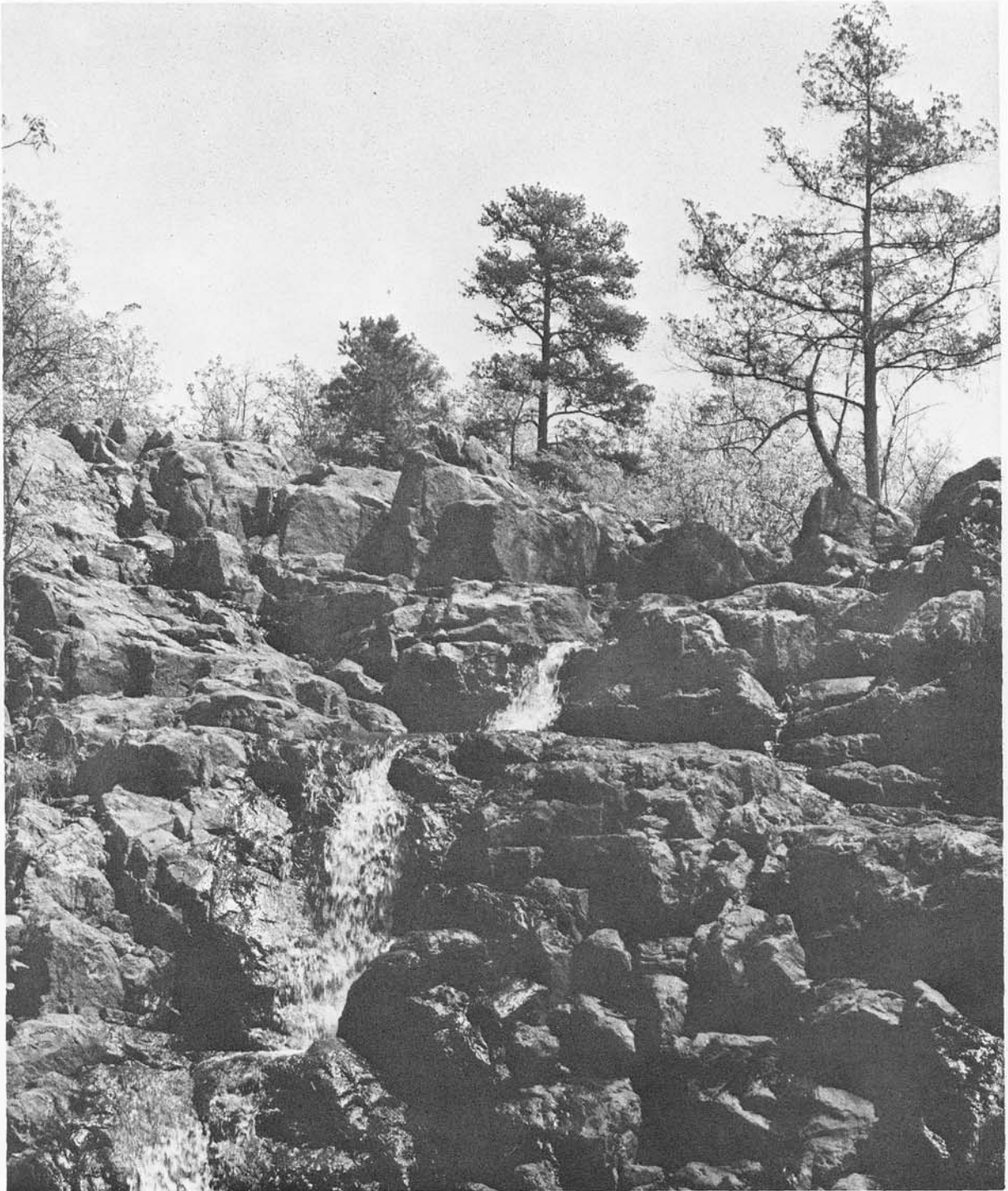# STUDIES IN PRECAMBRIAN GEOLOGY

Upper Mina Sauk Falls, Taum Sauk Mountain. A small stream tumbles over Hogan Mountain Rhyolite to produce Missouri's highest waterfalls, with a total drop of 132 feet, in several cascades.

MISSOURI PRECAMBRIAN REVISITED: PROGRESS IN STUDIES OF PRECAMBRIAN GEOLOGY, 1961-1976

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INTRODUCTION

The St. Francois Mountains of southeast Missouri represent one of the few large exposures of Precambrian igneous rocks in the Midcontinent region of the United States. As such, they have long attracted the attention of geologists because they provide an excellent opportunity to study these rocks in outcrop. Several reports and field guidebooks have been published in the past that served to introduce researchers and visitors to the Precambrian geology of the area.

Worldwide interest in Precambrian terranes increase significantly in recent years because of a variety of factors. These ancient terranes hold the clues of continental crustal evolution and the origin of living organisms on our planet. They contain a great variety of minerals, and as mankind is using up its nonrenewable mineral resources at an alarming rate they are regarded with renewed interest for their inherent potential as a mineral-resource base for the future. Technological advancements and refinements in analytical techniques contributed to the surge of interest in the Precambrian, as they permit identification and interpretation of Precambrian events and geologic processes on a more sophisticated level.

The Missouri Precambrian has received its share of interest from both the research community and the mineral industries. The exposed Precambrian rocks in southeast Missouri, near the apex of the Ozark Uplift, are but a small fraction of the crystalline basement that forms the cratonic foundation of the Midcontinent. Elsewhere in the state the basement is buried beneath a relatively thin cover of Paleozoic and younger sedimentary rocks. Intensive mineral

exploration in the last 20 years dramatically increased the data on the buried Precambrian, in the form of drill-core samples, underground-mining data, and geophysical maps. The data indicate that in a substantial part of southern Missouri the basement rocks are very similar to those exposed in the St. Francois Mountains (Muehlberger et al., 1966; E.B. Kisvarsanyi, 1973a). The St. Francois Mountains therefore may be regarded as a huge outdoor laboratory where detailed geological investigations may be carried out. These investigations may permit interpretations and extrapolations that can subsequently be extended to the buried part of the basement. Combined with the subsurface and geophysical data, they may shed light on the early history of a little-known segment of the Precambrian crust in the North American continent, and may be vital in identification of potential mineral resources.

The Precambrian rocks of Missouri have an impressive record of mineral production and a not yet fully explored mineral-resource potential. They have been the major source of the state's iron-ore production for more than 150 years. Production in the past has largely come from ore deposits close to the surface in the St. Francois Mountains area, but exploration for additional sources of metals by a number of mining companies has resulted in development of new deep mines and has indicated orebodies in buried Precambrian rocks to depths of more than 2,000 ft below the surface. Current production, which is exclusively from the deep ore deposits, reached 2.1 million long tons of iron ore in 1975. Copper mineralization and recoverable amounts of apatite are associated with some of the iron-ore deposits. Locally, the exposed Precambrian rocks contain manganese and lead-silver-tungsten mineralization and have been the source of marginal production of these metals in the past.

The Mississippi Valley-type lead-zinc-copper deposits of the Lead Belt and Viburnum Trend mineral districts, northeast and west-southwest of the St. Francois Mountains, respectively, occur in Upper Cambrian sedimentary rocks that were deposited over the rugged Precambrian surface. Intensive exploratory drilling between 1955 and 1963 resulted in the discovery and subsequent development of

the Viburnum Trend ore deposits, and indirectly contributed valuable information on the composition and structure of the buried basement rocks because many of the drillholes bottomed in Precambrian rocks. It has become increasingly apparent that the topography and structure of the Precambrian basement exerted a profound influence on the development of favorable depositional environments and sedimentary facies of the ore hosts. Recognition of these relationships added momentum to creative endeavors in investigations of the Missouri Precambrian.

The scientific community and government agencies rose to the challenge afforded by the availability of cores, mining data, and new geological information. The annotated bibliography compiled by the writer in 1973 (E.B. Kisvarsanyi, 1973b) dramatically illustrated the increased amount of research literature pertinent to the Missouri Precambrian. Whereas an earlier bibliography covering the period from the mid-1800's to 1959 listed 200 titles (Wills and Bertram, 1959), in the 14-year period from 1959 to 1973 more than 180 reports and publications were issued. They reflect a variety of approaches and concepts and the cumulative efforts of many individual investigators. Some of the recent research resulted in discoveries that necessitate reappraisal and reinterpretation of some previously accepted ideas and concepts; some of it reinforces and supports the work of earlier investigators.

The opportunity to review the current state of Precambrian studies in Missouri is being provided by the 23rd annual meeting of the Association of Missouri Geologists. The meeting and attendant field trips are being held in the St. Francois Mountains again for the first time since 1961. Both meetings have been hosted and organized by the Missouri Geological Survey. Hayes (1961) prepared a comprehensive guidebook to the geology of the St. Francois Mountains for the 1961 event and included a number of papers pertinent to the geology of the area. This volume uses a different approach. The roadlogs in Part 1 highlight only a few selected aspects of the Precambrian geology of the area. They were chosen in order to introduce and set the stage for the Precambrian studies contained in Part 2 of the volume, and on the basis of accessibility. They focus attention to those parts of the St. Francois Mountains

area that were previously inaccessible (i.e., new road-cuts, etc.), and that have been most intensely investigated in recent years. Therefore, they frequently contain references to the corresponding articles in Part 2.

The collection of studies in Part 2 of this volume emphasizes results of recent investigations. While building on the foundation laid by earlier workers, these studies brought new results and solved outstanding problems by the employment of new methods and concepts. They provide an excellent opportunity to review and analyze the current status of our understanding of the Precambrian geology in southeast Missouri, to formulate remaining problems, and to point out specific fields where future research efforts need be concentrated.

The purpose of this paper is to serve as an introduction to Part 2 of this volume and to provide some of the background information which is required by the symposium format, but is inevitably lacking in the individual articles.

OPERATION BASEMENT

During the 1960's new surface and subsurface data on the Missouri Precambrian increased rapidly. The Missouri Geological Survey recognized the need for orderly and systematic handling of the data, and anticipated the need to coordinate research efforts. Consequently, in 1968 the Survey established the Operation Basement program which was designed to meet these needs.

Operation Basement has a three-fold objective: a) to obtain drillhole and underground-mining data relative to the structure and composition of the buried basement by maintaining close cooperation with exploration and mining companies; b) to expand mapping in the Precambrian outcrop area and actively support and conduct research related to Precambrian geology and mineral resources; and c) to publish the results of the first two objectives in the Contribution to Precambrian Geology series.

As a result of the favorable response of the mining industry to Operation Basement, drillhole data and core samples were made available to the Survey at an increased rate. A drill-core and corresponding thin-section library of Precambrian samples was established at the Survey, which enabled geologists to study basement rocks from a large segment of the state for the first time. Comprehensive petrographic analyses of these samples permitted precise identification of basement rocks and recognition of their distribution in the subsurface (E.B. Kisvarsanyi,

1974). Earlier maps (Adams, 1959; Hayes, 1962) depicting the configuration of the Precambrian basement in Missouri were based on scantier data and were revised (E.B. Kisvarsanyi, 1975). Core samples were made available for geochemical and geochronologic studies, and the age relationships among buried basement rocks have become better understood.

In accordance with the second objective of Operation Basement, the Survey supported several mapping projects in the St. Francois Mountains area. The results of some of these projects are summarized by Berry, Blades and Bickford, Sides, and Sinha and G. Kisvarsanyi in Part 2 of this volume.

To date, five publications have been issued in the Contribution to Precambrian Geology series. Four of these (Tolman and Robertson, 1969; R.E. Anderson, 1970; Amos and Desborough, 1970; E.B. Kisvarsanyi, 1972) are reports of investigations conducted before the establishment of the Operation Basement program. The fifth report (E.B. Kisvarsanyi, 1975) is a direct result of the first objective of the program in that it summarizes drillhole and petrographic data on the buried Precambrian basement of Missouri. This volume is the sixth contribution in the series and emphasizes recent investigations conducted mostly in the outcrop area of Precambrian rocks in southeast Missouri.

MAPPING PROJECTS

The currently most widely used and referred-to geologic map of the exposed Precambrian rocks in southeast Missouri is included with the report by Tolman and Robertson (1969). Published at the scale of 1:125,000, this map was compiled by Robertson in the 1950's from areal geologic maps of 1:62,500 scale. The bulk of the original mapping was accomplished during the 1930's and 1940's under the supervision of Dr. Carl Tolman of Washington University in St. Louis, Missouri, and with support from the Missouri Geological Survey. The list of contributors to that comprehensive mapping project is given by Tolman and Robertson on page 4 of the 1969 report and will not be repeated here.

On the basis of their considerable background and experience in mapping the igneous rocks, and utilizing petrographic and petrochemical data, Tolman and Robertson established a sequence of Precambrian igneous activity in the St. Francois Mountains. They have grouped the exposed Precambrian rocks into three major categories; a pre-batholithic sequence of dominantly rhyolitic volcanic rocks, a batholithic sequence of dominantly granitic intrusive rocks, and a postbatholithic sequence of mafic rocks. Within each of these sequences they have recognized distinct lithologic varieties and assigned formal names to many. The comprehensive report on the exposed Precambrian rocks by Tolman and Robertson and the areal geologic map were essentially completed by the late 1950's, and Hayes briefly summarized the named Precambrian rock units in the 1961 guidebook to the St. Francois Mountains. It is regrettable that unavoidable delays caused postponement of publication of the Tolman and Robertson report until 1969. Nevertheless, manuscript copies of the map and report were in open file at the Missouri Geological Survey and served as an indispensable introduction for many investigators to the geology of the St. Francois Mountains.

In 1962, R.E. Anderson made a significant contribution to the Precambrian geology of Missouri. He recognized that many of the volcanic rocks previously interpreted as lava flows were actually rhyolitic ash-flow tuffs. Utilizing the emplacement characteristics and lithologic variations of ash-flow tuffs, he mapped a portion of the western St. Francois Mountains (fig. 1) and defined a stratigraphic sequence that was not consistent with the simple model proposed by Tolman and Robertson.

Previous investigators regarded the bulk of the volcanic rocks as products of lava flows, although bedded tuffs and agglomerates were also recognized among them locally. They did not attempt to explain the widespread lateral distribution of some of the volcanic-rock units, although rhyolitic lavas would not be expected to spread laterally and cover large areas, because of their high viscosity. Ash flows, on the other hand, are charged with volatiles which impart a high degree of mobility; they may cover thousands of square miles. Furthermore, successive ash-flow sheets, deposited on top of one another, provide a degree of analogy to stratified sedimentary rocks. The recognition of ash-flow tuffs in the St. Francois Mountains therefore was a major step toward reappraisal and redefinition of the volcanic rocks and provided the basis for a stratigraphic treatment.

It is of interest to note that, although the literature of ash-flow tuffs is extensive, Precambrian ash-flow tuffs had generally remained unrecognized until the 1960's because devitrification, recrystallization, and in some cases metamorphism have all but completely changed their original character. Ross and Smith (1961) referred to only three occurrences of Precambrian ash-flow tuffs in their treatise on ash-flow tuffs: in the Anti-Atlas region of Morocco, in central Sweden, and in two deep drillholes in Texas. Their study and subsequent investigations in the younger volcanic terranes of the western United States have contributed significantly to the recognition of ash-flow tuffs in older terranes, by providing precise criteria on the identification of field and microscopic characteristics of these rocks.

In 1968, mapping of the Precambrian volcanic terrane of the St. Francois Mountains was renewed under the direction of J.E. Anderson and M.E. Bickford of the
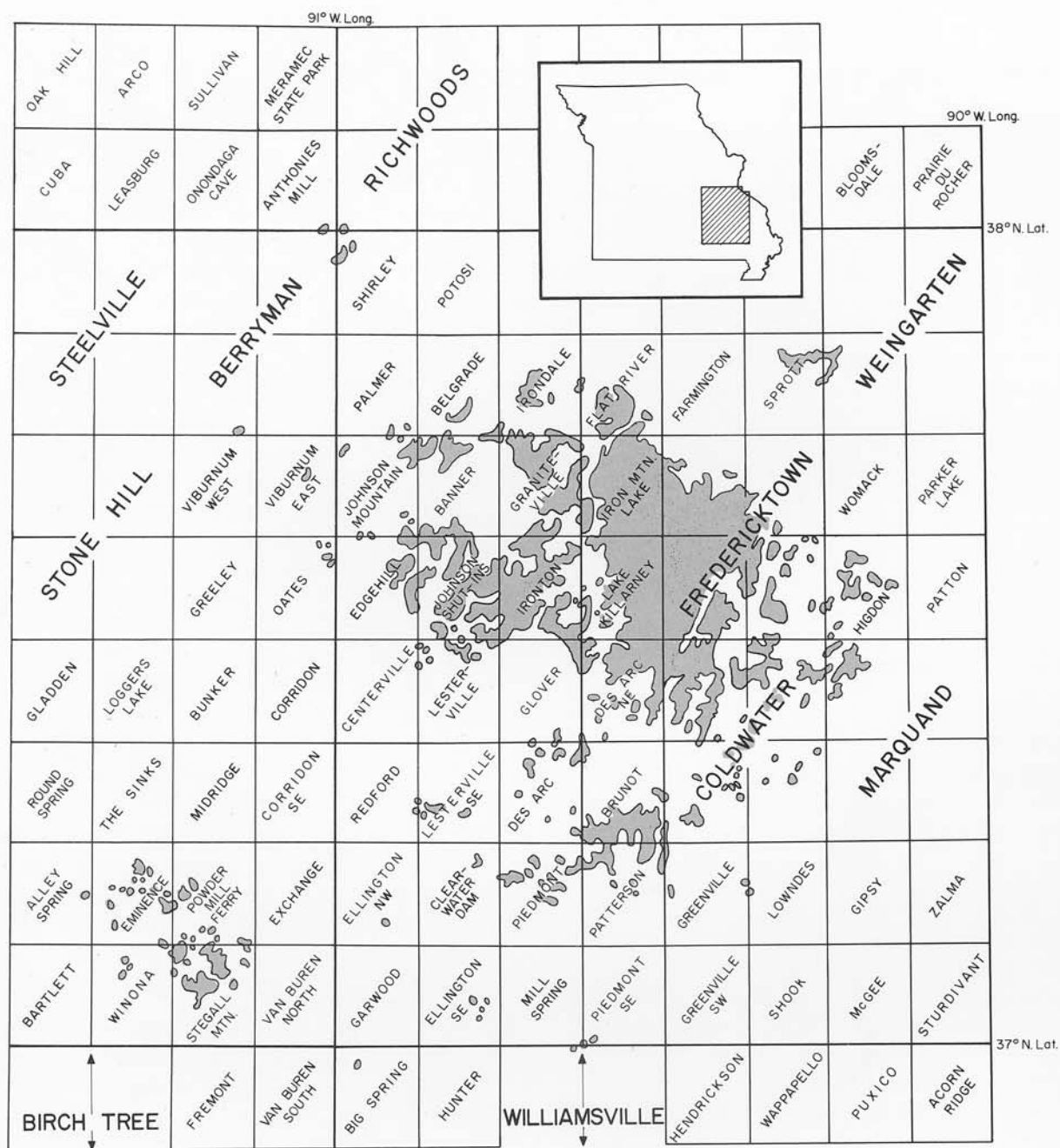
Figure 1

Exposed Precambrian rocks in southeast Missouri. The map shows the general distribution of Precambrian outcrops in relationship to 7½-minute and 15-minute topographic quadrangle maps.

