and others, 1966). The stratigraphic and structural findings are reported here together with new data on the chemistry of the volcanic rocks.

ACKNOWLEDGEMENTS

This investigation was made possible through the financial support of the National Science Foundation (grant G6590 and G16742). The laboratory facilities at Washington University, St. Louis, were used extensively.

Special thanks are accorded to Walter Hays and I-Chi Hsu, both of whom shared in the work, and to W. F. Weeks and H. L. Scharon, under whose direction the work was done. The Hanna Mining Co. gave permission to study core samples. J. Earl Anderson and M. E. Bickford kindlysupplied isotopic data in advance of their publication (1969).

Many helpful criticisms and suggestions were made in early reviews of the manuscript by T. H. Kiilsgaard and W. D. Quinlivan. Kiilsgaard's comments were especially valuable because of his familiarity with the geology of the region as were Quinlivan's because of the depth of his knowledge concerning ash-flow tuffs and related rocks. Provocative and helpful reviews were also received from C. A. Anderson and D. W. Rankin to whom sincere thanks are extended.

TERMINOLOGY

The volcanic rocks have been modified extensively by alteration and recrystallization to dense crystalline felsites. It would be appropriate, therefore, to refer to them as felsites prefixed by suitable modifiers indicating mineralogy, chemistry, color, or weathering habit as has been the convention in almost all earlier reports. In this paper, however, the genetic terminology developed by Ross and Smith (1961) and Smith (1960) for ash-flow tuffs and related rocks is used whenever the mode of origin of the rocks is known or can be reasonably inferred. A description of rock textures and structures that are common to several of the map units precedes the section on stratigraphy to avoid redundancy. Special attention is given some textures and structures that are not comprehensively treated in the two reports mentioned.

† † † † †

REGIONAL SETTING AND GEOLOGIC HISTORY

The St. Francois Mountains are centrally located in the midcontinent region of the craton. In a summary of the tectonic history of the midcontinent, Snyder (1968) makes several specific references to the St. Francois Mountains. Heyl and others (1965) summarize the regional structure of the southeast Missouri mineral district, focusing most of their concern on structures in Paleozoic rocks. The age pattern of the midcontinent basement as revealed by isotopic data is summarized by Goldich and others (1966). The reader is referred to these reports for a broad perspective because the present summary is concerned primarily with local patterns and events recorded by Precambrian rocks.

The St. Francois Mountains form the structural apex of the Ozark uplift — a broad warp in the craton (Heyl and others, 1965). Supracrustal igneous rocks of Late Precambrian age are exposed within the subcircular apex area of about 700 square miles in southeastern Missouri (fig. 1). The Precambrian rocks form a cluster of knobs that represent the exhumed higher parts of a Precambrian surface that was buried to a depth of about 5,000 feet by Paleozoic sandstone, limestone, and shale (Heyl and others, 1965; Ohle and Brown, 1954, p. 211). Elsewhere in southeastern Missouri knobs of Precambrian rock lie buried beneath the mantle of Paleozoic sedimentary rocks.

Granitic intrusive rocks predominate in the northeastern part of the St. Francois Mountains and rhyolitic volcanic rocks in the southwestern part.

Bayley and Muehlberger (1968) infer that this general distribution extends into the surrounding subsurface area. Published surface and subsurface isotopic data indicate that the St. Francois igneous rocks are part of a broad terrane of supracrustal Precambrian igneous rocks that extends from Ohio to Texas (Muehlberger and others, 1966). Mineral and whole-rock isotopic ages from subsurface samples within this terrane indicate that the major igneous activity occurred between 1,350 m.y. and 1,100 m.y. before present (Muehlberger and others, 1966). Whole-rock Rb-Sr determinations on surface samples from the St. Francois Mountains indicate that two separate igneous events occurred there at 1,415 m.y. and 1,320 m.y. ago (Bickford and Odom, 1968, Anderson, et al., 1969). Each is represented by silicic intrusive and extrusive rock types. Rhyolitic rocks of the older event and intrusive granite porphyry of the younger event occur within the area described in this report.

An accumulation of several thousand feet of dominantly rhyolitic volcanic rocks is the oldest geologic event recorded in the mapped area of about 150 square miles in the western St. Francois Mountains. The prevolcanic surface onto which these volcanics flowed has not been observed nor have lithic fragments of prevolcanic rocks been identified in the volcanic strata. A whole-rock Rb-Sr isotopic determination from the upper part of the section gave $1,400 \pm 24$ m.y. A value of $1,416 \pm 21$ m.y. was obtained on felsite exposed northeast of the mapped area where geologic reconnaissance indicates the presence of volcanic strata wholly older than those mapped (Anderson, et al., 1969). Most of the mapped strata are rhyolitic ash-flow tuffs interstratified with minor-bedded tuff. Minor amounts of rhyolitic felsite and trachyandesite of uncertain mode of origin occur low in the stratigraphic section. The thick volcanic rocks are similar in age and generally similar in chemical composition to at least three granitic masses of combined batholithic proportions that lie east of the mapped area (Rb-Sr data supplied by J. E. Anderson; chemical data compiled by Hayes, 1959). The possibility seems good that these plutonic and volcanic rocks are cogenetic.

The mapped volcanic rocks form a structural depression (pl. 1) that is interpreted as a broad sag in the roof of a granite batholith. Scattered exposures of granitic rocks believed to be part of the batholith occur adjacent to the mapped area on the north and southeast. Geophysical evidence indicates that the scattered exposures are parts of two broad plutonic masses. Within the mapped area plugs and sheet-like masses of rhyolite and granite porphyry intrude the volcanics along a vaguely arcuate belt (pl. 1). These masses are interpreted as shallow extensions of the inferred subjacent batholith. Whole-rock Rb-Sr determinations (Bickford and Odom, 1968; Anderson, et al., 1969) indicate that the granites marginal to the mapped area as well as their inferred shallow extensions within the mapped area belong to the younger (approximately 1,320 m.y.) of the two igneous events.

Contacts between intrusive and extrusive rocks are sharp and lack evidence of deep-seated syntectonic emplacement of even the largest granitic masses. The batholithic rocks were probably emplaced at shallow crustal levels. It has been suggested by Hamilton and Myers (1967) that locally they may have been roofed only by their own ejecta.

The period of granitic intrusion was accompanied by pervasive hydrothermal alteration of the volcanic and rhyolitic intrusive rocks. Alteration effects include silicification, sericitization, propylitization, potassium metasomatism, albitization, and replacement by hematite of the volcanic rocks. Noncommercial iron ore deposits in the mapped area and important commercial deposits in the surrounding region of Precambrian rocks were probably formed during this period of widespread alteration and replacement.

Dikes of diabase and gabbro that are widespread in the St. Francois area postdate the period of granitic intrusion and alteration and mark the youngest known episode of Precambrian igneous activity. Subsequent to this activity and prior to invasion by Late Cambrian seas, the area was uplifted and eroded to form a surface of considerable relief. That this ancient erosion surface was very similar to, but probably somewhat more rugged than, the present topographic surface is shown by the distribution of Upper Cambrian basal clastic rocks in many of the major and minor present-day valley bottoms. Post-Paleozoic uplift and erosion produced the present land surface.

† † † † †

ROCK TEXTURES AND STRUCTURES

The Precambrian volcanics in Missouri contain many of the macrotextures and microtextures and structures typical of ash-flow tuffs (Ross and Smith, 1961). These include structures that arise from the shape and distribution of pumice and shards (figs. 2 and 4), spherulitic and axiolitic devitrification textures (fig. 2), and vapor-phase textures and structures (figs. 2, 3, and 4).

In many of the tuffs these primary features have survived in spite of extensive recrystallization (fig. 4A), pervasive alteration (fig. 2E, F; fig. 4B, C), and, in some rocks, complete replacement (fig. 4F). Groundmass textures of some welded tuffs are almost uniformly crystalline, ranging from microcrystalline to finely crystalline. Close examination of thin sections of these rocks commonly reveals slight differences between the groundmass crystallinity and that of pumice and/or shards. Pumice and shards tend to be fibrous or bladed and the remaining matrix tends to be granular (fig. 2B).

Differences in mineral composition between shards or pumice and matrix are also recognizable, particularly in rocks in which shards are composed almost entirely of bladed alkali feldspar and the matrix of granular quartz and feldspar. The difference in refractive index arising from this contrast produces a dispersion of plane polarized light at shard borders, thus making them clearly discernible. In other altered or recrystallized rocks the primary textures are commonly revealed in plane polarized light as streaky, cuspate, or blotchy areas of fine opaque dust that originally coated or partially replaced shards (fig. 4A) or pumice (fig. 2F).

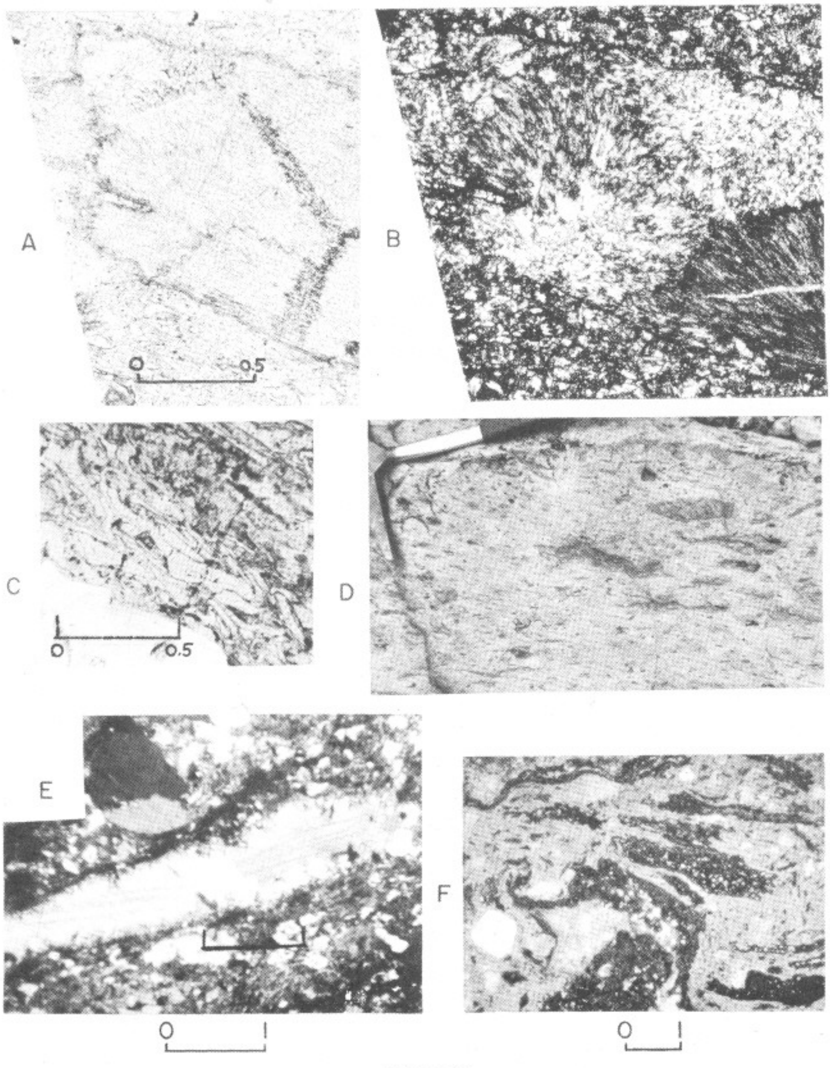


Figure 2

Unaltered and altered pumice and shards including (A) Pumice lapillus showing well preserved internal tubular structure; (B) Spherulitic or bladed crystallization pattern in pumice lapillus; (C) Axiolitic crystallization pattern in devitrified and flattened shards; (D) Flattened pumice in tuff; (E) Lenticular lithophysa filled with coarsely crystalline calcite; and (F) Flattened pumice lapilli partially replaced by hematite (?).