University of Kansas, with support from the Missouri Geological Survey. New U.S. Geological Survey topographic maps of the area, prepared by photogrammetric methods and published at a scale of 1:24,000, provided an excellent base for the geologic mapping. Armed with the by then well-established and defined criteria for the identification of ash-flow tuffs, J.E. Anderson and others (1969), Berry (1970), and Berry and Bickford (1972) refined and extended the mapping begun by R.E. Anderson (1962, 1970), and defined a major volcanic structure in the western St. Francois Mountains, which they named the Taum Sauk Caldera. This mapping project covered the Johnson Shut-ins quadrangle and adjoining parts of the Edgehill, Johnson Mountain, Banner, Graniteville, Ironton, Lesterville, and Centerville quadrangles (fig. 1). These quadrangles include one of the largest continuous exposures of Precambrian volcanic rocks in the St. Francois Mountains. Subsequently, mapping was extended eastward and northeastward by Berry, in order to complete the Precambrian geologic map of the Graniteville and Ironton quadrangles.

The new mapping indicated that volcanic units of distinctive lithologies occur in recognizable stratigraphic succession and are mappable at 1:24,000 scale, and that assignment of formal stratigraphic names to them is warranted. Berry* proposes to subdivide the volcanic rocks in the western part of the St. Francois Mountains into 14 formations defined in accordance with the Code of Stratigraphic Nomenclature (AAPG, 1970). Berry's paper is a preview of a more detailed report in progress, and includes a synoptic chart that facilitates correlation of the proposed stratigraphic names with earlier formal and informal names used for the volcanic rocks of the area.

Blades and Bickford** report on an exceptionally well-exposed section of volcanic and intercalated tuffaceous sedimentary rocks in Johnson Shut-ins, in what is apparently the stratigraphically highest preserved portion of the volcanic pile associated with the Taum Sauk Caldera. The terms they have adopted for the fine-grained sedimentary rocks are somewhat at variance with those of Wentworth and Williams (1932), Pettijohn (1957), and Fisher (1961), and disagree with those used by Berry *** for the same part of the section. The contribution by Blades and Bickford also includes a brief review of the

development of ideas that led to the current understanding and definition of ash-flow tuffs.

Mapping in the Lake Killarney quadrangle (fig. 1) was begun by Sides in 1974 under the direction of M.E. Bickford of the University of Kansas. Sides reports some of the results they have obtained so far.[†] Attempts to correlate the volcanic-rock units mapped in the Lake Killarney quadrangle with those of Berry have not been successful, but a major anticlinal structure that strikes northwest and appears to dominate the central portion of the area was recognized (Sides and Bickford, 1976).

Precambrian outcrops east of Eminence in Shannon and Carter Counties are some 40 mi distant from the main area of exposed Precambrian rocks of the St. Francois Mountains, and have traditionally received less attention. Sinha and G. Kisvarsanyi[††] report on mapping in a portion of the Stegall Mountain quadrangle, southeast of Eminence. They have identified ash-flow tuffs in the volcanic section of this area that are very similar in all respects to those occurring in the St. Francois Mountains, are probably coeval, and may prove to be correlative with them.

Mapping in the St. Francois Mountains continues. In 1975 Robert L. Nusbaum of the University of Kansas began mapping in the Iron Mountain Lake quadrangle (fig. 1), but the deadline for submission of papers to this volume was too early for him to report on his results. By the summer of 1976, M.E. Bickford of the University of Kansas will have begun mapping in the western half of the Fredericktown 15-minute quadrangle in connection with a comprehensive, NSF-supported study of Precambrian crustal evolution in the Midcontinent area. Plans for a cooperative study of the mineral resources of the Rolla 2-degree quadrangle are being developed by the Geologic Division of the U.S. Geological Survey and the Geological Survey, Missouri Department of Natural Resources. This project will utilize all available geologic maps of the area and, as the quadrangle includes both the St. Francois Mountains and the Eminence-area Precambrian, the new maps will be integral parts of it.

The recent mapping and subsurface data indicate that ash-flow tuffs are widely distributed in both the exposed and buried portion of Missouri's Precam-

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brian basement. The volcanic pile includes lava flows of rhyolitic, trachytic, andesitic, and basaltic composition, lesser amounts of bedded tuffs and tuffaceous sediments, and at least one occurrence of Precambrian limestone. Stinchcomb* discusses the limestone of Cuthbertson Mountain, in the southeast part of the Ironton quadrangle (fig. 1). He recognizes distinct stromatolitic structures in the limestone, and discusses the possible environments in which primitive organisms may have lived between periods of volcanic eruptions.

Although the new data do not support the simple subdivision of the volcanic pile into two groups, as proposed by Tolman and Robertson (1969), they do indicate that all the Precambrian volcanic rocks of southeast Missouri are related to a period of large-scale, dominantly rhyolitic volcanism. Geochronologic data (Muehlberger et al., 1966; Bickford and Mose, 1975) have been instrumental in establishing the fact that the volcanic rocks of the region are coeval. It may be expected that other volcanic source areas, similar to the Taum Sauk Caldera, will be identified through detailed mapping. Undoubtedly, other formations and groups of formations will be identified in addition to those defined by Berry in the western St. Francois Mountains. In recognition of the fact that the Precambrian volcanic rocks of southeast Missouri constitute an assemblage of related formations and groups, the Missouri Geological Survey adopted the formal name St. Francois Mountains Volcanic Supergroup for this assemblage.**

STUDIES OF THE INTRUSIVE ROCKS

Tolman and Robertson (1969) gave formal names to several of the petrographically and petrochemically distinct granitic rock types that they mapped in the St. Francois Mountains. Robertson (1965) assigned the granites to a batholith which he named after the St. Francois Mountains.

The intrusive rocks include granite, quartz monzonite, minor granodiorite, and their hypabyssal equivalents. Petrochemical data (Tolman and Robertson, 1969; E.B. Kisvarsanyi, 1972) have shown them to be comagmatic with the volcanic rocks. Subsurface data indicate that syenite and diorite intrusions are locally associated with the intrusive complex of the southeast Missouri Precambrian (G. Kisvarsanyi, 1973; E.B. Kisvarsanyi, 1974). Geochronologic data indicate (Muehlberger et al., 1966; Bickford and Mose, 1975) that the age of the intrusive rocks is slightly younger than that of the St. Francois Mountains Volcanic Supergroup. In other words, the granites and their related suite of intrusives have engulfed and intruded their own ejecta at shallow crustal levels.

The acidic intrusive rocks of the St. Francois Mountains cannot be separated from the cogenetic volcanic rocks of the region. Together, the extrusive and intrusive rocks define a petrogenetically distinct volcanic and plutonic association, similar to those discussed by Buddington (1959) and Raguin (1965). Quoting Klüpfel, Raguin (1965, p. 227) states that "plutonism is only a continuation of volcanism under other conditions".

The subvolcanic granite massifs of southeast Missouri are similar in mineralogy, petrochemistry, mode of emplacement, and tectonic environment to those described from the Precambrian of the Anti-Atlas region of Morocco (Raguin, 1965), to the "younger" granites of Nigeria (Jacobson et al., 1958), and to several other epizonal and postkinematic complexes described from around the world and referred to by Raguin (1965) and Marmo (1971). These complexes are located in rigid regions where there are great linear fractures, and are related to fissure volcanism. Erosion in many places has removed their volcanic cover to a greater extent than in the St. Francois Mountains. The granitic rocks of these complexes·are typically alkalic and leucocratic, consist of perthitic alkali feldspars, quartz, and smaller amounts of biotite and hornblende, and may include fayalite, riebeckite, and arfvedsonite. They are frequently associated with ring-dike development and cauldron-subsidence structures, are characterized

*See p. 122, this volume.
**See p. 2, Generalized Stratigraphic Column

by extensive development of granophyre near their contacts with the volcanic rocks, and have a well-developed suite of related hypabyssal porphyries.

Granite emplacement in the Precambrian of southeast Missouri has become much better understood during the last 15 years through availability and study of drill cores. Recent studies indicate that the simple two-stage model proposed for the emplacement of the batholithic rocks of the St. Francois Mountains by Tolman and Robertson (1969) should be modified. G. Kisvarsanyi (1973, 1975) concluded that Musco Group granites (Slabtown and Stono Granites), previously interpreted as belonging to an earlier stage of granite emplacement, are marginal, chilled facies and in-situ differentiates, and are transitional to Bevos Group granites with depth. Similar transitional relationships have been observed in drill cores from the Eminence area, and from other parts of the buried basement. Mapping of the volcanic rocks associated with the Taum Sauk Caldera (J.E. Anderson et al., 1969) indicates that Musco Group granite porphyries (Munger and Carver Creek) were intruded along arcuate faults of a ring-fracture system associated with the Caldera.

Logging and evaluation of thousands of feet of drill core were also essential in the recognition of intrusive rocks of intermediate composition in the Precambrian plutonic association of southeast Missouri (G. Kisvarsanyi, 1966, 1975), and in the recognition of a late stage of granite emplacement (G. Kisvarsanyi, 1973, 1975) that caused extensive hybridization of the intruded rocks and may be represented in outcrop by the Graniteville Granite.

Detailed mapping, petrographic analysis, and trace-element analysis of some of the intrusive bodies (Corbitt, 1966; Davis, 1969; Hansink, 1965; Lemmon, 1964; Klimstra, 1964; Marko, 1964) established certain petrogenetic trends within individual intrusive bodies. Malkames and Hood* report on the petrology of the Mudlick Dellenite, one of the distinct hypabyssal intrusive units mapped by Tolman and Robertson (1969).

Lowell and Sides (1973) identified rapakivi granite in the Butler Hill Granite, which is exposed in the northeastern area of Precambrian outcrops in southeast Missouri. The isolated Precambrian outcrops in Ste. Genevieve County, about 10 mi northeast of the main area of exposed igneous rocks, have been investigated in detail by Lowell.** He mapped several distinct varieties of intrusive rocks in this area, including an interesting rapakivi-porphyry dike, and recognized a unique granodiorite gneiss, the only metamorphic rock reported in outcrop from the southeast Missouri Precambrian. Bickford and Mose (1975) reported an age of 1,500 ± 30 m.y. for the gneiss and concluded that it is coeval with other samples from the St. Francois Mountains studied by them.

The petrology of the mafic intrusive rocks in the eastern part of the St. Francois Mountains has been discussed by Amos and Desborough (1970). Current studies by M.E. Bickford of the University of Kansas will concentrate on the petrology and structure of the batholitic rocks in the northeast part of the Precambrian outcrop area.

Proposed amendments to the code of stratigraphic nomenclature in reference to intrusive igneous rocks (to be published as a Stratigraphic Note in the AAPG Bulletin) suggest the provisional adoption of the name St. Francois Mountains Intrusive Suite for the cogenetic intrusive rocks of the St. Francois Mountains area.*** As "batholith", "pluton", "dike", and similar names are not stratigraphic terms, the proposal recommends that the term "intrusive suite" be used (Article 10 (i)) where "several intrusive bodies form a larger unit approximately equivalent in rank to a 'group' in standard rock-stratigraphic terminology". Furthermore, each part of an intrusive suite does not require a formal name equivalent to a formation, and only the more uniform and larger intrusive bodies should be named; most smaller bodies should retain informal status.

*See p. 132, this volume.
**See p. 140, this volume.
***See p. 2, Generalized Stratigraphic Column.

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GEOCHRONOLOGY AND CHRONOSTRATIGRAPHY

In the 15-year period under consideration, geochronology and radiometric dating have come of age. Compared to the few random age determinations of Precambrian rocks from the St. Francois Mountains available in 1961, data were obtained on a more systematic basis and have become more reliable. The age of the St. Francois Mountains igneous province has been determined as approximately 1,500 m.y. old (Bickford and Mose, 1975). Bickford* gives a comprehensive review of geochronologic studies in Missouri, and discusses the relationship of the St. Francois Mountains igneous terrane to other 1,450- to 1,500-m.y.-old igneous rocks.

Various attempts have been made in recent years to subdivide Precambrian time into formal chronostratigraphic units on a global scale. Isotope dating of igneous and metamorphic rocks indicates several major diastrophic events of worldwide significance in Precambrian time. As yet, there is no international agreement on terminology or, for that matter, on the specific age brackets for chronostratigraphic units. James (1972) gives a comparison of current classification schemes in Canada, Australia, and the United States. He introduces an interim scheme adopted by the U.S. Geological Survey and used in the 1974 edition of the geologic map of the United States. According to this classification, four time units are distinguished in the Precambrian of the United States and are designated by letters of the alphabet. The St. Francois Mountains igneous province corresponds to Precambrian Y, the upper and lower geochronologic boundaries of which are set at 800 and 1,600 m.y., respectively.** It is to be emphasized that this scheme was intended for interim use only, in order to facilitate discussion of Precambrian rocks in the United States, and was not a proposal for worldwide classification.

Subdivision of the Precambrian should be done by integrating global geochronologic data with the natural stages of geological history as recorded by specific features (gross composition, tectonic structure, metamorphism, plutonism, and organic remains, where present) observed in the Precambrian rocks themselves. Salop (1972) emphasizes the worldwide occurrence of diastrophic cycles and points out many similarities in composition and tectonic style between Precambrian terranes formed during the same time intervals. The following quotes are taken from Salop (1972, p. 257) in order to illustrate the similarity of the St. Francois Mountains and the buried Precambrian of southeast Missouri to Precambrian terranes formed during the time interval between the Karelian (2,000 to 1,900 m.y.) and Grenville (1,100 to 1,000 m.y.) diastrophisms (Neoprotozoic Group of Salop).

> *"In many regions of the world within this interval, mainly about 1,600 to 1,700 m.y., the occurrence of peculiar plutonism of a platform or 'undeveloped' orogenic type is related to the formation of differentiated metal-bearing intrusions of gabbro-norites, labradorites, granophyre granites, alkaline syenites and, especially, intrusions of rapakivi-granites."*

> *"Many of the subdivisions are made up of subaerial volcanics of acid, less often of basic compositions, that alternate with red sandstones and conglomerates. Later comagmatic intrusions of rapakivi-granites and granophyres as well as sills and dikes of diabases are commonly associated with volcanics."* (Salop, 1972, p. 257).

The Subcommission on Precambrian Stratigraphy of the International Union of Geological Sciences was formed in 1966. Its principal task was the establishment of a unified stratigraphy for the Precambrian. The combined efforts of geochronologists and field geologists, including those currently working on the Precambrian of Missouri, will be required to reach this goal.

*See p. 149, this volume.
**See p. 2, Generalized Stratigraphic Column

GEOCHEMISTRY, ORE DEPOSITS, AND METALLOGENESIS

Trace-element analyses of the Precambrian rocks of Missouri so far have been largely of a reconnaissance nature (E.B. Kisvarsanyi, 1961; Malan, 1972; Ebens and Connor, 1972), or were part of other projects (G. Kisvarsanyi, 1966; Hansink, 1965; Davis, 1969). There is a definite lack in our understanding of the geochemical evolution of this igneous terrane and systematic data are needed to formulate ideas about the generation of its magmas.

The Precambrian of southeast Missouri is an important metallogenic province. Both historically and currently, iron ore is by far its most important commodity. Besides iron ore, current production from the Precambrian includes rare-earth-bearing phosphates, dimension stone, and roofing granules. In the past, Precambrian rocks were the source of marginal production of manganese, silver, tungsten, lead, and feldspar.

The geology and genesis of the Pilot Knob magnetite orebody, located in the central part of the St. Francois Mountains and a current producer of iron ore, are discussed by Wracher.*

In a comprehensive geochemical and petrological study of the magmatic iron-ore deposits of southeast Missouri (G. Kisvarsanyi, 1966; G. Kisvarsanyi and Proctor, 1967) the genetic links between the Precambrian igneous rocks and the ore deposits were investigated on the basis of the ferride-element geochemistry of the host rocks and ore minerals.