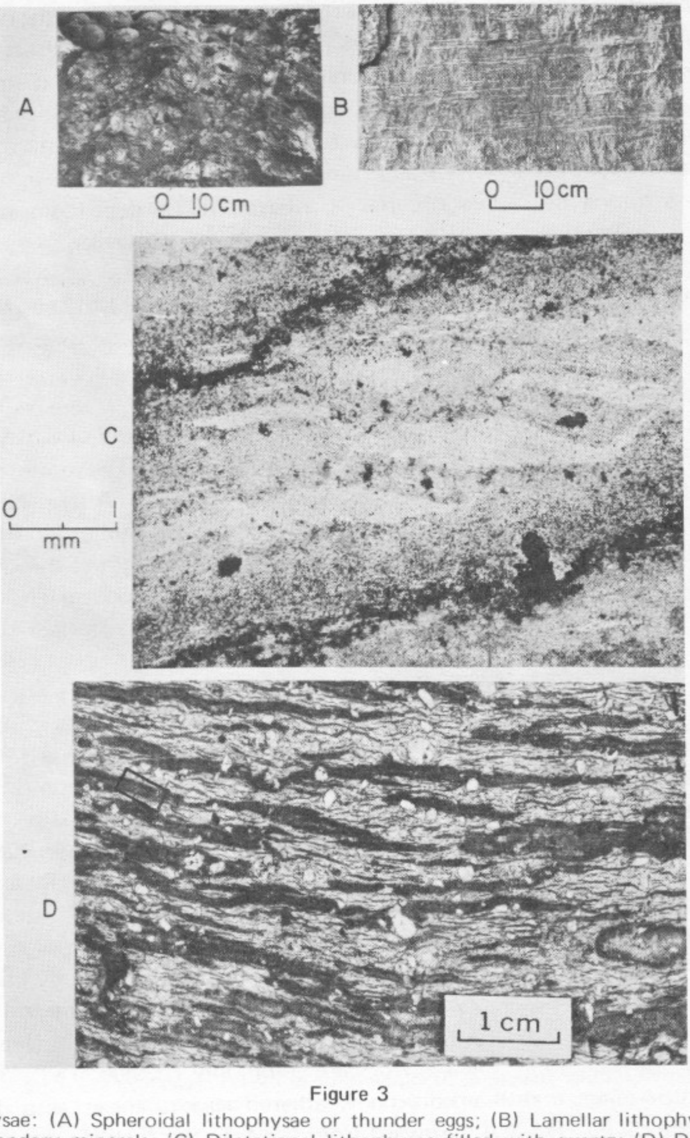


Figure 3

Lithophysae: (A) Spheroidal lithophysae or thunder eggs; (B) Lamellar lithophysae filled with secondary minerals; (C) Dilatational lithophysae filled with quartz; (D) Dilatational lithophysae in plane normal to compaction foliation.

Ash-flow tuffs generally do not retain more than a few tenths of a percent of pristine water dissolved in the glass phases, but the physical effects produced by this water are grossly disproportionate to its amount (Ross and Smith, 1961, p. 40). Major effects are the formation of lithophysal and vapor-phase cavities that are druse-lined or filled with a mesh-work of vapor-phase crystals. These features result from expansion of and transport by volatiles that are exsolved from the glass during devitrification that is inferred to be dependent on cooling. Martin (1959) referred to this process as autopneumatolysis.

In the tuffs from Missouri, as in most tuffs, some of the cavities formed from pumice (fig. 2E), but in most of these rocks no relationship between the cavities and pumice is apparent. The problem of distinguishing pumice that has been replaced or partially replaced by vapor-phase crystals from true lithophysal cavities, which may also contain vapor-phase minerals, is discussed by Ross and Smith (1961, p. 27) and by Martin (1959, pp. 406-407). The problem does not exist where the cavities are spheroidal lithophysae (fig. 3A). Although spheroidal lithophysae are common in the tuffs of Missouri most cavities are discoidal or lenticular and in extreme cases they are lamellar with length-to-thickness ratios in excess of 100. Tuffs that contain lamellar structures look much like fluidal lavas (fig. 3B). Some of the lenticular to lamellar structures probably formed by growth of cavities parallel to the compaction foliation as a result of high vapor or solution pressure. In some rocks lateral growth may have been augmented by small amounts of flow along the compaction foliation. Structures formed in this manner are referred to as lithophysae although in their early stage of formation they probably nucleated on pumice. Evidence for lateral expansion is found in a few thin sections which show that phenocrysts that lay in the path of laterally expanding lithophysal cavities were split in two; other thin sections show rotation of groundmass segments that were attached to both of the dilated walls of the cavity.

Regardless of their shape the lithophysal cavities are generally lined with a druse of tabular feldspar crystals of probable vapor-phase origin and filled or partly filled with secondary quartz, hematite, calcite, and flourite (figs. 2E and 4E). The filled or partly filled cavities are commonly encased in a halo of devitrified groundmass that is visible on weathered rock surfaces as a dark rind around the cavity (fig. 3D). Outward from the halo the rock is generally a vivid

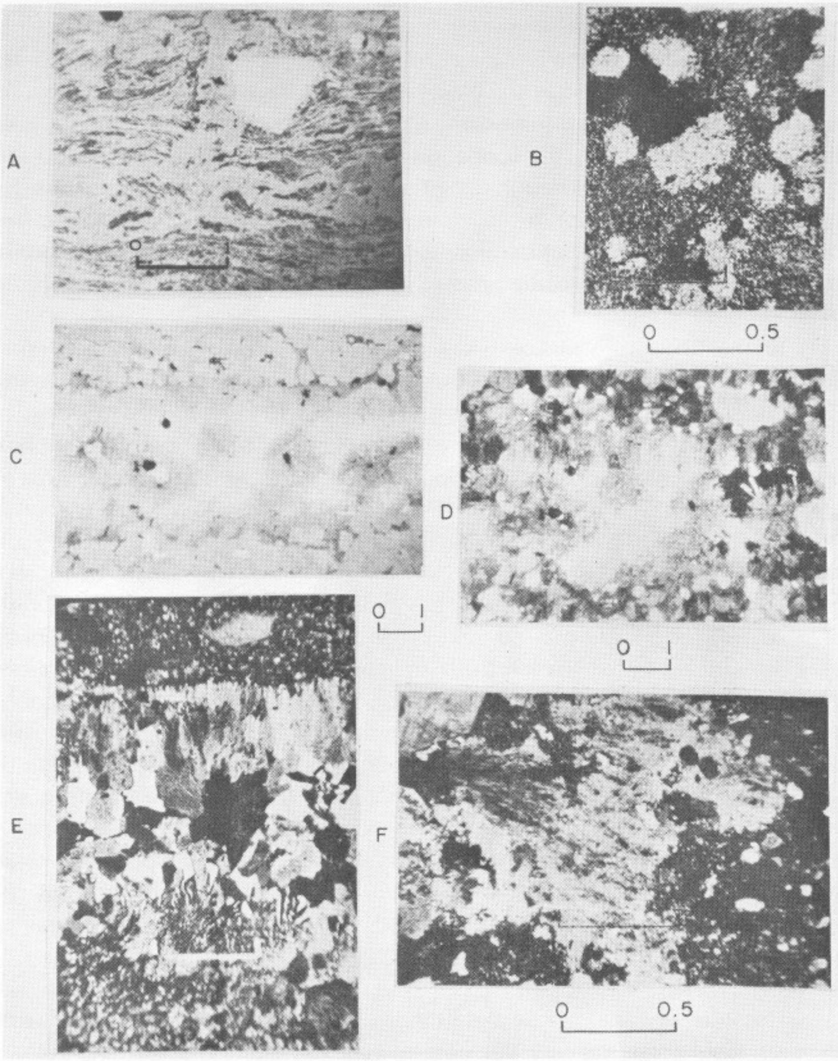


Figure 4

Groundmass textures and effects of alteration: (A) Devitrification "dikes" extending upward from a devitrification "sill"; (B) Micropoikilitic quartz masses in very fine grained felsic groundmass; (C) and (D) Lamination structure in the rhyolite on Russell Mountain – in plane polarized light – (C) and with crossed nicols (D); (E) Zonation of secondary minerals in a section through lamellar lithophysa in welded tuff; (F) Replacement of felsic groundmass by calcite.

red or orange. In thin section the halos appear as colorless areas composed of tiny granules of feldspar and magnetite in a quartz base. These pass outward to a reddish turbid cryptocrystalline matrix that contains abundant submicroscopic opaque dust. The matrix probably remained vitric subsequent to total cooling as evidenced in some rocks by the presence of perlitic cracks. A thin band of highly concentrated hematite (?) sometimes separates the halo from the matrix (fig. 3C). This iron oxide may represent an advancing front of material that was expelled from around the cavity as devitrification progressed. The iron oxide that remained behind crystallized to form the tiny magnetite granules in the colorless areas. Some tuffs devitrified completely and only the lithophysal structures are discernible.

Many of the welded tuffs contain spheroidal, discoidal, or lamellar masses that lack evidence of the formation of a cavity at their centers or along their axial planes. Therefore, they are not lithophysae. Discoidal to lamellar structures up to 2 meters in length occur in several of the welded tuffs. Their internal texture is micrographic to microgranitic and generally distinctly coarser grained than the enclosing rock. These could be highly collapsed pumice blocks similar to those described and pictured by Ratté and Steven (1967, p. H12) in the fluidal welded tuff of the Tertiary Willow Creek Member of the Bachelor Mountain Rhyolite in Colorado. However, they are referred to in the stratigraphic descriptions as devitrification structures prefixed by a modifier indicating shape.

In many of the welded tuffs crystallization nucleated at scattered centers and progressed outward forming small masses of abundant tiny granules of feldspar and magnetite imbedded in a skeletal framework of commonly oriented quartz. These "micropoikilitic masses" range in abundance from a few percent to 100 percent of the groundmass and seldom do they exceed 3 mm in diameter. Where rare, they occur as scattered, nearly spheroidal masses contained in a turbid microcrystalline base (fig. 4B), but where they comprise 100 percent of the groundmass they form a close-packed array and are irregular in shape. In some rocks they are more abundant adjacent to lithophysae or pumice than elsewhere in the groundmass, thus suggesting that they resulted from primary rather than secondary crystallization.

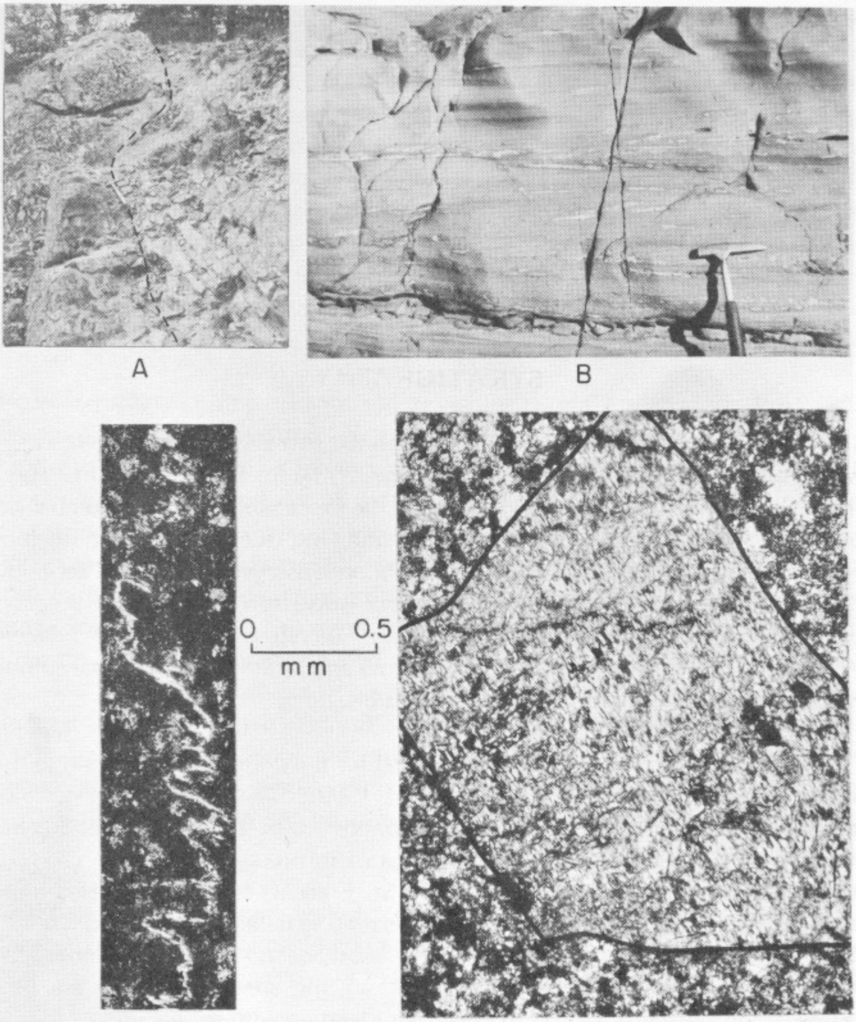
† † † † †

STRATIGRAPHY

The nomenclature of exposed Precambrian rocks in southeastern Missouri was published in a guidebook to the geology of the St. Francois Mountain area (Hayes, 1961a). The areal geologic map of the Precambrian rocks accompanied by a detailed description of mapped rock units has recently been published as No. 1 in the "Contributions to the Precambrian Geology of Missouri" series by the Missouri Geological Survey (Tolman and Robertson, 1969). Formal names of units presented in the above publications will be referred to whenever possible in this report. However, correlation of the volcanic strata mapped by the author with the formal rock units is not always possible.

The majority of volcanic rocks mapped for the present study belong to the Van East Group (Tolman and Robertson, 1969) the younger of two major groups of volcanic strata. The writer is aware of no published stratigraphic breakdown of the volcanic rocks in the area of this report. Based on rapid geologic reconnaissance of almost the entire St. Francois area, it is believed most unlikely that any area will be found as well suited to detailed stratigraphic breakdown as the one reported here. Therefore, an original nomenclature is presented informally. Stratigraphic units are named for the area where they are best exposed, and reference is made to possible correlation with formal units.

Many ash flows throughout the world are spread widely over hundreds or even thousands of square miles as mappable sheetlike bodies. Ideally, therefore, correlation of ash-flow tuff cooling units over areas much more extensive than



A B C D

Figure 5

Miscellaneous photographs showing (A) Contact between bedded tuff and welded tuff (?); (B) Thin bedded and cross bedded tuff; (C) Stylolite-like band of white mica in fine grained felsic groundmass; (D) Patch–perthite in tuff.

that covered by plate 1 is done with certainty. Vertical variations between zones of no welding, partial welding, and dense welding as well as zones of glassy and crystalline rock (Smith, 1960) commonly are useful correlation criteria. Vivid to subtle color variations that accompany the zonations are also very useful. In the rocks of Missouri original color variations, if they existed, were largely obliterated by the effects of alteration, as were initial postemplacement lithologies that may have included vitric, vitrophyric, nonwelded, and partly welded zones as well as densely welded material. Although these modifications inhibit correlation by tending to mask lithologic zonations, some of the ash-flow tuffs in the middle part of the stratigraphic section (tuff of Stouts Creek) are distinctive and serve as key horizons.

Unit contacts are placed either at horizons of thin, laterally persistent bedded tuff or at horizons separating rocks of contrasting lithology. Contacts that are marked by bedded tuff probably represent a cooling break but others may only represent a lithologic change within an ash-flow tuff cooling unit. It would probably not be possible to map every cooling unit separately because many of the primary cooling zones have been obscured by subsequent recrystallization. It is particularly difficult to recognize cooling breaks in the thick ash-flow unit mapped as tuff of Taum Sauk Mountain (pl. 1). Several of the knobs composed of this tuff are circumscribed by benches or terraces visible on aerial photographs. On the ground the benches are traceable as zones of complex flowage-type structure and varied lithology. Rocks resembling volcanic agglomerates and flow breccias occur locally within the zones, but bedded strata are generally absent. The significance of the complex zones in terms of the cooling break concept is not known. They are shown on the geologic map (pl. 1) as intraformational contacts.

The descriptions of mapped units that follow, although abbreviated individually, are lengthy in sum. Because of their combined length they are preceded here by a summary of some general features of the volcanic section.

An estimated 11 cooling units of dominantly rhyolitic ash-flow tuff with a combined thickness of about 5,000 feet accumulated in what is inferred to be an extra-caldera environment. The ash flows are interstratified with minor dark-gray or red bedded tuffs. Minor amounts of rhyolitic felsite and trachyandesite of uncertain origin occur low in the section. They are correlated across the area with uncertainty as are the ash flows low in the section. The ash flows in the middle of the section (tuff of Stouts Creek) are spread widely as relatively thin sheets that display a consistent and distinctive pattern of vertical lithologic gradations. They contrast with the overlying tuff (tuff of Taum Sauk Mountain) which is thick (2,500? feet) and consists of several thick, massive monolithologic intervals of similar appearing densely welded tuff separated by the thin lithologically and structurally complex zones previously described. Also, the tuff of Taum Sauk Mountain tends to be pale-red or salmon colored with conspicuous large phenocrysts in contrast to the tuff of Stouts Creek which are mostly gray and purplish-gray with smaller and less abundant phenocrysts. No diagnostic features of the uppermost tuff (tuff of Johnson Shut-ins) are apparent because exposures are areally restricted and the rocks are generally similar to others lower in the section.

Neglecting the severe local effects of alteration such as are associated with fault or stratigraphically controlled iron mineralization, field and petrographic studies suggest that (1) propylitic alteration and accompanying albitization is most common in the rocks low in the section, (2) effects of potassium metasomatism occur throughout the section but are evidenced primarily by hydromica in the lower strata and K-feldspar in the upper strata, and (3) secondary fluorite is common in the upper and uncommon in the lower strata. The first two patterns are broadly similar to zonal patterns revealed by drill hole investigations of altered volcanic strata at the thermally active Wairakei and Waiotapu areas, New Zealand (Steiner, 1955, 1963) and suggest the need for a systematic study.

The effects of postemplacement alteration inhibit petrographic determination of feldspars and preclude unambiguous identification of mafic silicates. In the study of about 200 thin sections of volcanic rocks, an attempt was made to reconstruct original phenocryst assemblages from the altered and secondary assemblages.

The ash-flow tuffs contain from 2 to 30 percent phenocrysts. All contain phenocrysts of alkali feldspar that usually greatly outnumber all other phenocrysts. In most rocks the primary alkali feldspar was probably sanidine or soda-sanidine. In all rocks the alkali feldspar has been altered to patchy or veined turbid microperthite by either exsolution or replacement or both (fig. 5D). Plagioclase phenocrysts are absent from most of the ash-flow tuffs, but tend to occur (and in some flows to predominate) in the upper flow or flows of each of the major ash-flow units. The plagioclase is highly sodic, a feature probably attributable more to albitization than to primary mineral composition. Quartz phenocrysts are present in most of the tuffs. Their absence is not an indication of subsilicic chemistry, or, indeed, of a less silicic rock than the quartz-bearing varieties. The absence of quartz indicates that either high magma temperature or low water vapor pressure or both prevented the crystallization path from reaching the quartz eutectic of the natural system. No phenocrysts of biotite, hornblende, or recognizable pseudopmorphs after these minerals were observed in the ash-flow tuffs. Magnetite (commonly partly altered to hematite and ilmenite) is the only primary mafic phenocryst. Several of the ash-flow tuffs, especially those forming the lower half of the stratigraphic section, contain idiomorphic masses of secondary minerals (generally hematite, calcite, albite, epidote, and chlorite in any combination) that are probably pseudomorphous after pyroxene or olivine.

Plagioclase, biotite and/or hornblende are almost ubiquitous phenocrysts in calc-alkalic, rhyolitic ash-flow tuffs (unpublished data in the files of the U.S. Geol. Survey, Denver). The absence of such suites and the lack of evidence of their former presence in tuffs from Missouri indicate that these tuffs do not belong to a calc-alkalic suite. Phenocryst assemblages in most of the tuffs are more typical of peralkaline rocks. Such rocks generally contain sanidine, quartz, iron-rich clinopyroxene, and fayalite. The presence of sodic amphibole or pyroxene in the groundmass of a rock is a sure indication of peralkaline chemistry (D. C. Noble, written comm., 1966). Soda amphibole of probable vapor-phase origin is present in some of the rhyolite of Stouts Creek, thus strongly suggesting peralkaline chemistry for those rocks. Several major Tertiary peralkaline ash-flow tuffs in Nevada are spread widely as thin sheets with common fluidal structures and lithophysae much like those observed in the ash flows in Missouri. This field similarity is further indication of peralkaline chemistry (Walker and Swanson, 1968).