Studies of trace-element fractionation in selected rock types, initiated by G. Kisvarsanyi (1966), should be extended. The Precambrian metallogenesis of the region in the context of its petrogenesis and tectogenesis is discussed by G. Kisvarsanyi.**

Studies of the isotope geochemistry of the Precambrian rocks of the St. Francois Mountains igneous province (Mose, 1971; Wenner and Taylor, 1972) should be continued and extended. The origin of large volumes of rhyolitic ignimbrites is one of the problems of igneous petrology that has not yet been unequivocally resolved. Some workers have attributed their origin to large-scale melting of sialic crustal material, but there is some evidence that rhyolites of ancient shield areas may have been derived directly from a primitive mantle (McBirney, 1969). The rubidium and strontium isotopic composition of the rocks may offer clues to their origin.

The mineral-resource potential of Missouri's Precambrian basement, particularly that of its buried part, has not yet been thoroughly appraised. Deep exploration so far has been directed primarily toward areas of high magnetic anomaly in search of buried iron orebodies. The possibility of other types of mineralization exists. The need for increased efforts in basic geological research, geochemical and geophysical exploration, and development of new exploration concepts is emphasi'ed by G. Kisvarsanyi and E.B. Kisvarsanyi (in press).

REGIONAL STRUCTURE, GEOPHYSICS, AND REMOTE SENSING

No review of progress pertaining to studies of the Missouri Precambrian would be complete without reference to the insights gained on the structure of the basement through the combination of surface and subsurface geologic data and geophysical methods. As early as 1938, and almost exclusively from field geologic observations, Graves (1938) inferred the fundamental block-faulted pattern of Precambrian structures in southeast Missouri. Without identifying their precise boundaries, he referred to the St. Francois Mountains block and the Shannon County block and interpreted them as uplifts due to movements along Precambrian fault planes which were assumed to define their boundaries.

*See p. 155, this volume.
**See p. 164, this volume.

Regional geophysical surveys in Missouri began during the 1930's and resulted in the publication of a state ground-magnetic map and a state gravimetric map in 1943. During the 1940's, the U.S. Geological Survey, in cooperation with the Missouri Geological Survey and interested mining companies, started the aeromagnetic mapping program by 15-minute quadrangles in southeast Missouri, covering the St. Francois Mountains. During the 1960's the Missouri Geological Survey continued the aeromagnetic mapping program and extended it into central Missouri and parts of west and southwest Missouri.

Continuing air-photo coverage of the state by the U.S. Department of Agriculture, U.S. Geological Survey, and other federal, state, and private agencies served to provide visual imagery of the terrain and was very helpful in geologic mapping and structural interpretation. The development of high-altitude and space photography during the 1960's and 1970's (U-2 and Skylab flights) and of remote-sensing techniques (side-looking radar, or SLAR, imagery) further contributed to regional geologic studies by giving a bird's-eye view of large segments of the terrain, and led toward increasingly wider application of lineament analysis in regional structural investigations. The contribution of space-age technology to geologic studies culminated in 1972 with the launching of the first Earth Resources Technology Satellite (LANDSAT-1, formerly ERTS-1), which has continued to return a series of high-quality images of the Earth's surface from space for nearly three years. Electronic data acquisition from space has continued through the LANDSAT-2 satellite, which was launched in 1975.

Both conventional geophysical methods and remote-sensing techniques received application in regional interpretation and definition of basement structures in Missouri (H.J. Allen, 1969; W.H. Allen et al., 1973; Allingham, 1964; Baker, 1967; Beyer, 1969; Bissada, 1965; Erwin, 1968; Gillerman, 1968; Hayes, 1962; Lin, 1971; Mitchell, 1971; Segar, 1965; Tikrity, 1968; Zietz et al., 1966; and others). Geophysical data have been used in attempts to define the relationship between basement structures and mineralization (Allingham, 1966; Leney, 1964 and 1966). The distri-

bution of ore deposits and igneous intrusions in the context of regional structure has been discussed by Heyl (1972) and Snyder (1970). G. Kisvarsanyi and E.B. Kisvarsanyi (1976) integrated surface and sub-surface geologic data with geophysical and remote-sensing data and defined several major structural lineaments in the exposed and buried Precambrian basement of southeast Missouri. The relationship between structural lineaments and mineralization is discussed by G. Kisvarsanyi and E.B. Kisvarsanyi.* Investigations currently underway at the Geological Survey, Missouri Department of Natural Resources (NASA Contract NAS5-20937) utilize LANDSAT imagery in a statewide analysis of structural and ground patterns. As many of the major structural features identified on the imagery correspond to known or inferred basement structures, these investigations are expected to contribute to a better understanding of the Precambrian geology of Missouri.

Seismological studies of the deep crustal structure of Missouri are essentially studies of the physical properties and behavior of its Precambrian basement and underlying crustal layers to depths reaching the mantle. Data derived from these studies can contribute significantly to a regional crustal and tectonic interpretation of the Missouri Precambrian (Stewart, 1968, Phelan, 1969). Nuttli** summarizes the results of recent seismological investigations in Missouri with particular reference to crustal structure in southeast Missouri.

During the last 15 years a considerable amount of geophysical data (magnetic, gravity, and seismic, in order of abundance) has been obtained for Missouri that is pertinent to the structure and composition of its basement complex. Some of the transcontinental geophysical surveys of the Upper Mantle Project included parts of Missouri (Warren, 1968, Zietz and Kirby, 1968). However, interpretation of geophysical data in terms of and to supplement direct geologic data from drillholes and outcrop is generally lacking. Synthesis of all the geophysical studies in a regional tectonic analysis could be expected to provide solutions to some outstanding problems pertaining to the Precambrian geology of Missouri.

*See p. 174, this volume.
**See p. 184, this volume.

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PROPOSED STRATIGRAPHIC COLUMN FOR PRECAMBRIAN VOLCANIC ROCKS, WESTERN ST. FRANCOIS MOUNTAINS, MISSOURI

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INTRODUCTION

The St. Francois Mountains of southeast Missouri have been recognized for more than a century as an exhumed Precambrian terrane. The complex consists of acidic volcanic rocks and shallow granitic intrusions which represent the only extensive exposure of similar Precambrian igneous rocks extending 1,700 km from the Texas panhandle to southern Ohio. The St. Francois Mountains, structurally the core of the Ozark Uplift, form a number of hills, peaks, and irregular ridges which stand above lower-lying Paleozoic marine sediments. Many have investigated portions of the 900-km^2 region, but structural relationships of the igneous rocks were not well understood until R.E. Anderson (1962, 1970), J.E. Anderson, Jr. et al. (1969), Berry (1970), and Berry and Bickford (1972) recognized the spatial distribution of the layered volcanic rocks, the arcuate fault patterns, and the granitic intrustions which reveal the Taum Sauk Caldera. The recognition of the caldera in the western part of the region is only a beginning to the understanding of the entire St. Francois Mountains, an understanding which hopefully can be extrapolated along the entire volcanic belt.

Current investigators of the volcanic belt, although aware of each other's work, are not using a common nomenclature for the layered volcanic units. The purpose of this paper is to propose a unified stratigraphic column for the volcanic rocks in the western portion of the St. Francois Mountains, with names and formation descriptions, to assist current and future investigations of the region. The stratigraphic column is based on the work of numerous investigators, and in part upon lithologic, petrographic, and structural studies currently in progress by the writer. Details of these studies have not been

EDITOR'S NOTE: In order to assist the reader in locating the outcrop areas of the formations defined in the column, Berry's 1970 geologic map of the northeastern part of the Taum Sauk Caldera is reproduced in figure 2. The symbols on the map correspond to the legend of Berry (1970) and Berry and Bickford (1972) on the synoptic chart. The companion map, shown as figure 1, covers the central and western part of the Taum Sauk Caldera, and was prepared by Berry on the basis of heretofore unpublished maps of the Johnson Shut-ins quadrangle by him and J.E. Anderson. Figure 1 is based on field work during 1968-1970 and was supported by the Missouri Geological Survey. The two maps (figs. 1 and 2) are shown facing each other in order to convey their geographic relationship. Together, they depict the spatial distribution and the structural and stratigraphic relationships of the 14 formations mapped and defined in the area of the Taum Sauk Caldera in the western St. Francois Mountains.
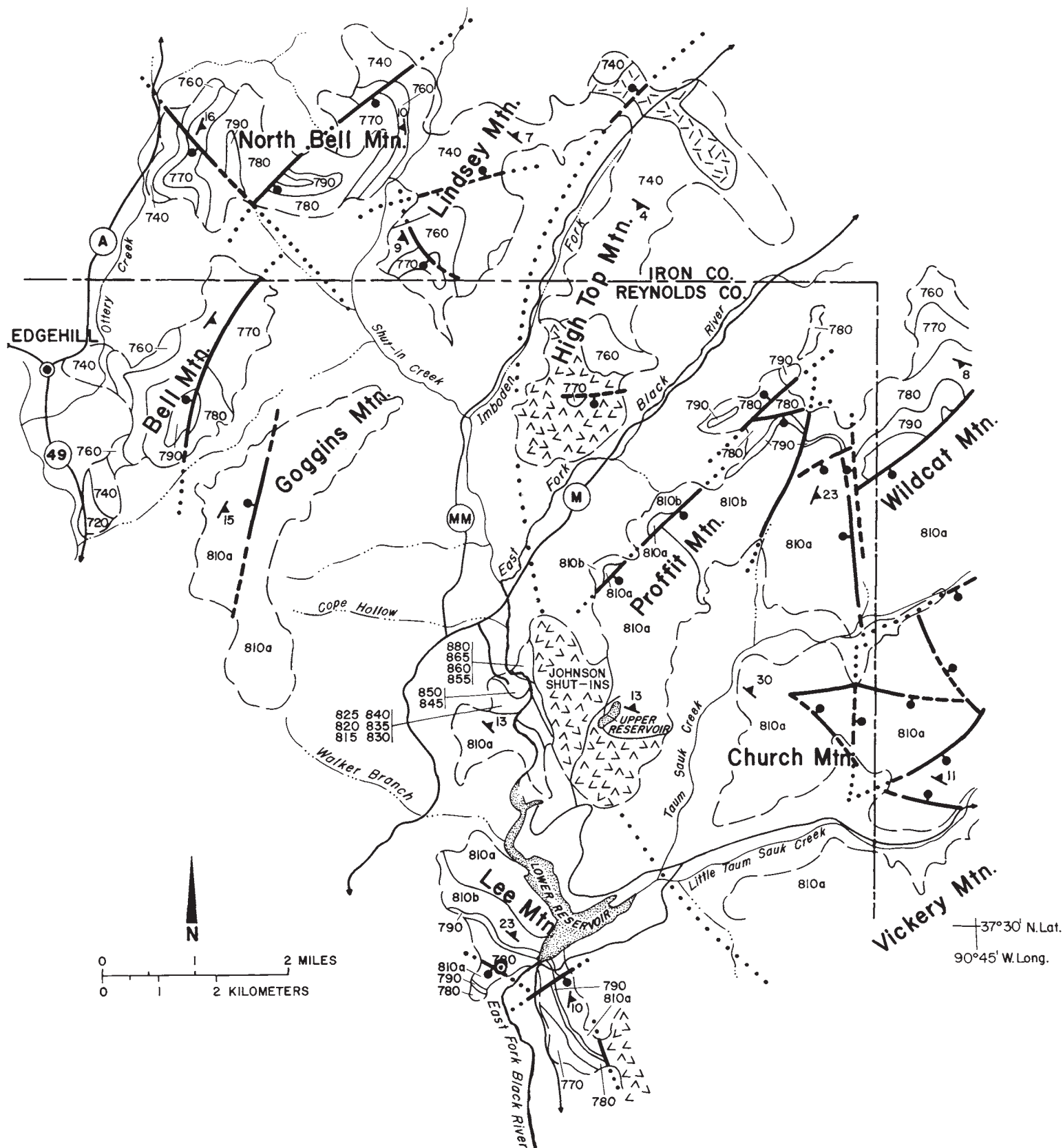
81

Figure 1

82   *Geological map of the western portion of the Taum Sauk Caldera, St. Francois Mountains, Missouri. See figure 2 (facing page) for legend.*
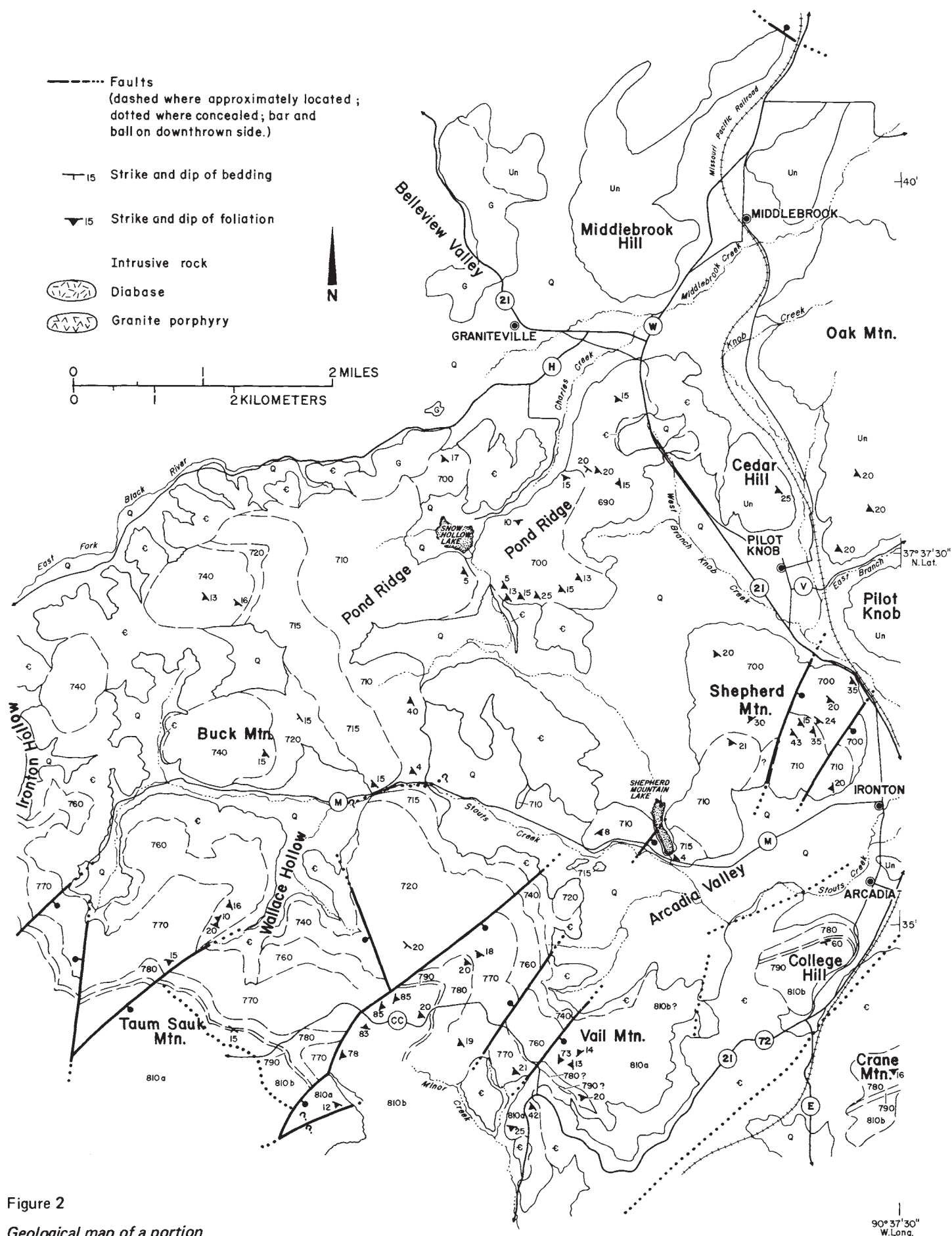
Figure 2

Geological map of a portion
of the Taum Sauk Caldera, St. Francois Mountains, Missouri.

included because of the limitations of the publication format, but a more comprehensive report is in preparation.

The proposed stratigraphic column attempts to combine the work of recent investigators into a sequence of 14 formations which constitute the layered volcanic rocks in the western part of the St. Francois Mountains. Individual formations,

consisting of ash-flow tuffs, air-fall tuffs, lava flows, or combinations of the preceding, were apparently deposited in a single episode of volcanic activity, since no sign of extensive erosion has been observed among them. The ejecta studied to date associated with the Taum Sauk Caldera are over 6 km thick and have a volume in excess of 3,000 km^3, ranking it with the world's most productive volcanoes.

RATIONALE FOR DEFINING AND NAMING UNITS

The writer approached the problem of naming and delineating individual volcanic units by reviewing the published literature and attempted to put together a stratigraphic column that, as far as possible, is in general agreement with the major papers about the region. Most of the delineation and naming has been derived from R.E. Anderson (1962, 1970), Berry (1970), Berry and Bickford (1972), Hayes (1961), and Tolman and Robertson (1969). The contributions of many other workers (Bonham, 1948; Dake, 1930; Graves, 1938; Johnson, 1961; Meyer, 1939; Murphy and Ohle, 1968; Snyder and Wagner, 1961; and Robertson, 1940) have been incorporated into the major works listed above.

Tolman and Robertson (1969) subdivided the volcanic rocks into two major groups on the basis of stratigraphic position and the $K_2O:Na_2O$ ratios. Their stratigraphic column was established before the regional structure was understood. The stratigraphic marker between the two major groups was the Ketcherside Tuff. In fact, Tolman and Robertson considered all bedded tuffs to be the Ketcherside. More recent work (R.E. Anderson, 1962, 1970; Berry, 1970; Berry and Bickford, 1972) reveals the occurrence of several bedded tuffs in a stack of conformably emplaced volcanic units.

Recognition of ash-flow tuffs and recognition of the layered structure of the Taum Sauk region (R.E. Anderson, 1962) were major discoveries in the understanding of the region. Later studies (J.E. Anderson

et al., 1969; Berry, 1970) verified the presence of ash-flow tuffs and the existence of the Taum Sauk Caldera.

Tolman and Robertson based the $K_2O:Na_2O$ classification upon only 38 chemical analyses of samples randomly collected from the entire St. Francois Mountains region (Hayes, 1959). Lipman et al. (1966) and Scott (1966) report $K_2O:Na_2O$ ratios which vary more within a single unit than the values Tolman and Robertson used to delineate their major groups. Based on the above evidence the writer believes the column as presented by Tolman and Robertson needs fundamental revision.

The writer has defined 14 formations in the Taum Sauk region. Individual formations are characterized by lithologic homogeneity, or homogenities if the formation is composed of several members. They are mappable at a scale of 1:24,000, and in most cases the formations are exposed along strike for at least several miles.

Three formations proposed in Johnson Shut-ins, however, are only exposed within the shut-ins. One might question giving these exposures formation status, but formalizing these excellent exposures as three distinct formations will greatly assist in their recognition elsewhere.

The proposed stratigraphic column is presented on the following four pages in the form of a synoptic chart. The 14 formations are arranged in order, beginning with the youngest, the Cope Hollow

TABLE 1
PROPOSED FORMAL STRATIGRAPHIC COLUMN FOR THE PRECAMBRIAN VOLCANIC ROCKS
IN THE WESTERN PART OF THE ST. FRANCOIS MOUNTAINS

FORMATION DESCRIPTION & TYPE SECTION	THICKNESS (m)	BERRY (1970) BERRY AND BICKFORD (1972)	TOLMAN AND ROBERTSON (1969)**	R.E. ANDERSON (1962)	R.E. ANDERSON (1970)	EXPOSURES & REMARKS
Cope Hollow Formation						
D — Maroon ash-flow tuff with 10% quartz and feldspar phenocrysts and lithophysae.	?		MB	Upper part of Johnson ash-flow and air-fall tuffs.	Upper part of tuff on Johnson Shut-ins	Exposed north of the swimming area of Johnson Shut-ins State Park. Consists of units 855, 860, 865, and 880 of Berry and Anderson (in preparation).
C — Dark-gray, cross-bedded air-fall tuff containing lithophysae and a basalt lava flow.	28					
B — Deep-maroon ash-flow tuff containing less than 5% quartz and feldspar phenocrysts.	5					
A — Black, cross-bedded air-fall tuff.	9					
SW¼, NW¼, sec. 16, T. 33 N., R. 2 E. Johnson Shut-ins Quadrangle, Missouri.						
Johnson Shut-ins Rhyolite						
Upper — Gray ash-flow tuff with 15-20% quartz and feldspar phenocrysts and abundant lithophysae.	27		Vh	Center part of Johnson ash-flow and air-fall tuffs.	Center part of tuff of Johnson Shut-ins.	Exposed in the swimming area of Johnson Shut-ins State Park. Composed of units 845 and 850 of Berry and Anderson (in preparation).
Middle — Cross-bedded, water-deposited tuff filling a former stream channel in the lower member.	0 - 5					
Lower — Maroon ash-flow tuff with 15-20% quartz and feldspar phenocrysts and abundant lithophysae.	23					
NW¼, SW¼, sec. 16, T. 33 N., R. 2 E. Johnson Shut-ins Quadrangle, Missouri.						
Proffit Mountain Formation						
F — Gray, cross-bedded air-fall tuff.	7		Vh	Lower part of Johnson ash-flow and air-fall tuffs.	Lower part of tuff of Johnson Shut-ins.	Exposed at the south end of Johnson Shut-ins. Composed of units 815, 820, 825, 830, 835, and 840 of Berry and Anderson (in preparation).
E — Red, cross-bedded air-fall tuff.	15					
D — Rose-gray ash-flow tuff containing 30% phenocrysts of quartz and feldspar.	56					
C — Deep-maroon ash-flow tuff with 20% quartz and feldspar phenocrysts.	39					
B — Red or gray, cross-bedded air-fall tuff.	5					
A — Red ash-flow tuff with 25% quartz and feldspar phenocrysts, vividly lineated.	16					
SW¼, sec. 16, T. 33 N., R. 2 E. Johnson Shut-ins Quadrangle, Missouri.						

TABLE 1 *(continued)* . . . . .

FORMATION DESCRIPTION & TYPE SECTION	THICKNESS (m)	BERRY (1970) BERRY AND BICKFORD (1972)	TOLMAN AND ROBERTSON (1969)**	R.E. ANDERSON (1962)	R.E. ANDERSON (1970)	EXPOSURES & REMARKS
Taum Sauk Rhyolite Red to dark-maroon ash-flow tuff containing up to 30% phenocrysts of alkali feldspar and quartz; fiamme may or may not be present. Sec. 15, T. 33 N., R. 2 E. Johnson Shut-ins Quadrangle, Missouri.	>1000*	810a	Vh on Hogan, Lee, Goggins, Proffit, Wildcat, and Taum Sauk Mountains.	Taum Sauk Mountain ash flows.	Tuff of Taum Sauk Mountain.	Exposed on Hogan, Lee, Goggins, Proffit, Wildcat, and Taum Sauk Mountains and may be present in several places to the south and east of the Taum Sauk Mountain region.
Royal Gorge Rhyolite Red to maroon lava flow containing 5% phenocrysts of quartz and alkali feldspar; vividly banded red and white in many localities. *Massive* — S½, sec. 14, T. 33 N., R. 3 E. Ironton Quadrangle, Missouri. *Banded* —SE¼, SE¼, sec. 3, T. 33 N., R. 3 E. Ironton Quadrangle, Missouri.	0 - 700	810b	Vh on Lee, Proffit, Taum Sauk, and Crane Mountains; Vs and MB on College Hill; Vs, Vh, and MBr in the region of the Royal Gorge.	Russell Mountain rhyolite where banded; undifferentiated felsite where unbanded.	Intrusive rhyolite.	Exposed on Lee, Proffit, Taum Sauk, Russell, and Crane Mountains, in the Royal Gorge, and on College Hill. A discontinuous lava flow fits the regional structure much better than an intrusive rhyolite. Named for the exposures in the Royal Gorge.
Bell Mountain Rhyolite Maroon to dark-maroon air-fall tuff containing lapilli and a 2- to 5-m-thick zone containing lithophysae from a few mm to nearly 25 cm in diameter. SE¼, NE¼, sec. 2, T. 33 N., R. 1 E. Edgehill Quadrangle, Missouri.	25	790	Vh on Lee, Bell, North Bell, and Wildcat Mountains; Vs on Taum Sauk, Russell and Crane Mountains; MB on College Hill.	Bell Mountain ash flows.	The upper part of Unit D, tuff of Stouts Creek.	Exposed on Lee, Bell, North Bell, Wildcat, Taum Sauk, Russell, and Crane Mountains and on College Hill. Named for the excellent exposures along the crest of Bell and North Bell Mountains.
Wildcat Mountain Rhyolite Deep-maroon ash-flow tuff containing 5-10% quartz and feldspar phenocrysts and many white stringers of microcrystalline quartz and feldspar. S½, NE¼, sec. 6, T. 33 N., R. 3 E. Johnson Shut-ins Quadrangle, Missouri.	90	780	Vh on Lee, Bell, North Bell, and Wildcat Mountains; Vs on Taum Sauk, Russell, and Crane Mountains; MB on College Hill.	Shut-ins fragmental ash flow.	Includes all but the upper part of Unit D, tuff of Stouts Creek.	Exposed on Lee, Bell, North Bell, Wildcat, Taum Sauk, Russell, and Crane Mountains and on College Hill. Named after exposures along the north slope of Wildcat Mountain.
Russell Mountain Rhyolite Brick-red to dark-maroon ash-flow tuff with abundant, large fiamme and 2-5% white feldspar phenocrysts. NE¼, SW¼, sec. 2, T. 33 N., R. 3 E. Ironton Quadrangle, Missouri.	300	770	Vh on Lee, Bell, and North Bell Mountains; V on Lindsey and High Top Mountains; Vs on Wildcat, Taum Sauk, Russell, and Vail Mountains.	Shut-ins banded ash flow.	Unit C, tuff of Stouts Creek.	Exposed on Lee, Bell, North Bell, Lindsey, High Top, Wildcat, Taum Sauk, Russell, and Vail Mountains. Named the Russell Mountain Rhyolite because of the large exposures on the east slope of Russell Mountain.

*Total thickness is unknown because the unit is not exposed continuously through its total thickness or is faulted.

TABLE 1 *(continued)* . . . . .

FORMATION DESCRIPTION & TYPE SECTION	THICKNESS (m)	BERRY (1970) BERRY AND BICKFORD (1972)	TOLMAN AND ROBERTSON (1969)**	R.E. ANDERSON (1962)	R.E. ANDERSON (1970)	EXPOSURES & REMARKS
Lindsey Mountain Rhyolite Violet-gray, blackish, or light-maroon ash-flow tuff with 5-20% quartz and alkali feldspar phenocrysts; it has conchoidal fracture. S½, NW¼, sec. 4, T. 33 N., R. 3 E. Ironton Quadrangle, Missouri.	500-700	760	MB on Bell and North Bell Mountains; Vh on North Bell Mountain; V on Lindsey and High Top Mountains; Vs on the north slope of Taum Sauk, Vail, Russell, and Wildcat Mountains.	Lindsey Mountain ash flow.	Unit B, tuff of Stouts Creek.	Exposed on Bell, North Bell, Lindsey, High Top, Wildcat, Taum Sauk, Russell, and Vail Mountains. Name based on R.E. Anderson (1962).
Ironton Rhyolite Dark-maroon to black ash-flow tuff containing 5-15% phenocrysts of quartz and alkali feldspar; it has conchoidal fracture. SW¼, sec. 33, T. 34 N., R. 3 E. Ironton Quadrangle, Missouri.	340*	740	Vs on Buck and Russell Mountains and on Pond Ridge; V on North Bell, High Top, and Lindsey Mountains.	Lindsey Mountain composite ash flows; High Top bedded tuff.	Unit A, tuff of Stouts Creek.	Exposed on Russell, High Top, North Bell, Lindsey, and Buck Mountains. The label "Stouts Creek" should be reserved for the excellent exposures in Stouts Creek Shut-ins. R.E. Anderson (1962) places an air-fall tuff above this unit. This tuff is discontinuous and is considered part of the Ironton Rhyolite.
Buck Mountain Shut-ins Formation Sequence of black, andesitic lava flows containing white plagioclase phenocrysts; interbedded with bedded air-fall tuffs and at least one rhyolitic ash-flow tuff. SE¼, sec. 33, T. 34 N., R. 3 E. Ironton Quadrangle, Missouri.	80-1000	720	MB low on north flank of Russell Mountain; Vs high on north flank of Russell Mountain; Vs in Buck Mountain Shut-ins and on Pond Ridge; V on High Top, Lindsey, and North Bell Mountains.	Buck Mountain andesite flows and tuffs (lower) and Buck Mountain bedded tuff (upper); also, the base of the Lindsey Mountain composite ash flows.	The tuff of Mill Creek, tuff and lava flows of Lake Springs, and the base of tuff of Stouts Creek, Unit A.	Exposed on Russell, High Top, North Bell, and Lindsey Mountains, on Pond Ridge, and in Buck Mountain Shut-ins. Because rhyolitic air-fall tuffs occur above, between(?), and below the andesitic flows and air-fall tuffs, it makes sense to combine all the members into a single formation. Named for location of excellent exposure.
Pond Ridge Rhyolite Dark-maroon to grayish ash-flow tuff containing up to 20% white to pinkish feldspar phenocrysts, a few quartz phenocrysts, and many large, reddish fiamme. NE¼, NW¼, sec. 3, T. 33 N., R. 3 E. Ironton Quadrangle, Missouri.	130	715	MB undifferentiated on Russell Mountain; Vs on Pond Ridge; Vs at Shepherd Mountain Lake.	Upper part of the Cedar Bluff felsite.	Upper part of undifferentiated felsite.	Exposed at Shepherd Mountain Lake dam, on Pond Ridge (W and NW of Pilot Knob), on the north slope of Russell Mountain, and on the ridge between Russell Mountain and Pond Ridge. Name based on R.E. Anderson (1962).
Cedar Bluff Rhyolite Brownish-maroon to grayish ash-flow tuff containing 25-50% white plagioclase phenocrysts of two types; perthitic and polysynthetically twinned larger phenocrysts are rounded; no snowflake texture. NE¼, NW¼, sec. 3, T. 33 N., R. 3 E. Ironton Quadrangle, Missouri.	580	710	MBp on Shepherd Mountain; MB near Cedar Bluff School; Vs on Pond Ridge; Vs on the southwestern edge of Shepherd Mountain.	Cedar Bluff rhyolite where it occurred in study area.	Upper part of undifferentiated felsite.	Exposed on the southern slopes of Shepherd Mountain; along highway M, 2 mi. west of Ironton (just east of Cedar Bluff School); on Pond Ridge (W and NW of Pilot Knob); and on the northerly extension of Russell Mountain.

*Total thickness is unknown because the unit is not exposed continuously through its total thickness or is faulted.

TABLE 1 *(continued)* . . . . .

FORMATION DESCRIPTION & TYPE SECTION	THICKNESS (m)	BERRY (1970); BERRY AND BICKFORD (1972)	TOLMAN AND ROBERTSON (1969)**	R.E. ANDERSON (1962)	R.E. ANDERSON (1970)	EXPOSURES & REMARKS
Shepherd Mountain Rhyolite Brick-red to dark-maroon ash-flow tuff containing white to slightly pink plagioclase phenocrysts and many fiamme; it generally has well-developed snowflake texture and has neither quartz nor perthitic plagioclase phenocrysts. Sec. 31, T. 34 N., R. 4 E. Ironton Quadrangle, Missouri.	600	700	MBp on Shepherd Mountain; Vs on Pond Ridge.	Not included in study area.	Lower undifferentiated felsite.	A distinctive unit exposed on Shepherd Mountain (NW of Ironton) and Pond Ridge (W and NW of Pilot Knob); petrographically very different from the rock of Pilot Knob; named after mountain having extensive exposure of the rock.

**Explanation of symbols in the Tolman and Robertson (1969) column:

V   Van East Group
Vh   Hogan Mountain Rhyolite
Vs   Stouts Creek Rhyolite
MB   Middlebrook Group
MBp   Pilot Knob Felsite
MBr   Royal Gorge Rhyolite

Formation, and ending with the oldest, the Shepherd Mountain Rhyolite. For each formation, a brief lithologic description, thickness, and location of the type section are given. The synoptic chart also provides for a comparison between terminologies used in existing literature of the area.

CONCLUSIONS

The proposal of 14 formations in the stratigraphic column of the western part of the St. Francois Mountains resulted from an extensive search of the existing literature, four summers' mapping in the field, and the study of over 500 thin sections from samples collected in the area. Studies currently in progress by the writer and others will extend the column to include the volcanic rocks of the Graniteville, Lake Killarney, Iron Mountain Lake, and southeastern Ironton 7½-minute quadrangles. Understanding of the structure and petrology of the western St. Francois Mountains area is very useful in the study of the entire volcanic belt, which extends in the subsurface from southern Ohio to the Texas Panhandle. The proposed column is an attempt to organize our present knowledge into a form that hopefully may be extended to include the entire belt of Precambrian volcanic rocks.

ACKNOWLEDGMENTS

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RHYOLITIC ASH-FLOW TUFFS AND INTERCALATED VOLCANICLASTIC TUFFACEOUS SEDIMENTARY ROCKS AT JOHNSON SHUT-INS, REYNOLDS COUNTY, MISSOURI

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INTRODUCTION

The rhyolitic ash-flow tuffs and intercalated volcaniclastic sedimentary rocks exposed at Johnson Shut-ins are part of the volcanic roof of the St. Francois Mountains batholith. The batholith has been interpreted as a relatively thin, sheet-like, shallow plutonic mass whose magmas have intruded their own ejecta. The stratigraphy of the volcanic rocks in the western part of the St. Francois Mountains is well understood due to detailed mapping by Berry (1970), but extension of this stratigraphy to other parts of the area is essential in gaining full understanding of the Precambrian geology of the St. Francois Mountains.