FELSITE

Rocks exposed on Shepherd Mountain in the northeast corner of the area were mapped by Meyer (1939) as a sequence of generally southwest-dipping strata composed of rhyolite porphyry, felsite, felsite porphyry, and pyroclastic rocks. These belong to the Pilot Knob Felsite and Stouts Creek Rhyolite of Tolman and Robertson (1969). This area was not remapped, but a rapid field reconnaissance failed to disclose rocks equivalent to those mapped to the southwest between Stouts Creek and Little Taum Sauk Creek. This fact, together with the southwest dip and map pattern, indicates that the rocks on Shepherd Mountain are the oldest in the mapped area and serve as a tie between Meyer's stratigraphy and that of the present report. Correlation of the felsite forming the small exposure northwest of Lesterville with the felsite on Shepherd Mountain is based on structural projection and is therefore questionable.

The felsites are divided into a lower part equivalent to rocks mapped by Meyer (1939) and an upper part consisting of dense, very faintly foliated pinkish-gray felsite exposed along Stouts Creek. Features diagnostic of an ash-flow tuff origin for the upper part are not recognizable in the field, but faint shardlike structures are visible in thin section. Rocks in the upper part are propylites that contain about 25 percent phenocrysts consisting of euhedral grains to broken angular chips of albitized plagioclase (79),* alkali feldspar (6.5), embayed quartz euhedra (2.5), and concentrations of secondary hematite, chlorite, sericite, calcite, epidote, and albite that are probably pseudomorphic after mafic phenocrysts (12). A chemical analysis and norm are given in table 1 (sample 1). The analysis indicates a strong enrichment in sodium associated with the albitization of the rock.

TUFF OF MILL CREEK

Three widely spaced exposures of altered rocks are tentatively assigned to the tuff of Mill Creek on the basis of their general field and microscopic similarities. The correlation of these exposures in the southern, western, and northeastern parts of the mapped area is strengthened by more positive correlations of younger units over the same area.

*The number following the mineral species is the percentage of phenocrysts based on at least 2,000 modal points per thin section.

Three conformable ash-flow tuff cooling units separated by thin-bedded air-fall (?) tuffs dip northeast along Mill Creek 2.8 miles east of Lesterville. These are shown as felsitic and associated extrusives (F) on the Tolman and Robertson map (1969). The base of the section is not exposed. The three cooling units are similar in general appearance and are distinctive in their lack of quartz phenocrysts and vapor-phase structures. Small amounts of indistinct to conspicuous highly collapsed pumice lapilli indicate dense welding in the top of the lower unit and throughout the other two. The rocks are purplish-gray with pink feldspar phenocrysts and pea-green veinlets and clots of secondary epidote. Some of the clots are partially replaced pumice lapilli. Phenocrysts comprise 10 to 15 percent of the rock and consist almost entirely of alkali feldspar with minor altered plagioclase (?) and mafic minerals. Abundant, well-preserved flattened shards are visible in the dense, finely crystalline groundmass of some thin sections. Shards are present even in the groundmass of one specimen that contains garnet and magnetite suggestive of thermal alteration.

Bedded strata separating the cooling units consist mostly of dark-gray to black, densely lithified, thin-bedded fine-grained tuffs. Some beds are rich in crystals and crystal fragments of feldspars and some are composed almost wholly of shards. Graded bedding and crossbedding are common on scales of a few millimeters and several centimeters respectively, indicating that these tuffs probably resulted from air-fall deposition and were locally reworked by wind.

Two cooling units separated by thin-bedded tuff are exposed in the extreme western part of the area 1.5 miles south of Edgehill and are correlated with the tuff of Mill Creek. These are part of an area of Hogan Mountain Rhyolite exposure on the Tolman and Robertson map (1969). The base of this sequence also is not exposed. In thin section the lower cooling unit is a quartz-free pumice-poor shard-rich welded tuff in which alkali feldspar phenocrysts are much more abundant than plagioclase. The tuff contains scattered lithic fragments, which in thin section closely resemble the plagioclase-rich upper part of the felsite described above. A partial chemical analysis of the tuff is given in table 1 (sample 2).

Along Stouts Creek the upper part of the felsite is overlain with apparent conformity by a grayish-red densely welded tuff with small blackish-red flattened pumice lapilli and 10 percent flesh-colored alkali feldspar. The rock appears to have contained minor amounts of plagioclase and mafic minerals that have been replaced by secondary minerals. On the basis of megascopic and petrographic similarity this tuff is correlated with the tuff of Mill Creek.

TUFF AND LAVA OF LAKE SPRINGS

West of Lake Springs in the southern part of the mapped area at least 600 feet of northeast-dipping ash flow and bedded tuffs and lava (?), mapped as the tuff and lava of Lake Springs, overlies the tuff of Mill Creek with apparent conformity. The ash-flow tuffs are massive, dark-gray densely (?) welded rocks that contain very indistinct pumice lapilli. Typically they contain about 10 percent phenocrysts consisting of albitized plagioclase as much as 4 mm in diameter (70), alkali feldspar (7.5), small partly resorbed and embayed quartz (15), altered and replaced mafic mineral (7) and minor accessory minerals. The phenocrysts and groundmass in one thin section are partially replaced by biotite. A blackish-red quartz-rich welded tuff that occupies a stratigraphic position similar to that of the tuffs west of Lake Springs crops out on a small knob just south of Lee Mountain. The rock contains 19 percent phenocrysts consisting of plagioclase (45), quartz (41), alkali feldspar (2), altered mafics (11), and minor accessory minerals. Quartz grains are more abundant, larger, and less resorbed than in the welded tuffs west of Lake Springs, but the rocks are otherwise very similar. One of the most distinctive petrographic features of these ash-flow tuffs is the abundance of completely replaced euhedral stubby prismatic mafic phenocrysts averaging about 0.5 mm in length. The outlines of the original phenocrysts are well defined by a rind of secondary iron oxide that commonly encloses a core of sericite, calcite, and epidote. The morphology suggests that the original phenocrysts were pyroxene or olivine.

The ash-flow tuffs west of Lake Springs are overlain by and interstratified with beds of dusky-red to dark-gray, crystal-rich to crystal-poor thin-bedded densely lithified ash. About 160 feet of similar dominantly bedded ash separates these strata from an overlying trachyandesite lava (?). The bedded interval is well exposed in a roadcut along State Highway 21, 0.3 mile west of Lake Springs. The basal contact of the bedded tuff at the roadcut (fig. 5A) is noteworthy because beneath the bedded rock is a 3-foot-thick breccia in which angular and plastically deformed fragments of lithified bedded ash are included in a dense felsic matrix. Bonham (1948, pp. 39, 41) described and illustrated a similar breccia in the unit he mapped as a felsite east of the mapped area. The writer and other geologists with the U. S. Geological Survey have observed similar breccias in the upper parts of rhyolite lavas of Tertiary age in southern Nevada. The rock directly subjacent to the bedded tuff along State Highway 21 is massive and pumice-free, and, therefore, the possibility that it is a lava and not welded tuff cannot be precluded.

About 40 feet of dense silicic grayish-yellow-green mottled rock in which bedding was not observed occurs within the well-bedded tuffs along Highway 21. The same sequence of thin-bedded ash and nonbedded siliceous rock occurs south of Lee Mountain stratigraphically above the blackish-red quartz-rich welded tuff previously described.

The lava portion of the tuff and lava of Lake Springs consists of a dense black trachyandesite with less than 5 percent conspicuous phenocrysts of pale-pink to white albitized plagioclase in a felty to poorly crystalline groundmass that contains a few small plagioclase laths. Magnetite is common as phenocrysts and as small euhedra in the groundmass. About 100 feet of the lava is exposed in the roadcut west of Lake Springs.

Trachyandesite lava that is megascopically and petrographically very similar to the lava near Lake Springs is exposed in the northeastern part of the area. Several hundred feet of drill core from holes penetrating the lava on Russell and Vail Mountains were made available for study through the courtesy of The Hanna Mining Co. As determined from the core data and from surface exposures on the northern slope of Russell Mountain, the section consists of several flows of massive to flow brecciated, mostly propylitized, porphyritic trachyandesite separated by thin zones of bedded tuffs that are partly, and in some places extensively, replaced by hematite. Cored thicknesses of individual flows range from 10 to at least 20 feet, but flow and bedding structures commonly form an angle of 10^{o} to 40^{o} with the core axis indicating lesser true thicknesses. East of Buck Mountain only one flow, about 200 feet thick, was recognized in outcrop. The flow is overlain by 150+ feet of densely lithified black crystal-lithic thin-bedded trachyandesitic tuff. Graded bedding, crossbedding, and lateral lensing are common in the tuff. Partial chemical analyses of the lava and overlying bedded tuff are given in table 1. The high Fe_2O_3 contents and the spurious alkali contents probably result from the hydrothermal alteration to which the rocks were subjected.

There is a good possibility that the felsite of Cuthbertson Mountain and some of the bedded tuffs mapped by Bonham (1948) are correlative with the tuff and lava of Lake Springs.

TUFF OF STOUTS CREEK

A widespread sequence of rhyolitic ash-flow and bedded tuffs is mapped as the tuff of Stouts Creek from excellent exposures in the upper drainage area of Stouts Creek on Taum Sauk, Wildcat, and Buck Mountains, where the tuffs have a composite thickness of about 1,700 feet. A broad fourfold division (units A, B, C, and D in ascending order), based partly on the presence or absence of quartz phenocrysts and partly on other distinguishing features, is made. The province-wide effects of metasomatism and hydrothermal alteration preclude unambiguous correlation of some of the tuffs, but unit D and the upper part of unit C are correlated with certainty.

Locally thin zones of densely lithified bedded tuff (not mapped separately) separate units A and D from the remainder of the tuffs of Stouts Creek. This relation suggests, but does not prove, that these units are individual cooling units. No bedded tuffs were observed within the individual units. An intraformational contact separating rocks of contrasting color and structure is drawn within unit C on the northern flank of Taum Sauk Mountain. The significance of this contact in terms of the cooling unit concept is not known; it may separate two ash flows within a multiple-flow compound cooling unit.

UNIT A

Unit A is exposed extensively in the northern part of the area. The base is exposed on Buck Mountain where about 300 feet of densely lithified very fine grained pale-red to moderate-reddish-brown rhyolitic bedded tuff overlies the trachyandesitic bedded tuff mapped with the tuff and lava of Lake Springs. The bedded tuff typically contains less than 1 percent phenocrysts of quartz and alkali feldspar in a highly altered groundmass of quartz, sericite, and iron oxide. Accretionary lapilli* are common at several levels in the bedded sequence indicating that the tuff is, in part at least, of air-fall origin. Similar bedded tuffs (not mapped separately) crop out in the extreme northern part of the area, north of High Top Mountain, where they are intruded by gabbro. A partial chemical analysis of the rhyolitic bedded tuff from Buck Mountain is given in table 1 (sample 6).

On Buck, High Top, and Lindsey Mountains the bedded strata are overlain by an ash-flow tuff as much as 500 feet thick that may be a compound cooling unit. The base of the unit is generally a medium-gray to grayish-purple rock that contains small angular lithic fragments, indistinct pumice lapilli, and about 10 percent phenocrysts consisting of subequal flesh-colored alkali feldspar and embayed and slightly resorbed quartz set in a very fine grained felsic groundmass. Ten to 50 feet above the base, the groundmass is dusky-brown and micrographically crystallized; lithic fragments and pumice lapilli are sparse to absent; and lenticular to lamellar devitrification structures impart a poorly defined flow or lava appearance to the rock. This rock generally persists to within 100 feet of the top of the unit and is interpreted as the micrographically crystallized lithoidal interior of the ash-flow tuff. Phenocrysts become less abundant and smaller and the rock becomes more reddish upward.

The upper 100 feet or so of unit A is unmistakably a welded tuff. It is a light-brownish-gray to dusky-red rock with conspicuous brownish-gray flattened pumice lapilli, minor small lithic inclusions (fig. 2D), and a much higher ratio of alkali feldspar to quartz than the rock lower in the unit. A modal analysis gave 10 percent phenocrysts consisting of alkali feldspar (86), quartz (9.5), replaced mafic mineral (2.1) and magnetite (2.4). The upper few feet of the tuff commonly contains abundant nearly spheroidal lithophysae averaging about 0.5 inch across in a densely welded reddish matrix. This part of the unit is generally poorly exposed.

*For a general description of and remarks on the genetic significance of accretionary lapilli the reader is referred to Moore and Peck (1962). Accretionary lapilli in the tuffs from Missouri are identical to those described by Moore and Peck.

UNIT B

Unit B is a medium-gray very dense, resistant, conchoidally fractured, cliff-forming welded tuff that is well exposed throughout the northern part of the area where it averages 400 feet thick and is locally separated from unit A by a few feet of bedded tuff. Except in the upper few feet, which contains abundant conspicuous pumice lapilli, the welded tuff contains 1 to 2 percent rounded to angular lithic fragments of flow-banded rhyolite, black andesite, and black cindery basalt (?). Small light-colored flattened pumice lapilli are locally conspicuous but mostly indistinct. Scattered pod-shaped to irregular cavities as much as 4 inches in length occur throughout the unit. These probably formed from pumice lapilli. Unit B is everywhere characterized by a regular upward decrease in phenocryst content from a relatively crystal-rich base with as much as 23 percent phenocrysts of conspicuous alkali feldspar grains as much as 2 mm (92), quartz (5), and replaced mafic mineral (2.5) to an upper part with as few as 8 percent phenocrysts of alkali feldspar (91), quartz (1.5), replaced mafic mineral (6), and magnetite (1.5). Shards and pumice are well preserved and are visible in most thin sections. A chemical analysis of unit B from south of Ironton is given in table 1 (sample 8). The percentage of alkalies was determined on sample 9, from Lindsey Mountain.

UNIT C

Unit C is well exposed and exhibits a regular pattern of vertical lithologic variation throughout the area. It is one of the most distinctive and easily recognized units in the entire stratigraphic sequence in spite of considerable lateral color variation. It rests conformably on unit B and nowhere were bedded tuffs observed separating the B and C units. They may well be parts of the same cooling unit. The description that follows is based on field and petrographic study of unit C where it is 550 feet thick on Taum Sauk Mountain.

An intraformational contact is drawn near the middle of unit C as noted previously. The rocks above and below this contact have a similar, if not identical, assemblage of phenocrysts (7) consisting of alkali feldspar that possibly includes some altered plagioclase (90), replaced mafic mineral with prismatic and octagonal forms that was probably pyroxene (8), and magnetite (2).

Quartz is absent. The rock below the intraformational contact is grayish-red to salmon colored and lithic-poor. It is distinguished by the striking development of lenticular lithophysae and devitrification structures (fig. 3D) except in the basal few feet where collapsed shards and small pumice lapilli are visible. Above the intraformational contact the rock is grayish-purple to reddish-purple with about 5 percent lithic inclusions of dusky-yellow felsite and black andesite up to 4 inches across, and 5 to 10 percent flattened pumice, as much as 6 inches in length but averaging 1.5 inch. The compaction foliation arising from the flattened pumice is much less distinct than the foliation in the rock below the intraformational contact. Chemical analyses of the lower and upper parts of the unit are given in table 1 (samples 10 and 11, respectively).

UNIT D

Unit D includes several ash-flow tuffs of widely variable lithology. Some are discontinuous laterally but others are remarkably persistent in spite of their thinness. Only the laterally persistent tuffs are described. The unit varies considerably in total thickness, but is generally less than 250 feet.

The lowermost tuff is generally about 100 feet thick and appears to be densely welded throughout. Locally it is separated from unit C by bedded tuff that is not mapped separately. It resembles the upper part of unit C but is distinguished from it by the presence of quartz phenocrysts and smaller lithic fragments and pumice. Phenocryst content ranges from 10 percent at the base to 5 percent at the top and consists of alkali feldspar (65), quartz (30), and minor iron oxide and replaced mafic minerals. Lithophysal cavities as much as 1 inch in diameter partly filled with quartz and fluorite occur in the upper few feet. A chemical analysis of the welded tuff is given in table 1 (sample 12).

A middle blackish-red welded tuff, in which neither pumice nor lithic fragments were observed, is a few tens of feet thick and generally poorly exposed. The rock contains from 9 to 16 percent phenocrysts consisting mostly of plagioclase with subordinate alkali feldspar, up to 7 percent replaced mafic minerals, and minor quartz. Flattened shards are visible in thin section. The abundance of plagioclase and replaced mafics makes the tuff unique to this portion of the stratigraphic section in that it is overlain and underlain by very thick accumulations of plagioclase-poor tuffs. A partial chemical analysis is given in table 1 (sample 13).

The upper welded tuff is nowhere more than 40 feet thick but it persists throughout the area. It is generally dusky-red and has a distinctive vertical zoning. The tuff is conspicuously poor in lithic fragments, pumice, and phenocrysts. It generally contains less than 1 percent of small highly resorbed quartz and scattered feldspar phenocryst. In its lower two-thirds the tuff has conspicuous quartz-filled lamellar lithophysae which grade upward through a zone of discoidal lithophysae to a zone of spheroidal lithophysae that are commonly only partially filled with quartz, magnetite, and fluorite. The lithophysae at all levels are surrounded by devitrification halos (p. 13) which in the lower two-thirds produce a spectacular streaked appearance on vertical weathered surfaces (fig. 3D) and in the upper one-third cause the rock to weather into close-packed smooth spheroidal nodules or thunder eggs as much as 5 cm in diameter (fig. 3A). This upper zone of thunder eggs is generally very well exposed in benches formed by the "stripping back" of a more easily eroded bedded tuff that everywhere overlies it. Several thin sections of the thunder egg zone show relicts of moderately compressed shards indicating that the tuff is welded to its very top. Ross and Smith (1961, p. 26) noted that some welded tuff units that are too thin to have welded as a result of load compaction form dense glass that in some places contains lithophysae and spherulites. The occurrence of lithophysae and welding in the upper few feet of an ash-flow tuff does not, therefore, appear improbable. The emplacement temperature and amount of retained volatiles of such tuffs was probably anomalously high. For the upper flow in the tuff of Stouts Creek and for other similar welded tuffs in Missouri this inference is substantiated by the low crystal content, evidence of crystal resorbtion, and abundance of lithophysal cavities. A partial chemical analysis of the tuff is given in table 1 (sample 14).

TUFF OF TAUM SAUK MOUNTAIN

A thick sequence of volcanic rocks comprised almost entirely of ash-flow tuffs is widely distributed throughout the central part of the map area. On Taum Sauk Mountain, for which they are named, the tuffs are well exposed and at least 1,500 feet thick. The maximum thickness of these tuffs is not known because no continuous and unfaulted section was found. The base of the sequence is exposed on Lee Mountain and the top is exposed near Johnson Shut-ins. The tuffs between have a nearly constant attitude, and if the section is not faulted, they may be as much as 3,500 feet thick. A thickness of 2,500 feet is inferred throughout most of the area (cross section, pl. 1).

The tuff of Taum Sauk Mountain is separated from the underlying tuff of Stouts Creek by 5 to 20 feet of remarkably persistent brick-red, very well bedded, fine-grained, densely lithified tuff. This bedded tuff generally rests directly on the thunder egg zone of the underlying tuffs. It is well sorted and is commonly cross-bedded on a small scale. It consists mostly of shards with sparse phenocrysts and locally some accretionary lapilli indicating that it is, in part, of air-fall origin. The thick sequence of tuff above the basal bedded tuff displays considerable lithologic variation, but no key horizon common to the mapped area is recognized. The intraformational contact on Taum Sauk, Wildcat, and Proffit Mountains is located at the top of a zone of flow-folded foliated welded tuff. It is uncertain whether the contact marks a single depositional horizon in that area, and (as noted previously) whether it represents a cooling break. Near the top of the zone, which is up to 100 feet thick in places, the tuff commonly contains abundant inclusions of plastically deformed bedded tuff and pumice. At several localities the zone is overlain by 10 to 20 feet of dense structureless crystal-poor rock that may be the shard-rich base of the overlying sequence of ash flows or cooling unit (?).

The flow-folded zone is not recognized on Goggins Mountain. The intraformational contacts shown there are placed at topographic benches or glades along which dense very fine grained rock that may be highly indurated bedded tuff is locally exposed. The remaining rock on Goggins Mountain typifies much of the tuff of Taum Sauk Mountain exposed elsewhere. It is predominantly a moderate-red to maroon densely welded devitrified tuff that contains 10 to 20 percent of prominent felsic phenocrysts and vague to definite compaction foliation. A fairly distinctive pale-red, massive-weathered tuff that contains as much as 25 percent of conspicuous large euhedral quartz, alkali feldspar, and magnetite phenocrysts is recognized throughout the area. It generally occurs above the lowermost intraformational contact. Lenticular and subplanar structures are rare in this tuff, but it does contain obscure pumice up to 10 cm in length. The Hogan Mountain Rhyolite (Tolman and Robertson, 1969) is equivalent to this tuff. It is overlain at Johnson Shut-ins by at least three ash-flow tuffs of widely different phenocryst contents and textures. The highest of these tuffs lacks quartz and contains some plagioclase. It has a widespread thunder egg zone at its ultimate top and structurally and texturally is very similar to the uppermost part of unit D or the tuff of Stouts Creek. Modal data from widely spaced samples of the tuff of Taum Sauk Mountain and Johnson Shut-ins are shown graphically in figure 6.