At Johnson Shut-ins, the East Fork of the Black River has cut through and exposed approximately 650 m of ignimbrites and intercalated volcaniclastic sedimentary rocks (fig. 1). Because the rocks dip at about 15° to the northeast and strike normal to the valley, it is possible to investigate an uninterrupted sequence of Precambrian volcanic rocks. The rocks are undeformed and unmetamorphosed, although devitrification has occurred over the great span of time since their emplacement. Preserved in incredible detail are the textures and features typical of their pyroclastic origin: fiamme, or flame-like, compacted pieces of pumice; shards and three-pronged splinters formed by the comminution of glass bubbles; lithic fragments; and pisolites. A distinct zonation has been impressed upon the rocks due to the sequence of events during eruption and subsequent crystallization.
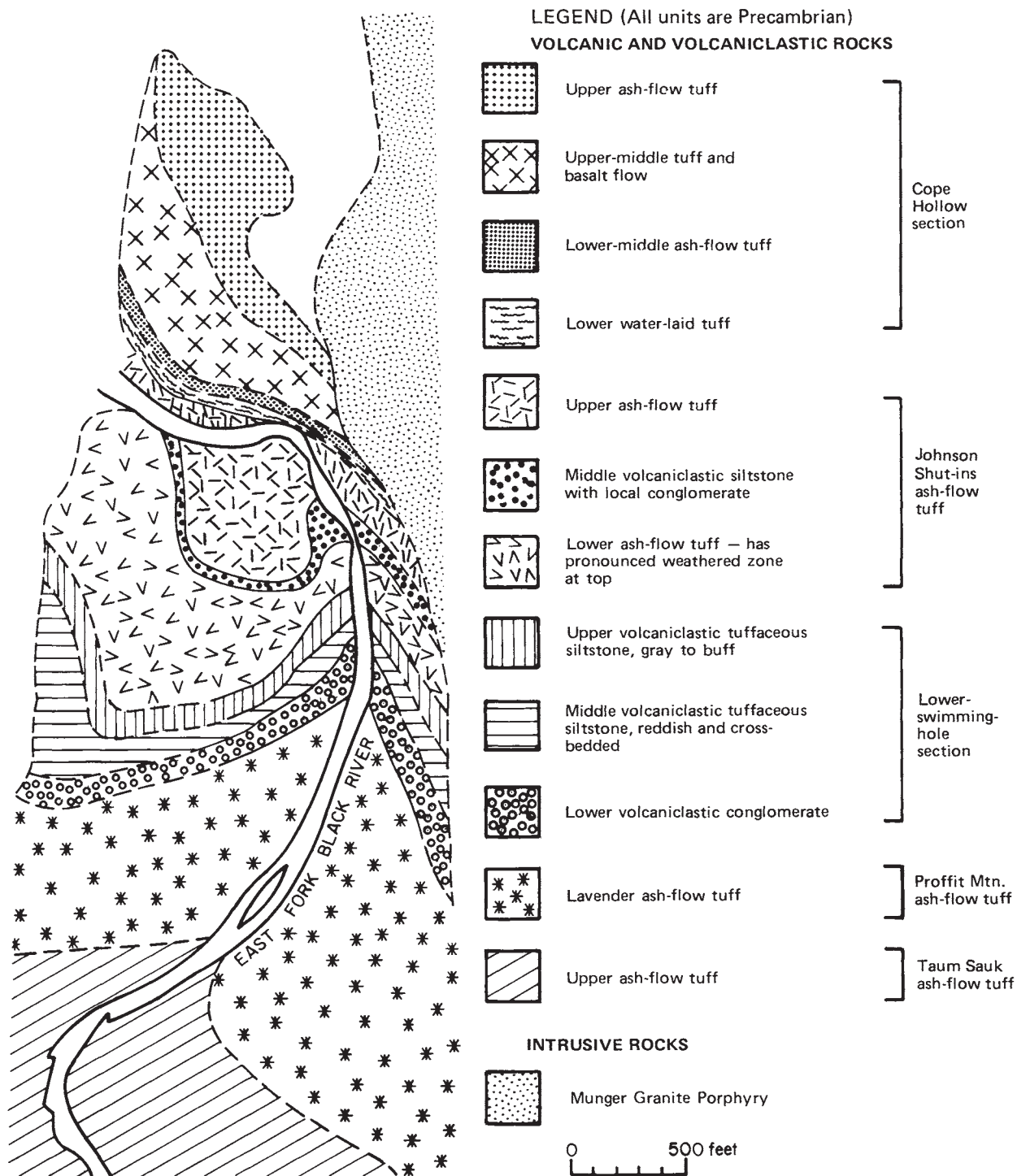
LEGEND (All units are Precambrian)
VOLCANIC AND VOLCANICLASTIC ROCKS

Upper ash-flow tuff

Upper-middle tuff and basalt flow

Lower-middle ash-flow tuff

Lower water-laid tuff

} Cope Hollow section

Upper ash-flow tuff

Middle volcaniclastic siltstone with local conglomerate

Lower ash-flow tuff — has pronounced weathered zone at top

} Johnson Shut-ins ash-flow tuff

Upper volcaniclastic tuffaceous siltstone, gray to buff

Middle volcaniclastic tuffaceous siltstone, reddish and cross-bedded

Lower volcaniclastic conglomerate

} Lower-swimming-hole section

Lavender ash-flow tuff

} Proffit Mtn. ash-flow tuff

Upper ash-flow tuff

} Taum Sauk ash-flow tuff

INTRUSIVE ROCKS

Munger Granite Porphyry

0   500 feet

EAST FORK BLACK RIVER

Figure 1

Geological map of Johnson Shut-ins area, Reynolds County, Missouri. Geology by A.W. Berry and E.L. Blades.

A measured stratigraphic section (fig. 2) through the units exposed in the shut-ins has been compiled and is based both upon observations made in the field during the summer of 1975 and upon petrographic study now in progress. The nomenclature used in this paper is not formal; it is merely working terminology.

The ash-flows of Johnson Shut-ins display the zonations and characteristic features described by investigators of modern flows. Given the age of these rocks, they are indeed noteworthy for their preservation of detail. As the Johnson Shut-ins are by far the best exposure of ignimbritic tuffs in the St. Francois Mountains, they are extremely significant. Perhaps of equal interest is the history of weathering, transportation and redeposition, as recorded by the intercalated volcaniclastic sedimentary units. The Johnson Shut-ins rocks will act as the prototype for a model in the interpretation of other less-well-exposed volcanic sequences in the St. Francois Mountains.

REVIEW OF ASH-FLOW TUFF CONCEPT AND TERMINOLOGY

The concept that ash-flow tuffs are emplaced by an explosive expulsion of gases, viscous liquids, and pyroclastic debris stems from the eyewitness accounts of the eruptions in 1902 of Mts. Pelée and LaSoufrière in the West Indies. As described by Anderson and Flett (1903) and LaCroix (1904), the eruptions consisted not only of viscous-flowing magma, but also, more notably, of incandescent clouds of turbulent volatiles, ash, and solid material which avalanched at tremendous velocities from the vent. Perret (1935) supported this description in his report of the 1929-1932 eruptions of Mt. Pelée. Fenner (1923) examined the deposits of the 1912 eruptions of Mt. Katmai in the Valley of Ten Thousand Smokes and concluded that they were emplaced by such a "nuée ardente", that is, a "fiery cloud". He theorized that a rapidly moving, gas-charged mass would cause the more solid constituents to be suspended within the cloud, which could therefore flow and spread much like a liquid.

Once this mechanism for rapid gaseous transport of pyroclastic debris was recognized, more and more investigators reported the existence of initially puzzling volcanic deposits which fitted the nuée ardente eruptive model. Marshall (1932, 1935) described a widespread rhyolitic sheet in New Zealand which exhibited bent, contorted, and flattened pumice fragments and shards. He reasoned that this volcanic debris had been deposited while very hot and, due to the gaseous nature of the nuée ardente, heat had been retained after the mass came to rest. If another flow were deposited immediately on top of the still-hot first flow, the malleable plastic particles of the first flow would be compressed and welded by the weight of the overlying flow.

Understanding of ash flows and their emplacement was further advanced through works by Smith (1960a, 1960b) and Ross and Smith (1961). They reviewed and defined the characteristics of ash-flow tuffs, described criteria for their recognition, defined specific terms, and accentuated the importance of zones within individual deposits. Zonation of ash-flow tuffs is helpful in the interpretation and classification of these rocks.

The most commonly used terminology of ash-flow tuffs is reviewed below for the reader's convenience. It is adapted from Smith (1960a) and Ross and Smith (1961).

ASH FLOW — A turbulent mixture of gas and pyroclastic materials, predominantly ash, that moves rapidly across the ground surface; the individual depositional unit of an ash-flow-tuff accumulation, corresponding to the deposit resulting from the passage of one nuée ardente.

ASH-FLOW SHEET — A sheet-like unit or group of units which are of ash-flow origin.

WELDED TUFF — A body of rock which has vitric particles with some degree of cohesion because at the time of deposition they were hot and plastic.
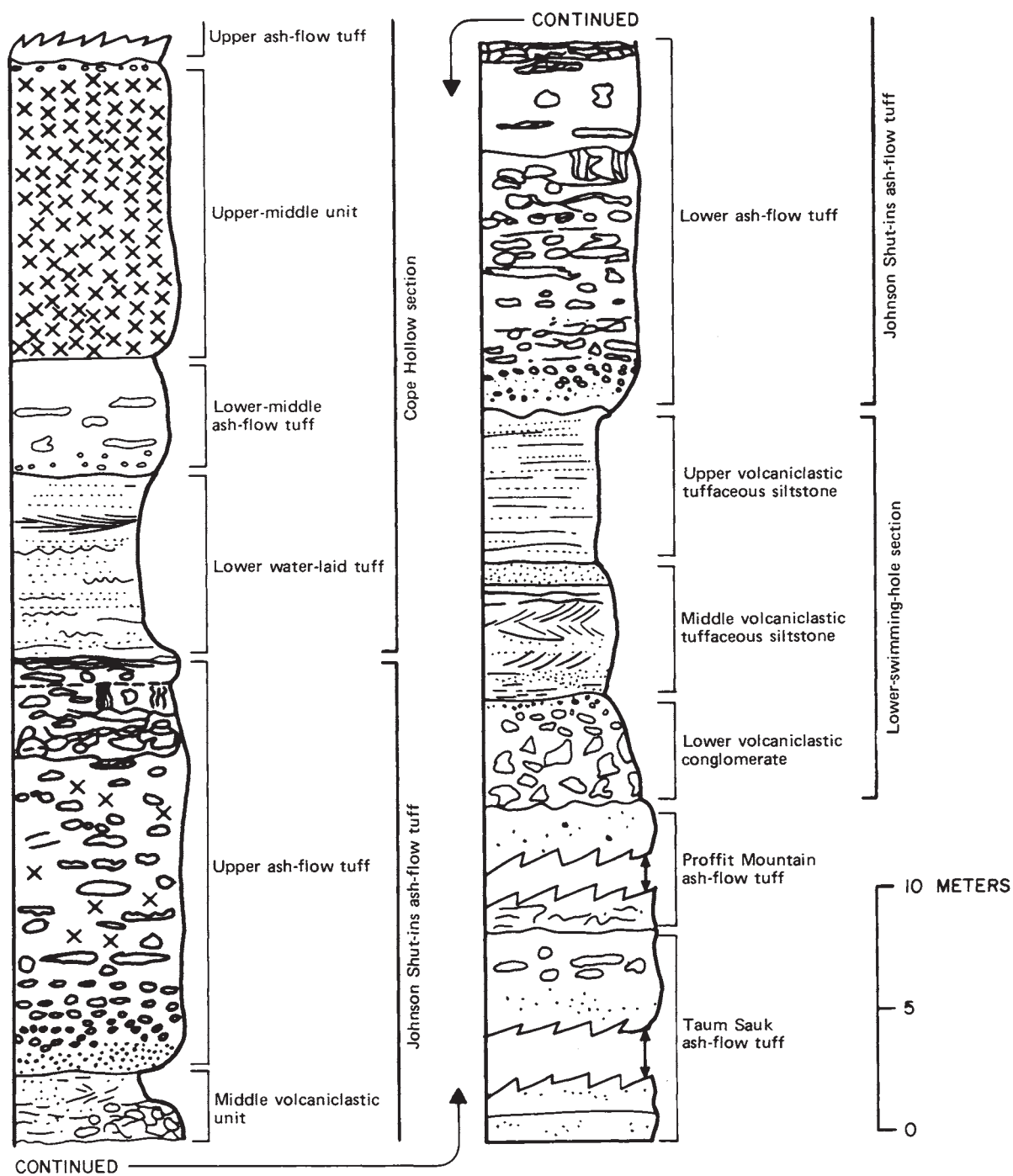
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Figure 2

Measured stratigraphic section of the units exposed in Johnson Shut-ins; terminology is informal.

WELDED TUFF —

(continued . . . . .)

*This type of tuff contrasts with a "fused tuff",
whose particles are deformed by heat applied after
original cooling, as by an overlying lava flow or
an intrusive body.*

*COOLING UNIT — A single or multiple ash-flow
deposit which has cooled continuously; that is,
no one part of the deposit had cooled completely
before another part was emplaced upon it.*

*SIMPLE COOLING UNIT — A cooling unit that has
had an essentially uninterrupted cooling history.*

*COMPOUND COOLING UNIT — A cooling unit
which has different characteristics than those of
a simple cooling unit because the time intervals
between successive ash flows were too great to
readjust to a simple cooling gradient.*

*COMPOSITE SHEET — An ash-flow sheet that
grades laterally from one cooling unit into two
or more.*

DESCRIPTION OF THE UNITS FROM FIELD AND PETROGRAPHIC EXAMINATION

Discussion of the Johnson Shut-ins area rocks begins
with the volcaniclastic sedimentary rocks informally
referred to as the lower-swimming-hole section (fig.
2). However, two thick ash-flow-tuff units, the
Proffit Mountain and the Taum Sauk, underlie this
section. They will not be considered in detail in
this paper. Reconnaissance mapping has shown them
to be essentially typical ash flows and very similar
to the better-exposed flows of the shut-ins.

The Taum Sauk ash-flow tuff* is red-maroon, with
dense, very fine-grained, vitreous matrix and approxi-
mately 30 percent alkali-feldspar phenocrysts. A
fragmented upper unit displays abundant fiamme
and lithic fragments. An intercalated tuffaceous
siltstone separates two major ash flows.

Overlying the Taum Sauk is a lavender ash-flow tuff,
the Proffit Mountain.** It, too, has a dense, fine-
grained, vitreous matrix, with 25 percent alkali-
feldspar and quartz phenocrysts. The middle section
is fragmental. Approximately 0.5 m of weathered
ash flow appears at the top of the formation.

LOWER-SWIMMING-HOLE SECTION***

LOWER VOLCANICLASTIC CONGLOMERATE

This unit consists of angular to subrounded clasts
ranging from 0.5 cm to 20 cm in average diameter

(pl. 1, n. 2). The clasts are of older ash-flow tuff,
in a matrix of fine ash and silt. The unit displays
crude graded bedding.

MIDDLE VOLCANICLASTIC TUFFACEOUS SILTSTONE

Overlying the 5-m-thick conglomerate is approximately
5 m of a dense, reddish, fine-grained, tuffaceous silt-
stone. This member is laminated, commonly cross-
bedded (pl. 1, n. 1), and displays coarser, more-contorted
units which may be due to slump and roll, and scalloped
features believed to be curled-up mud-crack polygons
(pl. 1, n.5). Rarely, the fine laminae have been depressed
by overlying pebbles (pl. 1, n. 3). The distinctly particu-
late nature of a sedimentary siltstone is unmistakably
exhibited in thin section (pl. 2, n. 1). Alteration to
epidote is common.

UPPER VOLCANICLASTIC TUFFACEOUS SILTSTONE

The uppermost unit of the lower-swimming-hole section
is a 7-m-thick sequence of gray and buff volcaniclastic
siltstone. In this unit, discontinuous, buff, sandy lenses
alternate with very fine-grained, uniform, gray laminae
(pl. 1, n. 6). The bottom part of this unit has very few
buff, sandy lenses, but their frequency increases upward
until they are in even proportion to the finer-grained
laminae.

The presence of this sedimentary sequence in the lower-
swimming-hole section indicates a period of time

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*Taum Sauk Rhyolite in Berry's proposed stratigraphic column, p. 85, this volume.
**Corresponds to lower part of Berry's Proffit Mountain Formation, p. 85, this volume.
***Corresponds to upper part of Berry's Proffit Mountain Formation, p. 85, this volume.

PLATE 1

Sedimentary features in the lower swimming hole section.
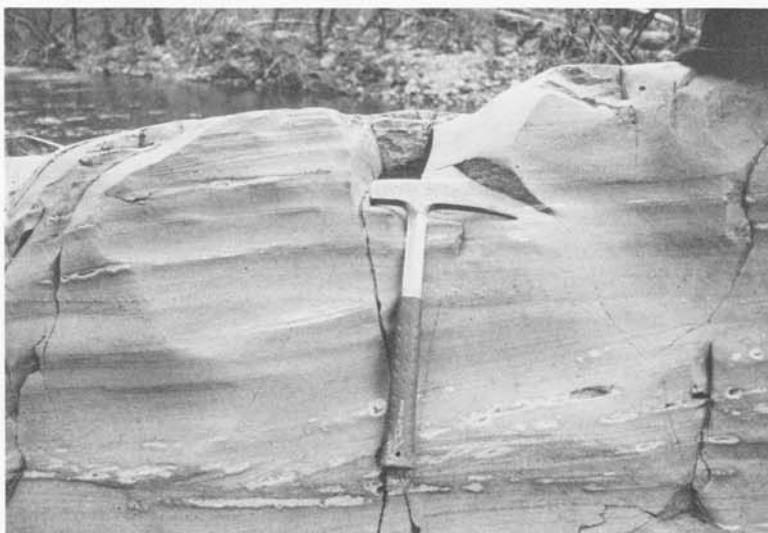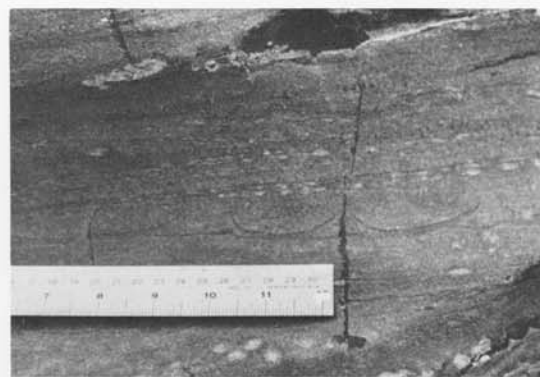

FIG. I

FIG 4

FIG. 2 — 3 INCHES
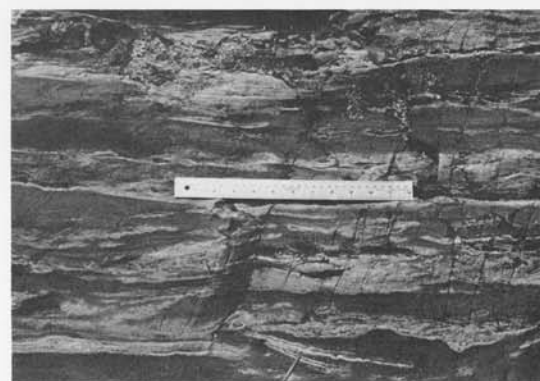

FIG. 5 — 3 INCHES

FIG. 3

FIG. 6 — 10 INCHES

between eruptions of ignimbrites, presumably a time of volcanic quiescence or dormancy during which erosive forces were dominant.