The data are positioned vertically in the figure according to the best estimate of the horizon represented by each sample. However, because no through-going marker horizons were recognized in the thick sequence of tuffs, the relative positioning in the figure is uncertain.

Three whole and two partial chemical analyses of the tuff of Taum Sauk Mountain are given in table 1. Although the sum of alkalies ranges from 6.9 to 9.0 and the K_2O/Na_2O ratio from 1.5 to 2.6, the rocks are similar chemically. Some of the chemical variation probably results from the mild but pervasive alteration to which the rocks have been subjected. The slightly lower silica and higher lime contents of specimen T-345 may reflect the slightly lower quartz content and presence of plagioclase in that rock (see modal data, fig. 6).

Flowage folds are common at several stratigraphic intervals and indicate an unusually high degree of postcollapse mobility for the tuff of Taum Sauk Mountain. Comments on their architecture, trends, and significance are deferred to the section on structural geology. A folded zone is located within 200 feet of the base of the unit on Taum Sauk Mountain. This zone probably correlates with a similar zone near the base of the unit on Lee Mountain 8.5 miles to the southwest. At both localities the folded zone is part of a thick phenocryst-rich devitrified tuff that contains prominent pale-reddish-gray coarsely crystalline lamellar devitrification structures in a moderate-red base. The laminae are 1 to 10 mm thick and are commonly a meter long. The laminated rock is separated from the basal bedded tuff by 50 to 100 feet of pale-red welded tuff that contains conspicuous lenticular lithophysae and fewer phenocrysts than the overlying rock. Similar variations in phenocryst content and type of structures are repeated higher in the tuff of Taum Sauk Mountain.

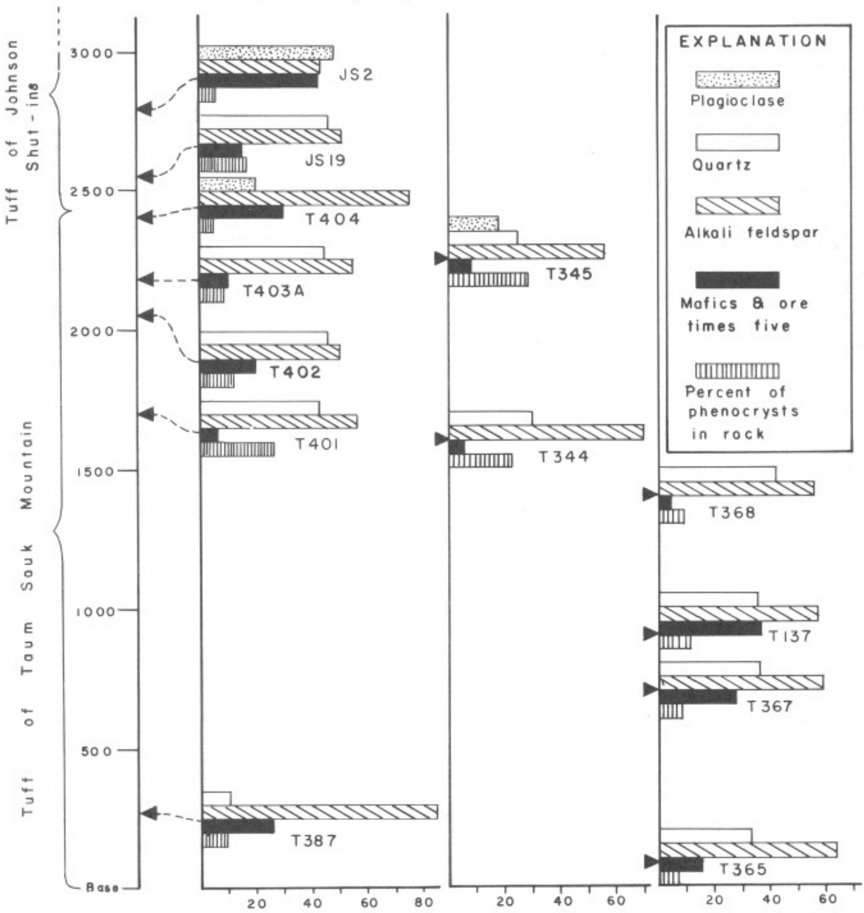


Figure 6

Histograms of modal analyses of phenocrysts in tuffs of Taum Sauk Mountain and Johnson Shut-ins from three areas: Lee Mountain - Johnson Shut-ins (column 1), Goggins Mountain (column 2), and Taum Sauk Mountain (column 3). Vertical scale is in feet; triangles indicate inferred horizons of samples.

TUFF OF JOHNSON SHUT-INS

Approximately 600 feet of northeast-dipping ash-flow and bedded tuffs are exposed at Johnson Shut-ins along the East Fork of the Black River in the west-central part of the area. These strata rest conformably on the tuff of Taum Sauk Mountain and are herein referred to as the tuff of Johnson Shut-ins. From the base upward they consist of about 95 feet of bedded tuff, at least two cooling units of ash-flow tuff separated by bedded tuff, and at least 130 feet of bedded tuff. Rocks equivalent to the basal bedded tuff and lowermost ash-flow tuff are exposed on the east flank of Goggins Mountain; rocks that are probably equivalent to the basal bedded tuff are exposed northwest of Hogan Mountain. Only the rocks exposed at Johnson Shut-ins are described.

The basal bedded tuffs are best exposed on a ridge bordering Johnson Shut-ins on the west. There, as on Goggins Mountain, they rest on the thunder egg zone of the underlying tuffs. They consist of varicolored densely lithified thin-bedded shard tuff interstratified with crystal-lithic tuff.

The lower of the two ash-flow tuffs is a densely welded gray to reddish-brown rock with moderately abundant phenocrysts of quartz and alkali feldspar (JS-19, fig. 6). The tuff is about 200 feet thick and contains conspicuous pumice lapilli and small lithic fragments in the upper 35 feet. It is separated from the overlying ash-flow tuff by about 20 feet of tuff breccia that passes upward into about 30 feet of densely lithified thin-bedded and cross-bedded fine-grained tuff. Some tuff beds consist almost entirely of shards; others contain abundant small phenocrysts and chips of feldspar. Prominent green lenses of secondary epidote and calcite are common (fig. 5B). The upper ash-flow tuff is similar in general appearance to the lower, but it lacks quartz and contains plagioclase in its upper part (JS-2, fig. 6). A cooling break is suggested near the middle of this tuff by the presence of 3 feet of tuffaceous breccia that contains angular blocks and fragments of the subjacent welded tuff in a flowage-streaked lithoidal matrix. Light-gray spheroidal lithophysae are common above and below the breccia zone.

The uppermost welded tuff is overlain by about 130 feet of dark-gray to black bedded tuff. This is the youngest volcanic rock recognized in the area mapped. The tuff is very fine grained, thin-bedded, and well sorted at the base and becomes coarser grained and thicker bedded upward. It is conspicuously cross-bedded and displays some graded bedding. Most of the tuff is rich in crystals (up to 50 percent of rock) consisting almost entirely of plagioclase and alkali feldspar. Pumice is sparse to absent as in almost all bedded tuff lower in the section.

RHYOLITE

A large sill-like or lensoid mass of rhyolite is exposed on Taum Sauk and Russell Mountains and east of Vail Mountain. It intrudes rocks as young as the tuff of Taum Sauk Mountain. Small unmapped masses of similar rhyolite are present on the northern flank of Proffit Mountain, where they also appear to be intrusive. Similar rock that is probably intrusive and possibly coextensive with the mass east of Vail Mountain is exposed along Highway 21 south of Vail Mountain. This rock was mapped as the felsite of Royal Gorge by Bonham (1948) after excellent exposures at Royal Gorge in the east-central part of the mapped area and was referred to as the Royal Gorge Rhyolite by Hayes (1961a) and Tolman and Robertson (1969). Bonham, as well as the writer (Anderson, 1962, pp. 43-44) concluded that this rock is an extrusive rhyolite. However, an intrusive origin is evidenced by crosscutting contact relationships with bedded tuff, baking (?) of bedded tuff, and by the inclusion of blocks of country rock in the rhyolite near some contacts.

The rhyolite is mostly light to moderate red, flow laminated or flow folded and contorted, and locally either massive or brecciated. It contains 5 to 10 percent phenocrysts consisting of crystals and crystal aggregates of alkali feldspar as much as 4 mm, smaller generally rounded and embayed quartz, and euhedral hematite pseudomorphous after magnetite. Locally, as on Russell Mountain, remarkably well developed flow laminae only a few millimeters thick persist laterally for as much as 100 feet. The laminae consist of alternating layers of devitrified formerly glassy rhyolite and lithoidal vapor-phase rhyolite 0.5 to 5 mm thick (fig. 4C, D). The lithoidal layers closely resemble subplanar lithophysae in the welded tuffs (pp. 10-13). Flowage features that are very similar in architecture and detail of alternating vitric and lithoidal layers are pictured by Molloy and Kerr (1962, pl. 3, figs. 2, 3, 4; pl. 4, fig. 3) from the Cray Hills Rhyolite in the Marysvale district, Utah.

A chemical analysis of the rhyolite from Royal Gorge is given in table 1 (sample 22). The low Na_2O (0.13) in this rock is very anomalous and suggests a high degree of sodium leaching. The high K_2O (8.52) is also anomalous and is nearly consistent with values of 8.0 and 6.2 obtained in partial analyses of this unit by the writer (tbl. 1, samples 20, 21). Texturally and chemically the rhyolite is an excellent example of a rock that has undergone potash enrichment during a state of post-cooling hydrothermal alteration (pp. 38-39).

GRANITE PORPHYRY

Granite porphyry exposed along Carver Creek southwest of Hogan Mountain was first described by Bonham (1948). It is described as the Carver Creek Granite Porphyry by Tolman and Robertson (1969). Similar rock is exposed discontinuously in an arcuate band extending southwest from Hogan Mountain to the upper drainage of Adkins Hollow and northward from there to Lindsey Mountain (pl. 1). The granite porphyry is inferred to be continuous in the shallow subsurface along this band (cross section, pl. 1). It is mostly a massive, structureless, pale-orange-brown rock that is well jointed and weathers to rounded or partly rounded bouldery surfaces.