JOHNSON SHUT-INS ASH-FLOW TUFF*

LOWER ASH-FLOW TUFF

The unit as a whole is a dense, vitreous, red ash-flow tuff, which overlies the lower-swimming-hole section. The contact (pl. 1, n. 4) is fairly conformable and may be seen at the western end of the base of what is called the "Diving Cliff."

It is possible to divide this unit into zones based upon degree of compaction and welding and upon features which appear in certain regions within the flow. It shows an upward gradation from a loose, relatively uncompacted zone at the base of the flow, to a very densely compacted, welded zone, to a zone of quite uncompacted tuff at the top. Crystallization from the vapor phase is related to the zonation. Coarse quartz intergrown with feldspar, and occasionally with muscovite (pl. 2, n. 2), is conspicuous in pore spaces, hence is associated with the relatively uncompacted zones at the base and the top where lithophysae occur.

The lower ash-flow tuff is mineralogically quite simple, consisting of euhedral, unmixed alkali-feldspar phenocrysts; plagioclase-feldspar phenocrysts twinned by the albite law; and euhedral quartz phenocrysts which are partially resorbed and embayed from reaction with the melt (pl. 2, n. 3). The matrix consists of ash and shards in the relatively uncompacted zones, but in the denser, more-welded middle zone what was initially glass has now devitrified to a matrix of intergrown microcrystalline quartz and feldspar (pl. 2, n. 4). Minor muscovite is associated with areas of vapor-phase crystallization, and secondary calcite occasionally fills some of the lithophysal voids. Some very altered, euhedral pyroxene crystals are found in the lower parts of the flow, and in the upper parts what are probably altered fayalite phenocrysts (pl. 2, n. 5) are very abundant. Magnetite and hematite occur both as phenocrysts and as oxidation stain.

As might be expected, the lower ash-flow tuff is uncompacted at the base and approximately 1 m above the contact is marked by the appearance of

Fig. 1. Cross-bedding in the middle tuffaceous siltstone.

Fig. 2. Angular to subrounded clasts of an older ash-flow tuff in the conglomerate.

Fig. 3. Finely laminated tuffaceous siltstone beds depressed by overlying pebbles.

Fig. 4. Upper contact of lower swimming hole section (below) with overlying Johnson Shut-ins ash-flow tuff (above).

Fig. 5. Scalloped features believed to be curled-up mudcrack polygons in the middle tuffaceous siltstone.

Fig. 6. Discontinuous sandy lenses alternating with fine-grained, uniform gray laminae in the upper tuffaceous siltstone.

*Johnson Shut-ins Rhyolite in Berry's proposed stratigraphic column, p. 85, this volume.

Figure 3
Pisolites resemble spherulite on exposed surfaces of Johnson Shut-ins ash-flow tuff.

abundant spherical objects about 3 to 5 mm in diameter. In the field these objects appear to be spherulites (fig. 3), but in thin section they are clearly seen to be accretionary lapilli or pisolites composed of ash and shards (fig. 4). The pisolites are believed to have agglomerated in midair during eruption and then to have fallen like a rain of hail to become incorporated in the gaseous cloud. As they were composed of hot, malleable material, they were easily shaped into little spherical clusters much as a snowball assumes a spherical shape with a rolling descent down a snowy hill.

The pisolites are very abundant and densely packed near the base of the flow; however, they are very round, their lack of deformation further indicating the uncompacted nature of this lowest zone. Many of the pisolites show radial devitrification textures in their central parts (fig. 5). Where pore space occurs (as in regions normally unfilled by a packing of spheres), a granular mosaic of intergrown anhedral quartz and feldspar appears and commonly partially rims individual pisolites. These rims are believed to be minerals crystallized from the vapor phase.

Fig. 1. The middle siltstone of the lower swimming hole section exhibits particulate (clastic) features characteristic of sedimentary rocks.

Fig. 2. Coarse quartz intergrown with feldspar and muscovite (acicular crystals in upper central part of the picture) related to vapor-phase crystallization in uncompacted zone in the Johnson Shut-ins ash-flow tuff. Crossed nicols.

Fig. 3. Phenocrysts of alkali feldspar (rectangular), plagioclase (twinned), and partially resorbed quartz (upper left corner) in lower part of Johnson Shut-ins ash-flow tuff. Note good preservation of shards in the matrix.

Fig. 4. Devitrified matrix of intergrown microcrystalline quartz and feldspar (left), anhedral intergrowth of coarser-grained quartz and feldspar of the vapor-phase crystallization (center), and altered plagioclase phenocryst (right) in the Johnson Shut-ins ash-flow tuff. Crossed nicols.

Fig. 5. Altered fayalite phenocryst in Johnson Shut-ins ash-flow tuff.

Fig. 6. Deformation of shards and fiamme around phenocrysts and lithic fragments in welded zone of Johnson Shut-ins ash-flow tuff.

Fig. 7. Fiamme (right) and resorbed quartz phenocryst (upper left) in fragmental zone of Johnson Shut-ins ash-flow tuff.

PLATE 2

Photomicrographs showing textural and miner-
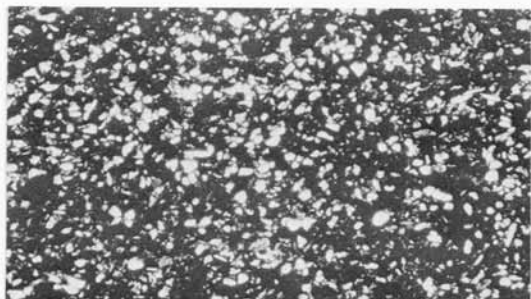alogical features in the Johnson Shut-ins section.

FIG. 1
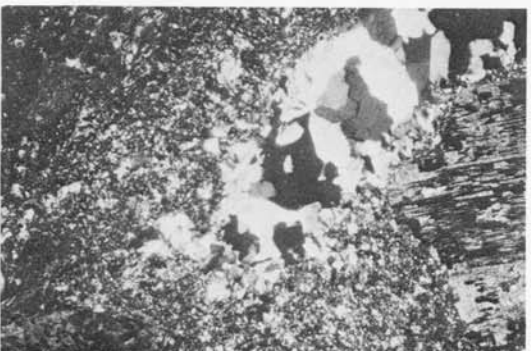

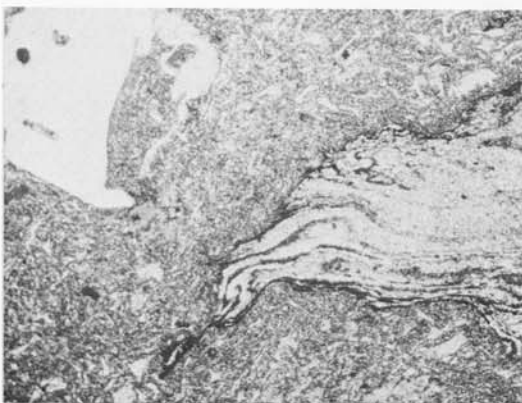FIG. 2

FIG. 3

FIG. 4
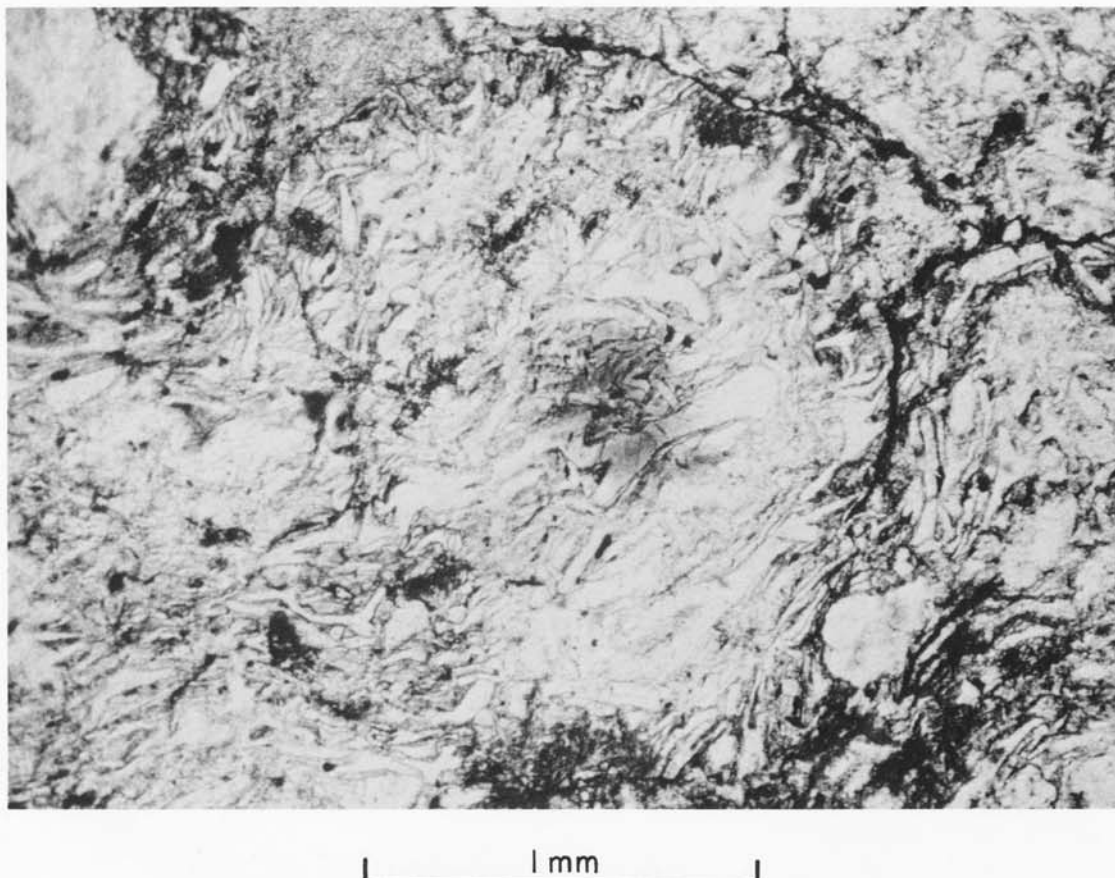

FIG. 5

FIG. 6

FIG. 7

1 mm

I mm

Figure 4

Photomicrograph showing spherical pisolite in the center; the pisolite is seen to be composed of fine ash and shards.

Progressing upward in the flow (moving laterally eastward along the face of the "Diving Cliff"), the pisolites persist to approximately 8 m above the base of the flow. Upward, the middle zone of the ash-flow tuff becomes increasingly more welded and compacted, with shards and fiamme deformed around phenocrysts and lithic fragments (pl. 2, n. 6). True spherulites (devitrification products) are seen in thin section. Lithophysal voids begin to appear at about 7 m above the base and rapidly increase both in number and in size. The lithophysae are filled by granular, anhedral quartz and feldspar or, rarely, secondary calcite. The tuff is extremely fragmental, with abundant fiamme, shards (pl. 2, n. 7), and rarely, unusually large lithic fragments (pl. 3, n. 1).

In the uppermost zone, lithophysae are very abundant and give the rock a pocked and streaked appearance. Lithophysae are flattened, with long axes parallel to dip of the rock.

Eleven meters above the base, the appearance of cylindrical concentrations of alkali-feldspar pheno-crysts marks what are believed to have been fumaroles (pl. 3, n. 3). These features may be best observed upon the flat surface which delineates the top of the first eruptive flow of the lower Johnson Shut-ins ash-flow tuff.

Products of vapor-phase crystallization disappear abruptly at the top of the first eruptive unit. Immediately overlying it is 5 m of a uniformly dense, gray ash flow

1 mm

Figure 5

Radial devitrification texture in the central part of a pisolite in the Johnson Shut-ins ash-flow tuff. Crossed nicols.

with approximately 10 percent to 15 percent alkali feld-spar phenocrysts and 2 percent to 5 percent quartz phenocrysts. Lithic fragments and fiamme are very abundant and easily observed. The matrix is composed of uncompacted shards and ash. The unit is devoid of the extensive vapor-phase crystallization which is so prominent in the first eruptive flow.

It may be concluded that the lower Johnson Shut-ins ash-flow tuff consists of two eruptive flows, the first of about 15 m thickness, the second of about 5 m. The length of time between eruptions must have been brief, possibly a few days, because lithophysae of the lower unit were hot enough to be deformed by the weight of the second flow. Subsequently, the entire stack cooled as a unit.

Of particular interest is the existence of approximately 2 m of weathered ash-flow tuff which caps the upper eruptive unit. This ancient regolith appears in the field as a nubbly, dappled, veined and mottled rock and in thin section is clearly altered ash-flow tuff, with relict shards, fiamme, lithic fragments, and altered alkali-feldspar and quartz phenocrysts still in place and aligned parallel to bedding. It is unmistakably a weathered zone at the top of the complete cooling unit of the lower Johnson Shut-ins ash-flow tuff.

MIDDLE VOLCANICLASTIC UNIT

Unconformably overlying the weathered top of the lower Johnson Shut-ins ash-flow tuff is another series of volcaniclastic sedimentary rocks consisting of a

PLATE 3
Structures in the Johnson Shut-ins ash-flow tuff.
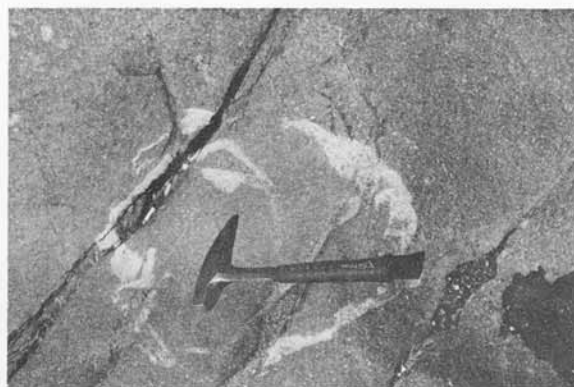

FIG. 1

FIG. 2

FIG. 3

FIG. 4

Fig. 1. Unusually large lithic fragment in the lower ash-flow tuff.

Fig. 2. Compacted lithophysae and other products of vapor-phase crystallization and fumarolic activity in the upper ash-flow tuff.

Fig. 3. Cylindrical concentration of alkali feldspar (light gray) mark what are believed to have been fumaroles.

Fig. 4. Eutaxitic structure showing fiamme and lithic fragments.

conglomerate much like that of the lower swimming hole section, which grades upward and laterally into a red, finely laminated and cross-bedded, tuffaceous siltstone.

UPPER ASH-FLOW TUFF

At the time this paper was written, petrographic study of the upper ash-flow tuff was still in progress. Field examination shows the upper flow to be very similar

to the lower, with essentially repeated zonation and features. The unit varies in that it is dark-gray and has much more extensive development of crystallization from the vapor phase. The lowermost 2.5 m contain pisolites, minor alkali-feldspar phenocrysts, and almost no quartz phenocrysts. Approximately 3 m above the base, relatively uncompacted lithophysae appear, rapidly become abundant, and persist to the top. Preliminary petrographic study reveals the products

of vapor-phase crystallization within these lithophysae to be anhedral quartz, feldspar, and muscovite, as in the lower Johnson Shut-ins ash-flow tuff.

Five meters above the base, a fragmental zone of relatively uncompacted shards, fiamme, lithic fragments, and about 5 percent to 10 percent alkali-feldspar phenocrysts occurs. These features persist into the densely compacted middle zone and upward to the top (pl. 3, n. 4). Fifteen meters above the base the ash flow's appearance is dominated by compacted lithophysae and other products of vapor-phase crystallization and fumarolic activity (pl. 3, n. 2).

As in the lower Johnson Shut-ins ash-flow tuff, the pattern of two eruptive flows which presumably cooled as a single unit is duplicated. Twenty meters above the base, the top of the first eruptive flow of the upper ash-flow tuff occurs. This flow is overlain by about 1 m of uniform, gray ash-flow tuff with minor feldspar phenocrysts. A very thin weathered zone occurs at the top of the second eruptive unit and may be considered analogous to the more extensively developed regolith capping the lower Johnson Shut-ins ash-flow tuff.

COPE HOLLOW SECTION*

As with the Taum Sauk and Proffit Mountain sections, the Cope Hollow was only mapped and examined in brief. It appears to consist of four distinct units:

LOWER WATER-LAID TUFF

A uniform, gray, fine-grained, water-laid tuff with ripple-marks, cross-bedding, and finely graded bedding. Some slightly contorted, sandy lenses have been mineralized with epidote and chlorite.

LOWER-MIDDLE ASH-FLOW TUFF

This unit is a dense, maroon ash-flow tuff with a vitreous matrix and approximately 15 percent feldspar phenocrysts.

UPPER-MIDDLE UNIT

This unit was previously described by Berry (1970) as a dark-gray, cross-bedded air-fall tuff with a small diabase dike or sill. Current studies indicate that the dike or sill is considerably thicker than originally mapped and has an amygdaloidal top, suggesting that much of this unit is actually a basalt flow.

UPPER ASH-FLOW TUFF

The maroon ash-flow tuff, which is of indefinite thickness, appears at the top of othe Cope Hollow section. It is fragmental and contains lithophysae and 10 percent quartz and alkali-feldspar phenocrysts.

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*Corresponds to Berry's Cope Hollow Formation, p. 85, this volume.

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STRATIGRAPHY OF VOLCANIC ROCKS IN THE LAKE KILLARNEY QUADRANGLE, IRON AND MADISON COUNTIES, MISSOURI

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INTRODUCTION

The Lake Killarney 7½-minute quadrangle is in the central part of the St. Francois Mountains in southeast Missouri (fig. 1). In this region of relatively high relief, Precambrian volcanic rocks form a substantial part of the outcrops, and the valleys are underlain by lower Paleozoic sedimentary rocks, which are covered with a thin veneer of alluvium.