The granite porphyry includes several distinct lithologies as evidenced by the following major phenocryst assemblages from different localities: quartz-alkali feldspar, alkali feldspar, alkali feldspar-plagioclase-quartz, and plagioclase. However, it typically contains about 5 percent large phenocrysts of feldspar and quartz in a holocrystalline groundmass ranging in texture from micrographic to granular. The groundmass in all rock types appears to be granitic in composition with iron rich chlorite and biotite as the chief mafic constituents.

Chilled margins of the intrusive masses occur locally. On the south flank of Hogan Mountain, for example, the margin consists of several feet of dense black porphyritic aphanite. The groundmass of this rock is composed of subrounded clots of very finely crystalline biotite, chlorite, and clay in a felsic base characterized by incipient micrographic texture. The rock becomes more coarsely crystalline inward, where it is characterized by large radial or plumose growths of spongy to micrographic quartz and alkali feldspar as much as 2 cm. Both the chilled margin and the crystalline interior contain a few percent of deeply embayed plagioclase phenocrysts or glomerophenocrysts averaging about 5 mm in diameter.

A chemical analysis of the granite porphyry at Johnson Shut-ins is given in table 1 (sample 23).

MAFIC ROCKS

Mafic rocks occur throughout the St. Francois Mountains as widely scattered dikes, sills, and irregularly shaped masses. They are the youngest Precambrian rocks known in the mapped area. They mainly form a linear group of east-dipping dike segments that are exposed discontinuously from Hogan Mountain northwestward to the northern part of High Top Mountain. An aeromagnetic anomaly along the trend of the dike between Wildcat and northern High Top Mountains suggests that the dike extends beneath the post-Precambrian deposits in the valley of the East Fork of the Black River. The dike is at least 7 miles long and averages about 200 feet in thickness near Devils Toll Gate.

The mafic rocks shown on plate 1 are mostly dark-gray to black, fine- to medium-grained olivine diabase. In most areas they are deeply weathered and poorly exposed. Locally they appear to be deuterically altered but nowhere were they observed to be hydrothermally altered. They probably postdate the period of widespread hydrothermal alteration. The mafic rocks were not studied petrographically because a comprehensive geologic investigation of them has been made by D. H. Amos and G. A. Desborough. Their findings are expected to be published at an early date in the "Contributions to the Precambrian Geology of Missouri" Series.

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CHEMISTRY AND ALTERATION

Complete or partial major oxide analyses of most of the rock units described in this report are given in table 1. Eighty-seven additional chemical analyses of Precambrian rocks from Missouri are tabulated by Hayes (1959). On the basis of analyses of 39 volcanic rocks, Hayes (1961a, p. 81) reported a stratigraphic breakdown of the volcanics into an older Middlebrook Group composed mainly of rhyolite flows which have a high K_2O-Na_2O ratio and a younger sequence of flows, the Van East Group, in which the K_2O-Na_2O ratio is of normal proportions. Representatives of both his groups occur within the mapped area. The contrast in K_2O-Na_2O ratio noted by Hayes does not, however, apply to the strata mapped. In fact, the K_2O-Na_2O ratio tends to be lower in the older strata than in the younger ones, the reverse of the contrast reported by Hayes. It should be recalled that the volcanic rocks provide abundant petrographic evidence indicating that they are mildly to intensely altered (p. 19). Their altered condition indicates that any broad chemical variation, such as is suggested by the alkali ratio, must be evaluated in terms of its relation to possible secondary effects before it can be accepted as a meaningful aspect of the stratigraphy. Such an evaluation is made in the paragraphs that follow.

The fine-grained bedded tuffs (samples 5 and 6, tbl. 1) are highly sericitized and appear to be enriched in secondary hematite. The high K_2O-Na_2O ratio as well as the strongly peraluminous character of these rocks reflects the fixing of K_2O and leaching of Na_2O during sericitization. In the lavas (samples 3 and 4, tbl. 1) mafic silicates are replaced by epidote, chlorite, and magnetite, plagioclase is albitized and partly replaced by chlorite, and the groundmasses are composed of secondary albite, chlorite and iron oxide. The high Na_2O contents and low K_2O-Na_2O ratios in these rocks (and in sample 1, see p. 21) reflect albitization and the probable accompanying expulsion of potassium. The high iron contents of the lavas suggest addition of iron consistent with the partial replacement of nearby bedded tuffs by hematite. Silica probably was added in some of the more high-silica rocks. Thin sections of several of the analyzed specimens display the effects of silicification in the form of quartz-filled vapor-phase cavities, overgrowths on quartz phenocrysts, or microveinlets of quartz. However, comparison of these sections failed to disclose any apparent difference between the degree of silicification in the rock with the highest silica content (sample 12) and the others.

The ash-flow tuff in the upper part of the stratigraphic section have high K_2O-Na_2O ratios and K_2O percentages ranging from 3.2 to 6.2 (samples 12-19, tbl. 1). They plot in the stability field of orthoclase on the normative ternary feldspar diagram (fig. 7) and are considered to be K_2O-rich rocks following the suggestion of Terzaghi (1948). The intrusive rhyolites represented by samples 20-22 are also K_2O-rich rocks. Correlations between alkali contents and secondary mineral assemblages can be inferred for some but not all of these K_2O-rich rocks. The two partially analyzed rhyolites (samples 20, 21), for which thin sections are available, contain abundant flow laminae (p. 34) that have a vein-like appearance in cross section (fig. 4C, D). Typically the laminae grade inward from a wall zone of highly concentrated, finely crystalline, locally spherulitic K-feldspar, and minor quartz and sericite through a zone of K-feldspar laths in quartz to a central zone of quartz and minor sericite. Commonly the K-feldspar laths are crudely oriented normal to the bands as in comb structure and are probably of vapor-phase origin. The quartz-sericite central zones appear to be cavity fillings and are probably of hydrothermal origin. A thin section of rock equivalent to that represented by analysis 22 shows similar effects. Sericite is insufficient to account for the anomalously high K_2O which probably resides in the wall zone as secondary K-feldspar produced by reaction between hydrothermal solutions and chemically normal porous and glassy (?) rhyolite. The wall zone of highly concentrated K-feldspar may be analogous to larger scale zones adjacent to quartz sericite veins common in areas of altered and mineralized rocks of similarly anomalous alkali contents (for a summary of the physical and chemical aspect of such systems see Fournier, 1967). The rhyolite is very similar to rhyolites described by Terzaghi (1948) from Esterel, France, where direct comparison can be made between fresh and altered rock equivalents. Sample 22 is chemically similar to her analysis 10 (1948, tbl. 1) which is a hydrothermally altered obsidian.

Comparisons between chemical and petrographic characteristics are less obvious in the high-K_2O ash-flow tuffs (samples 12-19). Of the two samples that lie closest to the orthoclase corner (fig. 7) sample 15 contains no obvious secondary minerals whereas sample 14 contains turbid interstitial areas of reddish poorly crystalline K-feldspar (?) between felsic poikilitic masses (p. 15). These turbid areas probably represent glassy groundmass that experienced alkali exchange during alteration. Among the tuffs with more normal alkali contents sample 18 contains small amounts of quartz, albite, calcite, sericite, opaque oxide, and flourite as replacement products of phenocrysts and groundmass. The altered condition of the rock is not obvious from the chemical analysis. Plagioclase is the principal phenocryst in samples 13 and 14, yet these rocks have K_2O in excess of Na_2O thus possibly indicating potassium enrichment of the groundmass.

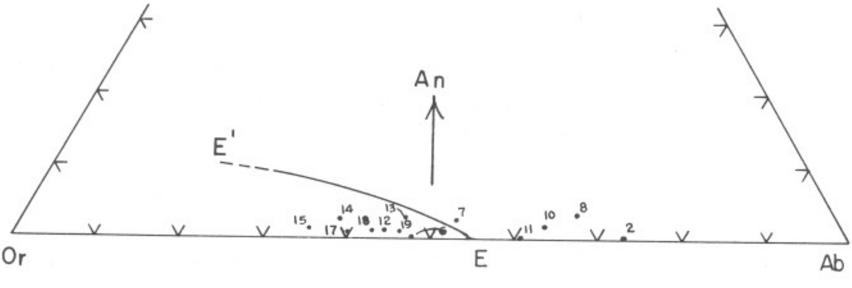

Figure 7

Plot of normative orthoclase : albite : anorthite ratios of 13 ash-flow tuffs. Line E - E^1 represents probable position of the orthoclase - plagioclase field boundary (after Terzaghi, 1948). Sample numbers from table 1.

Several of the welded tuffs that exhibit petrographic evidence suggestive of hydrothermal alteration (samples 1, 11, 13, 14, 16, 18) have approximately unit molecular ratios of $\frac{\Sigma CaO, Na_2O, K_2O}{Al_2O_3}$ (tbl. 1). These include Na_2O- and K_2O-rich varieties as well as some with more normal alkali contents. The approximate molecular balance suggests alteration reactions controlled by feldspar equilibria in the hydrothermal environments. By comparison, many glassy Tertiary rhyolitic ash-flow tuffs show considerably larger divergences from unit molecular ratios. Very commonly at least 0.5 weight percent Na_2O is leached from such rocks during hydration and reaction with ground water (Noble, 1967; Lipman, 1965, p. D18). The leaching is commonly not balanced by addition of K_2O as seems to be the common case in hydrothermal environments involving formation of alkali feldspars (Terzaghi, 1948; Fenner, 1936). In some of the Precambrian rocks of Missouri (samples 12, 15, 17) the molecular ratio is appreciably less than unity. The explanation for their rather highly peraluminous character is not apparent from study of thin sections.

Despite the pervasively altered condition of the volcanic rocks some of the chemical analyses may reflect rather closely their original composition. For the purpose of comparison with nonhydrothermally altered rocks, average chemical compositions of four Tertiary peralkaline rock units from Nevada, ranging from rhyolite to pantellerite, are given in table 1. The similarities between the chemical analyses of samples 7 and 24, 13 and 25, 11 and 26, and 8 and 27 (tbl. 1) support, but do not prove, the previous petrographic inference (p. 20) that some, if not most, of the volcanics from Missouri are peralkaline. Peralkaline rocks are characteristically lower in Al_2O_3, CaO, and MgO and higher in iron than calc-alkaline rocks of equivalent silica content (unpublished data in the files of the U. S. Geol. Survey, Denver). In Missouri the volcanics show similar departures from average variation trends for calc-alkaline rocks (fig. 8), a further indication of peralkaline affinity for the volcanics. In the absence of a systematic chemical and petrographic study of alteration effects, the only statement relating chemical composition to stratigraphic position that seems justifiable is that the bulk of the volcanic pile consists of rhyolite with probable peralkaline affinities whereas more low silica propylites with probable trachyandesite affinities occur low in the section. The widespread effects of alteration preclude interpretation of presently available chemical or petrographic data in terms of modern concepts that relate zonal variations in ash-flow tuffs to processes in the source magmas (Smith and Bailey, 1966; Lipman and others, 1966).

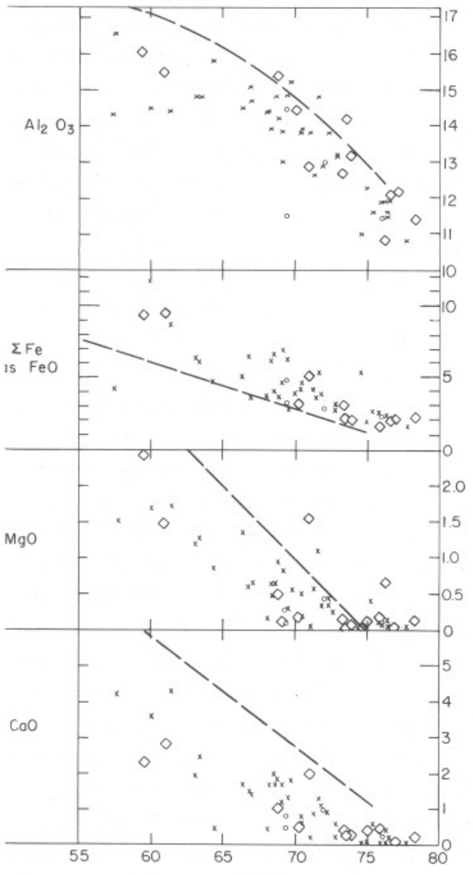

Figure 8

Silica variation diagrams showing a comparison between average trends for calc-alkaline rocks (dashed lines from Hamilton-1960) and some Precambrian volcanic rocks from Missouri. ◇ = data from new analyses (tbl. 1), X = selected analyses from compilation by Hayes (1959), o = averages for peralkaline rock units from Nevada (tbl. 1).

STRUCTURE

Eruption of the thick sequence of volcanics described herein was doubtlessly accompanied by seismicity and faulting centered mostly in and near the volcanic source area(s). The structurally uninterrupted layered accumulation of the strata in the mapped area provides no evidence of severe volcano-tectonic activity there. The only major sturctural feature in the mapped area is a broad depression, herein designated the Taum Sauk depression, composed of more than 5,000 feet of volcanic strata that are intruded by broad dikes and plugs (pl. 1). It has recently been described as the Taum Sauk Caldera by Anderson, et al. (1969). The center of the depression is located between Taum Sauk and Little Taum Sauk Creeks. Its size and shape are not accurately known because of insufficient exposures and mapping. Based on structural and aeromagnetic considerations (Anderson, 1962, p. 52-54) the depression probably covers at least 100 square miles and has at least 2,000 feet of structural closure. The tuff of Johnson Shut-ins, the youngest volcanic unit mapped, dips about 20^{o} toward the center of the depression. This dip is comparable to the average for all earlier strata, thus suggesting that the depression formed after extrusion of the youngest volcanic rocks. That the Taum Sauk depression is not of volcano-tectonic origin is thus implied by its late development and by the lack of evidence for volcano-tectonic activity during accumulation of the strata from which it is formed. Very complex fault histories and patterns are normally found in and adjacent to eruptive centers for ash-flow tuffs.

Granite bodies of batholithic proportions (as much as 150 sq. mi.) and smaller masses of granophyre are exposed in the St. Francois Mountains along with masses of granite porphyry and mafic rocks similar to those exposed in the area mapped. Medium- to coarse-grained equigranular granitic textures predominate in the larger masses but locally they have micrographic or porphyritic marginal zones. Micrographic and porphyritic textures predominate in the smaller masses. Most country rocks adjacent to even the large plutons are undeformed and the plutons themselves are nonfoliated (Snyder and Wagner, 1961). All dikes observed by the writer appear to be dilatational. These structural and textural features preclude a deep-seated syntectonic origin for the intrusive masses. Although some masses were probably emplaced along preexisting faults, no faulted contacts were observed, indicating that the intrusives, regardless of texture, were emplaced at approximately the same structural level.

Large granite masses in the St. Francois Mountains typically produce strong negative aeromagnetic anomalies (Anderson, 1962, pp. 54-56; Allingham, 1960; Snyder and Wagner, 1961, p. 89). Two such anomalies lie just beyond the north and southeast margins of the mapped area. The northern anomaly covers about 45 square miles and is produced by the Graniteville Granite (Graves, 1938) that is exposed locally near the margins of the anomaly. The anomaly to the southeast is similar in size and is probably produced by a buried granite mass (Snyder and Wagner, 1961). These known or inferred granitic plutons are considered parts of the St. Francois Mountains batholith. The rhyolite and granite porphyry masses in the area mapped are further interpreted as shallow extensions of the batholith, which thus is believed to extend beneath the Taum Sauk depression. The depression is interpreted as a broad sag in the roof of the batholith. This interpretation is consistent with the suggestion made by Snyder and Wagner (1961, p. 86) that the thick pile of volcanic rock along the Iron Mountain--Ironton Axis (which extends north from the northeast corner of the area shown on pl. 1) represents a roof pendant in the granite complex. Ash-flow tuffs are products of violent volcanic expulsion, and the apparent absence of prevolcanic lithics in them is an indication that such rocks did not exist between the magmas from which the ash flows were expelled and the surface. The magmas apparently worked their way into the shallow subsurface where they invaded ejecta from earlier volcanism or, in some areas, their own skin. The writer is familiar with several ash-flow and lava fields in the western Great Basin where volcanic rocks are invaded by coeval magma over broad areas, and Hamilton and Myers (1967) have suggested that the phenomenon of batholiths invading their own ejecta may be a common one. Also, a subjacent granitic mass could provide the heat necessary to produce the pervasive hydrothermal alteration to which the volcanic rocks were subjected.

FAULTS

The most prominent and persistent faults strike northeast; others strike north, northwest, and west. All appear to dip steeply and have little brecciated rock or gouge along them. Apparent vertical separation ranges from 1,200 feet on two faults that bound Russell Mountain to a few tens of feet on most other faults. The two large faults may have a component of lateral separation.

The upper Cambrian sedimentary rocks that rest on the faulted Precambrian rocks generally show no displacement. The development of the paleosurface onto which the sediments were deposited was partly controlled by faults as indicated by tongues of basal Upper Cambrian clastic rocks situated along fault projections. Because the present topographic surface is largely an exhumed one, the tongues of sedimentary rocks are found along many of the major and minor present-day valleys.

Northeast- and northwest-trending faults were active during the period of igneous activity as evidenced by localization of rhyolite and basalt dikes and iron veins along them. Possible further indication is found on Vail and Russell Mountains where vertical elements of devitrification structures have a consistent northeast strike parallel to the predominant fault trend (pl. 1). In that area the devitrification structures that parallel the plane of compaction are interconnected by coextensive masses oriented normal to the plane of compaction (fig. 4A). The result is an overall trellis-like pattern of devitrified masses as viewed in the plane normal to the compaction foliation. These structures are very similar to the devitrification dikes described by Simons (1962). The tuff was probably fractured subsequent to welding but prior to complete cooling thus permitting volatiles released during devitrification to flux further devitrification along the fractures. The possibility that the fractures developed subsequent to total cooling and that the dikes are not primary devitrification structures cannot be precluded.

FOLDS

The Taum Sauk depression appears to have formed without folding of its flanks. The tuff of Taum Sauk Mountain and the intrusive rhyolite are highly folded on a small scale. This folding is related to emplacement of the rocks and is therefore only of indirect tectonic significance.

Ash-flow tuffs or ignimbrites with a history of flowage after deposition and collapse have been described and designated rheoignimbrites by Rittman (1958, p. 528). Although not so designated, similar rocks have been recognized in the Canary Islands (Schmincke and Swanson, 1966), southeast Oregon (Walker and Swanson, 1968), the Oslo, Norway region (Oftedahl, 1957) and at the Nevada Test Site, Nevada (Hoover, 1964; F. M. Byers, oral comm., 1967). Both Hoover (1964) and D. A. Swanson (oral comm., 1966) concluded that flowage resulted from gravitational forces acting on tuffs that were deposited on sloping topography. Presumably it occurred before the rock cooled appreciably.

Subplanar to planar lithophysae and devitrification structures are common in the tuff of Taum Sauk Mountain. These structures are not the result of flowage, although some translation does occur along some of them. At several levels in the tuffs the planar structures are deformed into folds with wavelengths ranging from a few inches to as much as 100 feet. Nothing is known of the details of the larger folds. The small folds with wavelengths up to a few feet all appear to be of the similar variety. They are commonly either tight and asymmetric or recumbent. Crumpled zones occur in the lower parts of the axial regions of most anticlines. The upper limbs of recumbent folds are commonly translated along the axial planes in the direction of recumbency. In the other direction the axial planes pass into zones of detachment or décollement thus producing an overall structure similar to ramp structures in lavas. Translation along the décollement is, in essence, translation along the initial planar structure. In vertical section each rheoignimbrite interval is characterized by a succession of imbricated layers.

The overall fold pattern is distinctly disharmonic, but gives rise, in plain view, to well-defined alignment of axial plane traces (pl. 1). This alignment indicates movement mainly in the northeast-southwest direction. Almost all axial planes observed dip northeast (shown schematically in cross section, pl. 1) indicating a flow vector to the southwest. The most significant measurements were made on Lee Mountain, where the strata dip northeast but the indicated direction of translation is southwest, thus precluding the possibility that flowage was due to gravitational sliding into the Taum Sauk depression. The implied late development of the Taum Sauk depression is consistent with this observation. That is, the tuff of Taum Sauk Mountain was apparently erupted onto southwesterly sloping topography that existed across the present site of the depression.

The mechanism of flowage is a combination of similar folding, thrusting, and gliding of the imbricated layers. Each successively higher imbricated interval moved a greater distance southwest than the one below. The source area for these tuffs probably lies northeast of the mapped area, possibly in the vicinity of the Iron Mountain mining district 6 miles north of Ironton.

Most of the mapped units with well-developed planar structures show no evidence of flow, but all those that do are characterized by planar to subplanar structures. The possibility seems good that in order for flowage to occur there must first be a development of planar vapor-phase structures that can serve as shear and glide planes. This is consistent with the findings of both D. L. Hoover (written commun., 1966) and Schmincke and Swanson (1966), who noted the common development of vapor-phase crystals along planar structures. Many fluidal flow rhyolites observed by the writer exhibit very similar development of vapor-phase crystals along flow laminations.

The chemical composition of the tuff may be an important factor in causing flowage (Walker and Swanson, 1968) and the high total iron and low alumina characteristic of the ash-flow tuffs from Missouri may serve to reduce glass viscosity to the point of allowing flowage (Walker and Swanson, 1968, p. B47).

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ASH-FLOW TUFFS OF PRECAMBRIAN AGE IN SOUTHEAST MISSOURI RI 46

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MISSOURI GEOLOGICAL SURVEY & WATER RESOURCES

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