The Precambrian rocks in the quadrangle were mapped previously by Robertson (1940). His work was later incorporated into the regional Precambrian geologic map of Tolman and Robertson (1969). The recognition of ash-flow tuffs in the area to the west by R.E. Anderson (1962, 1970) cast some doubt on the validity of the stratigraphic model proposed by Tolman and Robertson. R.E. Anderson mapped a 368-km^2 area and described a 1,500-m-thick section of mostly silicic ash-flow tuffs. He mapped and named the Taum Sauk depression, which J.E. Anderson and others (1969) later defined as the Taum Sauk Caldera.

Berry (1970) mapped an area of about 117 km^2 immediately west of the Lake Killarney quadrangle, in which he measured a 6,000-m-thick section of mostly latitic and rhyolitic ash-flow tuffs. Berry's complete descriptions and modal data for his units are of value because these data enable geologists mapping adjoining areas to make stratigraphic correlations and comparisons.

The purpose of this investigation was to extend mapping based on utilization of the ash-flow-tuff concept, to describe and define mappable volcanic-rock units in the Lake Killarney quadrangle, and to attempt to correlate these units with those mapped
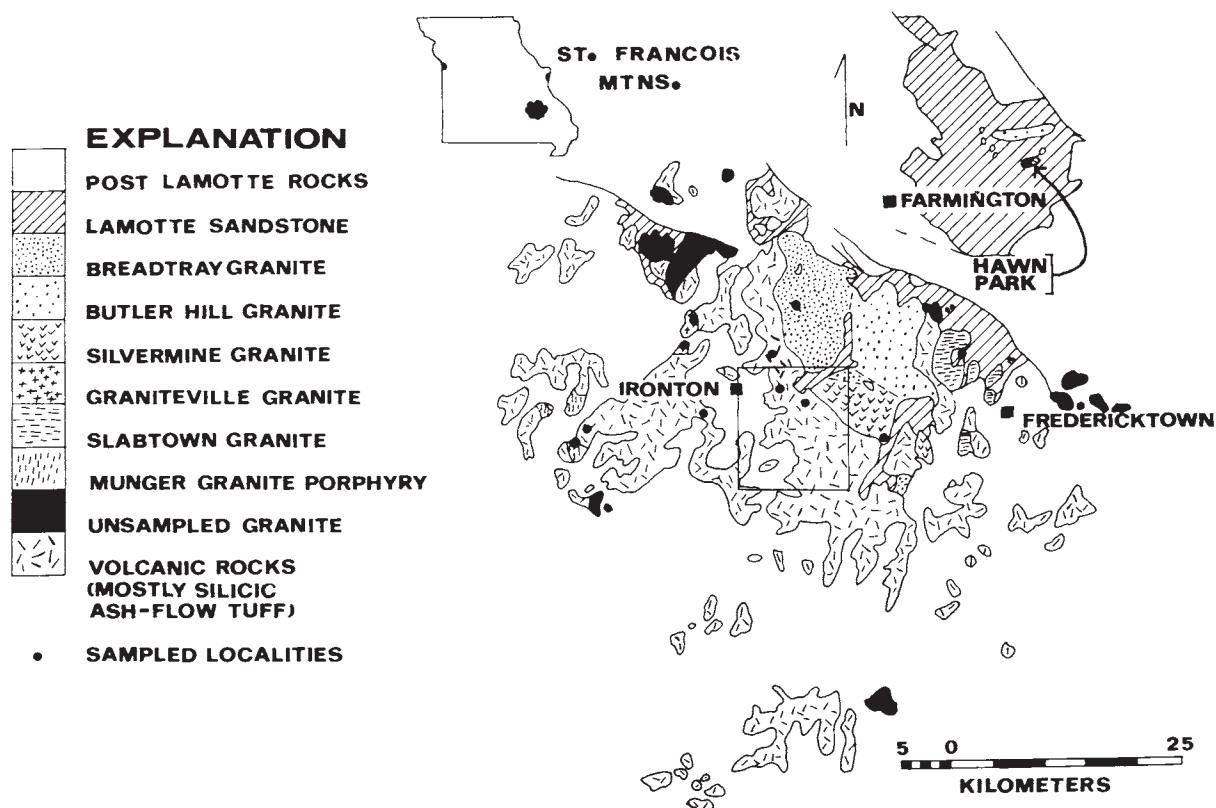
Figure 1

Location of Lake Killarney quadrangle in the St. Francois Mountains. Sampled localities refer to an earlier geochronological study.

by Berry. The investigation on which this report is based is not yet complete, and, although two summers of field work have been completed, thin-section petrography and modal analysis have only begun. It is not the purpose of this paper to present a final report, but rather to describe the major volcanic-rock units in the quadrangle so that current workers may compare them with units in their mapping areas. The structural aspects of this investigation have been summarized by Sides and Bickford (1976).

DEFINITION OF VOLCANIC-ROCK UNITS AND MODAL ANALYSIS

I have divided the volcanic rocks in the Lake Killarney quadrangle into three units. From youngest to oldest, these are the Pilot Knob felsite, Grassy Mountain ignimbrite, and Lake Killarney unit (fig. 2). The rocks of these units are distinct both in the field and in thin section. Tolman and Robertson (1969), however, included Grassy Mountain ignimbrite and Lake Killarney unit in their Stouts Creek Rhyolite unit. It should be pointed out that Grassy Mountain ignimbrite and Lake Killarney unit are temporary field terms and are not part of a formalized stratigraphic nomenclature. The Pilot Knob felsite is used in this paper in a more restricted sense than in the Tolman and Robertson (1969) terminology. Areas mapped by them as Pilot Knob felsite include areas mapped as Grassy Mountain ignimbrite and as Lake Killarney unit by the writer.
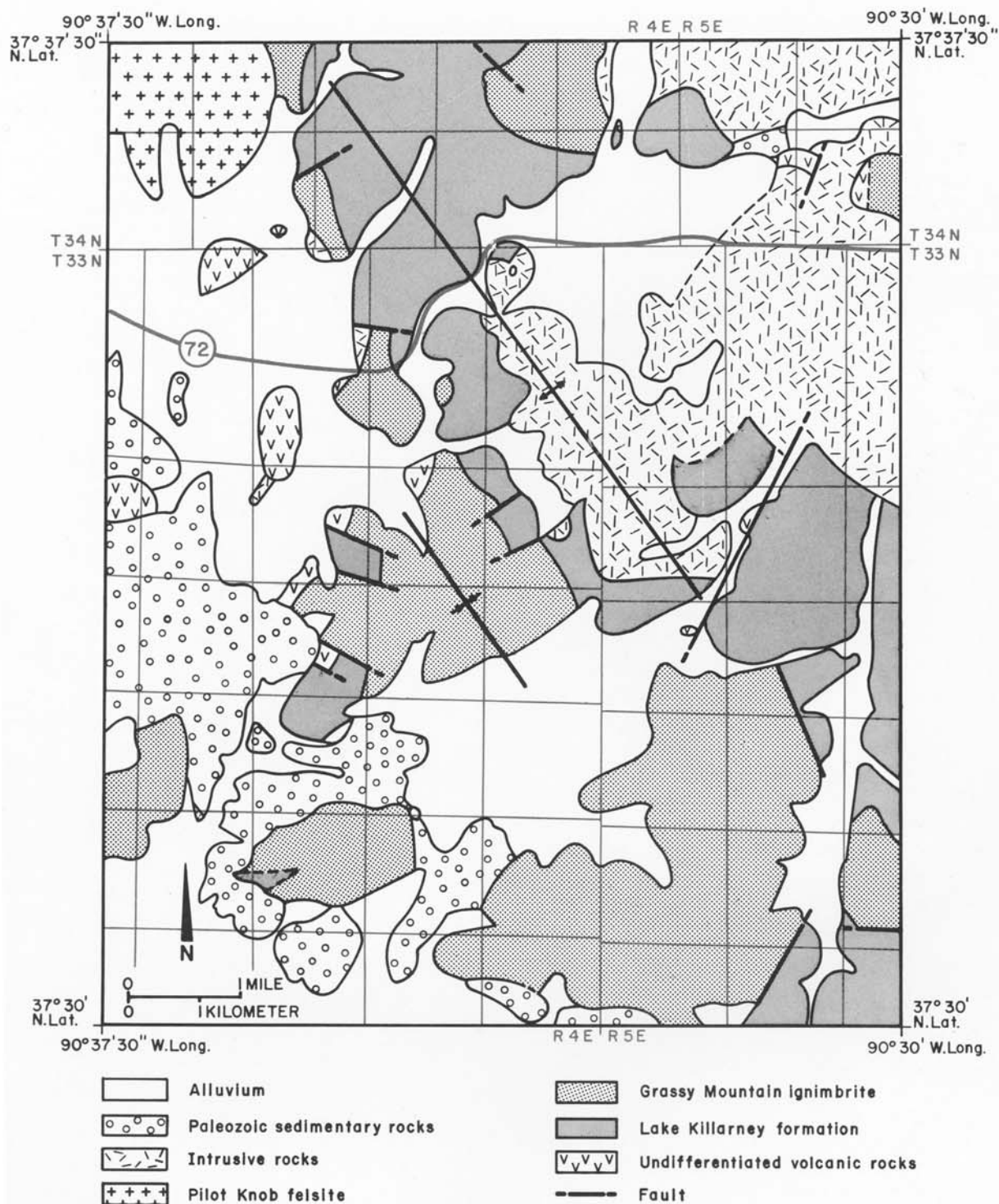
Figure 2

Generalized geologic map of the Precambrian rocks in the Lake Killarney quadrangle, Iron and Madison Counties, Missouri.

It is hoped that the descriptions offered in this paper will be of value in comparing the volcanic-rock units in the Lake Killarney quadrangle to others outside of the area. Descriptions alone do not provide quantitative data regarding these units, and for this reason modal analysis was done on available thin sections. Unfortunately, at the time this paper was written, only a limited number of thin sections were available and these were mostly of Grassy Mountain ignimbrite. The results of the modal analysis are presented in tables 1 through 4. It should be pointed out that those minerals listed in the tables are single

minerals or mineral aggregates which are at least 1 mm in length. This was done in order to avoid bias in counting small grains as matrix. The values listed in the tables, therefore, do not represent the true mineralogy, but rather represent the phenocryst mineralogy, which I believe will be a better comparative criterion. The samples for each unit were deliberately collected from widely distant locations in order to include as much variation as possible; nevertheless, the standard deviations about the means of the more abundant phenocrysts are remarkably small (tbl. 4).

PILOT KNOB FELSITE

Outcrops of Pilot Knob felsite are restricted to the northwestern part of the Lake Killarney quadrangle (fig. 2). Despite numerous local textural differences, the unit is fairly homogeneous. Differences in appearance from outcrop to outcrop are caused by local zones of brecciation, lithophysae, flow lineation, and epidotization. These features are emphasized by weathering, which bleaches the rock to pale shades of pink, red, and brown. The rock is very hard and breaks with a flinty fracture. Typical, fresh rocks of this unit are porphyritic, with reddish feldspar and a few small quartz phenocrysts in a dark-red to maroon matrix.

The unit includes small amounts of fine-grained, iron-rich, banded tuff near the contact with the underlying Grassy Mountain ignimbrite. Such tuffs are not seen elsewhere in the unit, unless one includes the tuffs on top of Pilot Knob with Pilot Knob felsite. Breccia zones of the felsite appear slightly mottled in shades of red and maroon on fresh surfaces; they are believed to be autobreccias.

The thickness of the Pilot Knob felsite is unknown and will be difficult to determine, because the attitude of the unit is unknown. Meager evidence suggests that the unit dips rather gently to the southwest; this attitude would indicate a thickness of about 150 to 350 m.

Attitudes measured in the field are extremely variable, but a steep dip is very unlikely. Along the eastern side of Radio Tower Hill, about 1 mi east of Pilot Knob, the felsite is in contact with vertically dipping Grassy Mountain ignimbrite. This contact is either a fault or, more likely, a major angular unconformity, as indicated by the lack of brecciation or cataclasis along the contact.

PETROGRAPHIC DESCRIPTION

Microscopic studies of this unit are in preliminary stages (tbl. 1), but the following description is

TABLE 1

MODAL ANALYSES OF PILOT KNOB FELSITE
(in volume percent)

SAMPLE NO.	6519	6521
Matrix	95.39	95.19
Quartz	1.61	1.86
Alkali feldspar	—	.11
Plagioclase	1.04	1.75
Chlorite	—	.22
Fluorite	.06	.05
Opaques	.17	.55
Calcite	—	.27
Epidote	1.73	—

probably representative. The matrix is composed of a fine-grained aggregate of quartz and feldspar, and tiny specks of opaque material. It often appears inhomogeneous due to the occurrence of snowflake texture and variation in microlite size. Quartz phenocrysts are up to 1 mm in diameter and are rounded and embayed, but sometimes have their crystal faces preserved. Anhedral quartz grains range from phenocryst size down to matrix size.

Feldspar phenocrysts are sodic plagioclase displaying albite twinning, and occur both as crystal fragments and as euhedra with rectangular outlines; these are mostly 1 to 2 mm in length and are extensively altered, mostly to white micas. Epidote, when present, occurs as tiny patches in the matrix, as ragged aggregates of grains which may reach 0.25 to 0.5 mm in diameter, or as small grains replacing feldspars. In the latter, replacement may be almost complete. Chlorite,

when present, occurs as irregular, acicular aggregates up to 0.5 mm in diameter. It is frequently associated with quartz, hematite, and, rarely, calcite.

Hematite generally occurs as small specks randomly distributed in the matrix and as rounded aggregates up to 1 mm in diameter. In one thin section it occurs as elongate, rectangular crystals up to 1 mm in length, which are so thin as to appear hair-like. Fluorite fills tiny fractures and is associated with hematite and mafic minerals. Calcite replaces feldspar in small irregular patches.

The mode of origin of the Pilot Knob felsite remains a problem. I believe that the unit is a sequence of rhyolitic flows because of a) relative abundance of lithophysae, b) abundance of local autobreccias, c) abundance of what appears to be flow lineation, and d) paucity of pumiceous inclusions.

GRASSY MOUNTAIN IGNIMBRITE

The Grassy Mountain ignimbrite, named for typical exposures on Grassy Mountain, is the best stratigraphic marker in the Lake Killarney quadrangle because it is homogeneous, has a distinctive appearance, and is exposed widely. Weathered outcrops are generally low in relief and locally have columnar jointing. Fresh samples of Grassy Mountain ignimbrite contain prominent phenocrysts of quartz and reddish alkali feldspar in black to very dark-maroon matrix. Weathered surfaces are gray, with many quartz and feldspar phenocrysts visible. Pumice fragments are not common, but when present, are weathered to a pinkish color and thus stand out.

If the contact between Pilot Knob felsite and Grassy Mountain ignimbrite on Radio Tower Hill is an unconformity, the ignimbrite is stratigraphically below the felsite. The attitude of compaction foliation in the ignimbrite gives an accurate and consistent measure of the attitude of the unit and is invaluable in defining structural relations, especially in the northern part of the area where the unit dips steeply. The thickness of Grassy Mountain ignimbrite

varies considerably from place to place; in the northern part of the area it is about 300 m. The unit thickens to the south, where its thickness may be on the order of 1,000 to 2,000 m.

PETROGRAPHIC DESCRIPTION

The modal mineralogy of Grassy Mountain ignimbrite is shown in table 2. Microscopically, the matrix is very fine-grained, nearly uniform, and is composed primarily of quartz and feldspar microlites. Occasionally, alignment of tiny hematite specks and quartz microlites imparts to it a faintly linear fabric. This probably resulted from local rheoignimbritic flow which occurred just after deposition of the hot ash. Quartz phenocrysts occur both as angular fragments and as hexagonal euhedra ranging from 1.0 to 2.5 mm in diameter. Quartz crystals are deeply embayed and sometimes completely rounded. Perthitic alkali feldspars, ranging in size from 1 to 5 mm, occur both as euhedral crystals and as crystal fragments and are slightly altered to clays and white micas. Hematite occurs as tiny specks

TABLE 2

MODAL ANALYSES OF GRASSY MOUNTAIN IGNIMBRITE

(in volume percent)

SAMPLE NO.	6413	7457	6425	546	6419	658	657	6517	6524	7537	7522
Matrix	76.07	78.14	74.96	78.70	69.04	52.30	71.98	64.79	70.04	75.78	74.62
Quartz	9.21	7.03	7.54	6.47	11.52	7.18	9.19	6.80	9.43	7.58	10.12
Alkali feldspar	13.76	13.43	12.38	13.64	13.20	9.44	13.98	16.69	12.11	8.61	9.64
Chlorite	—	—	—	.50	—	.11	—	—	.84	—	—
Amphibole	.96	.84	.28	—	3.15	—	1.16	.06	—	.60	—
Opaques	—	.28	.22	.06	.06	.11	—	—	.22	.11	.32
Fluorite	—	—	—	—	—	—	—	—	—	—	.05
Pumice	—	.28	4.62	—	3.03	16.11	3.69	11.44	2.34	6.88	.27
Lithic fragments	—	—	—	.63	—	14.75	—	.22	5.02	.43	4.98

in the matrix and as larger grains or grain aggregates up to 1 mm in diameter. It is frequently associated with mafic minerals and fluorite. Chlorite occurs as tiny patches distributed in the matrix and very irregular grain aggregates which are seldom greater than 1 mm in length.

A blue-green amphibole is distributed in the matrix as rounded grain aggregates up to 1.5 mm in diameter, and rarely as single grains up to 2 mm in length. Chlorite and blue-green amphibole appear to be mutually exclusive, implying some type of reaction relationship between them, although no direct evidence of this has been observed. Fluorite is rare, but occurs as tiny blebs usually associated with mafic minerals.

Fiamme are not very abundant, but occur as elongate, intimate intergrowths of quartz and feldspar. Lithic fragments are more evident in thin section than in fresh hand specimen. These angular fragments are commonly less than 2 mm in length and include different ash-flow tuffs, granophyres, and a fine-grained, plagioclase-rich rock, probably a basalt. In one thin section the remains of what appear to be fayalite phenocrysts occur. The phenocrysts are completely altered to hematite and an unidentified yellow, fibrous mineral. The hematite is distributed as if it had crystallized along curved fractures like those of olivine crystals, and the preserved euhedral outlines of the phenocrysts also suggest that they were originally olivine.

LAKE KILLARNEY UNIT

The Lake Killarney unit, named for typical exposures in the vicinity of Lake Killarney, is the most difficult volcanic-rock unit to characterize. It consists of three distinct zones, but the writer has been unable to define mappable contacts between them, and so they are not given separate names.

UPPER ZONE

The upper zone of the Lake Killarney unit is usually a prominent breccia; however, it is a fine-grained tuff at some localities. The tuff is dark-gray to dark-maroon, with less than 5 percent phenocrysts of quartz and

alkali feldspar, and contains up to 25 percent lithic fragments. The total thickness of the tuff is not well known, but appears to vary between 0 and 15 m. No thin sections of the tuff have been studied. The breccia is quite distinctive in outcrop and in fresh hand specimen. It has a light-brown matrix which is fine-grained and relatively uniform. The clasts are moderately to well rounded and vary in abundance from about 25 percent to over 75 percent. All clasts observed by the writer have been silicic volcanic rocks of highly varied nature, although clasts of ash-flow tuff predominate.

Microscopically, the breccia matrix is a fine-grained assemblage consisting mostly of quartz and feldspar. It is relatively dark under crossed nicols, possibly because of numerous dusty inclusions. The matrix frequently displays snowflake texture and rarely has a slightly linear fabric. The breccia matrix contains small amounts of rounded, resorbed quartz (1 mm in diameter) and alkali feldspar (2 mm in length) phenocrysts. The thickness of the breccia is highly variable. It is absent in some places and it reaches its greatest thickness of about 30 m northwest of Lake Killarney.

MIDDLE ZONE

In outcrop, the middle zone of the Lake Killarney unit is a porphyritic, light-maroon ash-flow tuff, with locally abundant fiamme and with phenocrysts of quartz and pink alkali feldspar. The rock rarely contains local autobreccias and lithophysae. In fresh hand specimen, the rock appears much the same as in outcrop, except the matrix is dark-maroon, and fiamme are much less in evidence. The modal mineralogy is shown in table 3.

Microscopically, the matrix is a fine-grained assemblage of quartz and feldspar. It may have linear fabric imparted by aligned opaque specks; tiny, elongate feldspars; and tiny, aligned blebs of quartz. The matrix of some thin sections has remarkably developed snowflake texture. Quartz occurs as tiny grains in the matrix, as large irregular grains in the centers of large fiamme, and as phenocrysts ranging in diameter from 0.5 mm to 1.5 mm.

Quartz phenocrysts occur as crystal fragments and as embayed, hexagonal euhedra. Alkali feldspars occur as microlites in the matrix, as small euhedra in larger fiamme, and as phenocrysts. Feldspar grains in fiamme generally project inward and are euhedral against irregular quartz grains. Phenocrysts are alkali feldspar and occur both as euhedral crystals and as crystal fragments, ranging in size from 1 to 3 mm in length. Feldspars are partially replaced by clays, chlorite, white micas, and, rarely, calcite. Fiamme are unusual in that their centers are sometimes replaced by small quartz and feldspar grains. In some thin sections, fiamme pinch and swell and change direction abruptly. Hematite occurs as tiny specks distributed in the

TABLE 3
MODAL ANALYSES OF LAKE KILLARNEY UNIT
(in volume percent)

SAMPLE NO.	846*	7538*	6417*	7528+
Matrix	94.43	84.41	84.96	91.54
Quartz	1.93	1.73	1.75	1.97
Alkali feldspar	3.53	5.63	6.14	6.15
Opaques	.11	.22	.21	.34
Calcite	—	—	.16	—
Pumice	—	7.91	6.67	—
Lithic fragments	—	—	.11	—

*middle zone
+lower zone

matrix, as single irregular grains ranging in size from 0.5 mm to 1 mm, and as aggregates of small grains ranging up to 2 mm in size. Chlorite is rare, but occurs as small, irregular grains up to 0.5 mm in size, which are associated with hematite and with alkali feldspars. Small grains of calcite rarely occur replacing alkali feldspar. Plagioclase is rare, but occurs as small (less than 1 mm in length), irregular grains which are altered (almost beyond recognition) to chlorite and white micas. One lithic fragment was observed in the middle zone of the Lake Killarney unit. It is porphyritic, with plagioclase occurring in the matrix and as phenocrysts, and is probably basalt.

The most distinctive feature of this zone is the common presence of abundant fiamme which are lighter in color than the remaining rock and impart to the rock an extremely foliate texture. At some outcrops the foliation is consistent and measurable, but at other outcrops foliation varies in a complex way, making it difficult to extract meaningful structural data from this zone. Clearly this zone is composed mostly of ash-flow tuff, but local autobreccias and rare lithophysae imply the presence of intercalated rhyolitic flows.

LOWER ZONE

The lower zone of the Lake Killarney unit is recognized in outcrop at only two locations and

has not yet been studied adequately by the writer. The following description may be subject to slight changes as new information becomes available.

In outcrop, the lower zone appears much the same as the middle zone, except that fiamme are much less abundant, and feldspars may be altered to nearly the same color as the matrix and appear less abundant.

Microscopically, the lower zone of the Lake Killarney unit appears much like the middle zone, except for a much lower abundance of fiamme. The only significant difference in mineralogy is in the mafic minerals, most of which are small aggregates less than 1 mm across, appearing

brown in both plain light and crossed nicols. These aggregates are associated with hematite blebs and closely resemble altered blue-green amphibole. Chlorite is rare, but does occur as tiny flakes associated with the brown mafic mineral.

The thickness of the unit is not well known because of lack of structural information and because it is unevenly truncated by various underlying intrusive bodies; however, it is probably between 500 m and 1,500 m thick.

The means and standard deviations of the modal mineralogy of the three volcanic-rock units that are defined in the Lake Killarney quadrangle are shown in table 4 for comparison.

TABLE 4

SUMMARY OF MODAL ANALYSES OF THE VOLCANIC UNITS DEFINED IN
THE LAKE KILLARNEY QUADRANGLE

	P. K. f.		G. M. i.		L.K.u.	
	mean	s.d.	mean	s.d.	mean	s.d.
Matrix	95.30	.15	71.50	7.61	88.86	4.90
Quartz	1.74	.18	8.26	1.81	1.85	.12
Alkali feldspar	.06	.08	12.87	2.69	5.36	1.25
Fiamme	—	—	4.42	5.22	3.65	4.24
Plagioclase	1.40	.50	—	—	—	—
Opaques	.36	.27	.13	.12	.22	.09
Fluorite	.06	.01	—	—	—	—
Chlorite	.11	.16	.13	.28	—	—
Amphibole	—	—	.64	.94	—	—
Lithic fragments	—	—	2.37	4.55	.03	.06
Epidote	.87	1.22	—	—	—	—
Calcite	.14	.19	—	—	.04	.08

P.K.f Pilot Knob felsite

G.M.i Grassy Mountain ignimbrite

L.K.u. Lake Killarney unit

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PRECAMBRIAN VOLCANIC ROCKS EXPOSED ON STEGALL AND MULE MOUNTAINS, CARTER AND SHANNON COUNTIES, MISSOURI

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INTRODUCTION

Stegall and Mule Mountains are about 9 mi northeast of Winona and 16 mi southeast of Eminence, in Carter and Shannon Counties, Missouri (fig. 1). They are among the highest of several hills and knobs in this area, some 40 mi southwest of the St. Francois Mountains, where Precambrian igneous rocks are exposed at the surface in Missouri. These outcrops are important representatives of a Precambrian terrane of the Midcontinent.
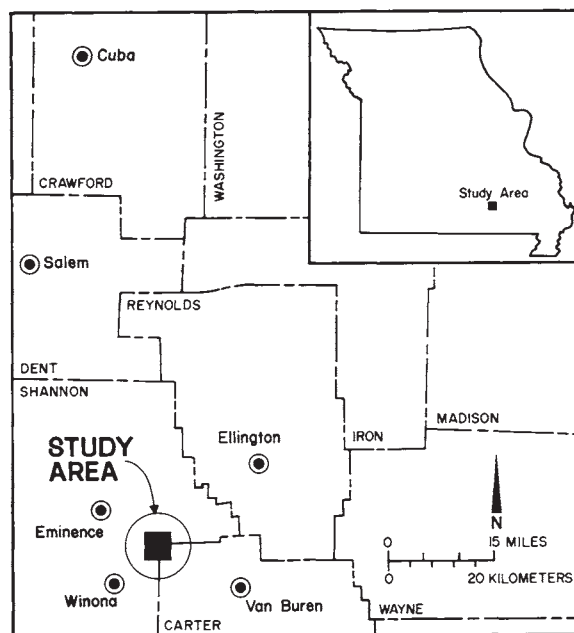
Figure 1

Index map to the location of Stegall and Mule Mountains in the Eminence area of southeast Missouri.

Previous mapping by Bridge (1930) and Tolman and Robertson (1969) established that the exposed Precambrian rocks in the Eminence area are predominantly rhyolites and include minor amounts of tuffs and agglomerates. The nearest granite outcrop occurs about 15 mi southeast of Stegall Mountain, near Van Buren, and diabase has been reported from only one locality (Fisher, 1969). However, drillholes around the Eminence-area knobs indicate that the buried Precambrian basement is more varied in composition and includes granite and adamellite porphyries, and several granite types (E.B. Kisvarsanyi, 1974).

The Precambrian geology of the Eminence area has not been studied in sufficient detail to make correlation with the St. Francois Mountains Precambrian possible. Evans (1959) included some petrographic data on the volcanic rocks in connection with his study of the copper deposits of the region, and Fisher (1969) mapped in detail a small area to the north of Stegall Mountain. Chemical data on the rocks are also meager (E.B. Kisvarsanyi, 1972; Mantei, 1962). None of these workers referred to the existence of ash-flow tuffs in the Eminence area, although reconnaissance geologic mapping by G. Kisvarsanyi in the northern part of the area in the late 1950's indicated that ash-flow tuffs may be present in the volcanic section.

The purpose of this study was to obtain detailed geologic data from one of the largest continuous Precambrian outcrops (4.5 mi^2) in the area and to apply this knowledge to problems associated with the volcanic rocks of southeast Missouri. The study included mapping, identification and description of lithologic units, and correlation within the study area. It is hoped that these data will be helpful to others mapping in adjoining areas in the future.

GEOLOGIC AND STRUCTURAL SETTING

The Precambrian rocks in the Eminence area are exposed as isolated knobs in a relatively rugged area where hills composed of Paleozoic sediments also form topographic highs. Stegall Mountain rises 1,348 ft above sea level and is among the higher peaks in the region. To the south the igneous rocks are partially buried by residual cherts derived from the Roubidoux Formation and Gasconade Dolomite of Ordovician age and from the Eminence Dolomite of Upper Cambrian age. To the north the igneous rocks are partially covered by the Eminence and Gasconade Dolomites. Igneous rocks are less well exposed and are topographically lower than those in the St. Francois Mountains. These two principal areas of Precambrian outcrops in southeast Missouri are separated by a distance of about 40 mi, which poses some difficulties in correlating them. The Precambrian basement between these outcrops is deeply buried by Paleozoic sediments.

The block-like nature of the Eminence-area Precambrian has been pointed out by Bridge (1930), Graves (1938), and Kisvarsanyi and Kisvarsanyi (1976). It has been suggested that it is a tectonic block within the Ozark Uplift and that it is bounded by northeast- and northwest-trending faults. The distribution of Precambrian knobs within the block also appears to have been structurally controlled (Kisvarsanyi and Kisvarsanyi, 1976) although, to date, no major faults have been confirmed in outcrop. Drillhole and geophysical data and satellite-imagery analysis, however, strongly suggest the existence of buried faults along the margins of and cutting across the Eminence tectonic block. Remote sensing also indicates several circular features within the block that may possibly be collapse calderas or similar volcano-tectonic features.

Stegall and Mule Mountains are near the southernmost corner of the Eminence tectonic block and are part of the eroded, faulted and fractured Precambrian volcanic terrane. Measurement of the strikes of 183 joints indicates that the dominant joints form an orthogonal pattern with strikes of N 45° E ± 10° and N 46° W ± 10°. Most of these joints may be followed along their strike for 10 ft or more and have a nearly vertical dip. Locally, horizontal jointing is developed in massive rhyolite and is believed to have formed through unloading. Combination of orthogonal joints with horizontal joints produces rectangular blocks of rhyolite upon weathering.

It is assumed that Stegall and Mule Mountains are crossed by two major fault-fracture systems that strike

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northwest. These systems are expressed by erosional and topographic features in the form of straight valleys that cut deeply into the main ridge of the mountain and separate Mule Mountain from Stegall Mountain (fig. 2). Joint and fracture directions are well expressed in the direction and distribution of erosional and topographic features that cut across lithologic units.

Other important joint directions measured in the field are N-S, N 10° E, N 10° W, N 80° E, N 80° W, and E-W. These joints also have steep dips. The minor joints combined with the major joints result in triangular and other polygonal joint patterns on outcrops.
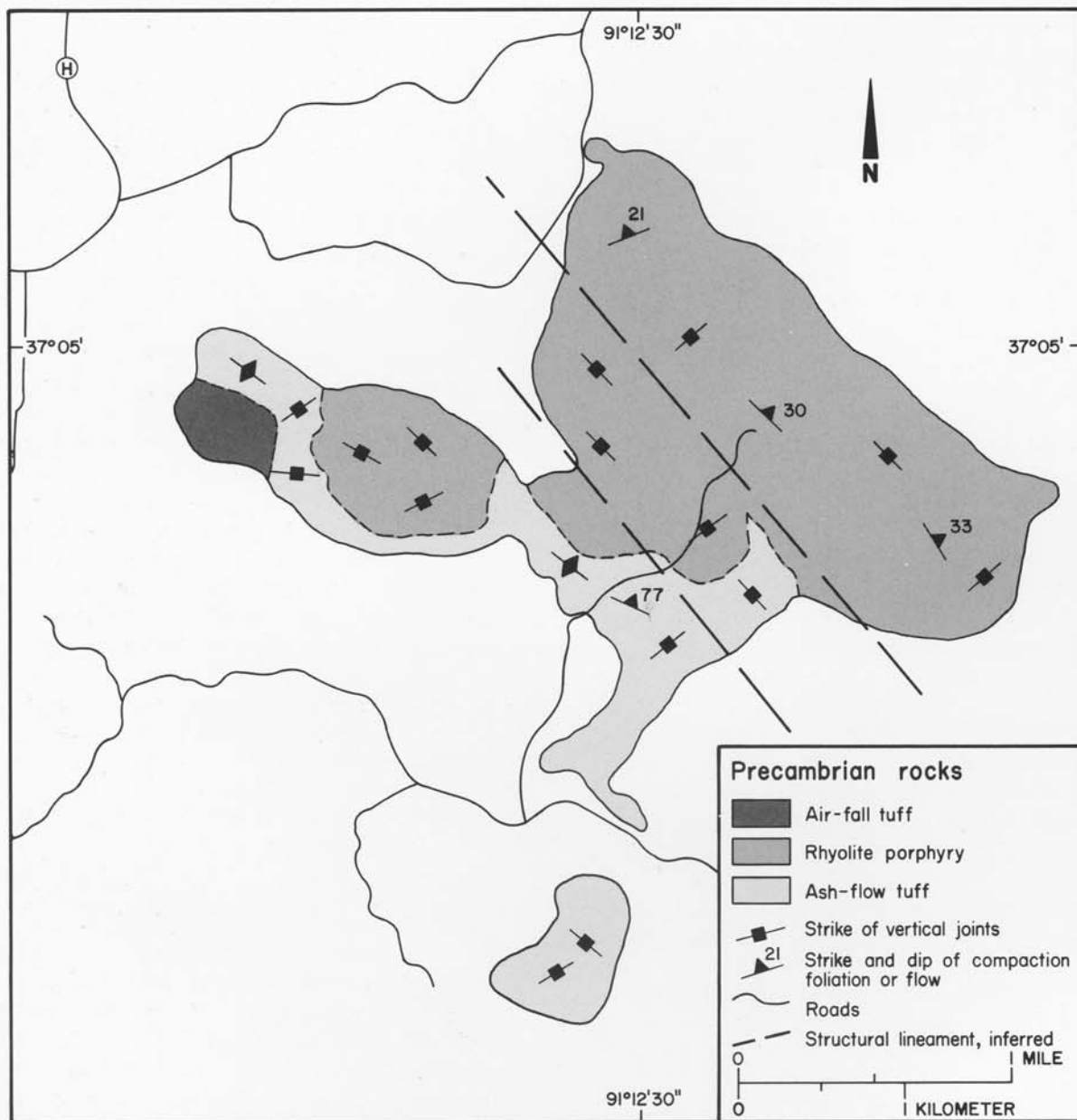
Figure 2

*Precambrian geologic map of the Stegall Mountain area, Carter and Shannon Counties, Missouri.
Stegall Mountain is on the east; Mule Mountain is the western lobe of Precambrian outcrops.*

DESCRIPTION OF VOLCANIC UNITS

Tolman and Robertson (1969) assigned the volcanic rocks on Stegall and Mule Mountains to their Stegall Mountain Rhyolite unit. We have defined two major volcanic units on the basis of detailed mapping and petrographic analysis: a lower ash-flow tuff and an upper rhyolite-porphyry flow. The contact between the two units is obscured by vegetation and soil cover. The composite exposed thickness of the units is between 500 and 600 ft, but the lower contact of the ash-flow tuff is not exposed. Small outcrops of a dense, aphanitic air-fall tuff were also observed in the study area on the southwestern slope of Mule Mountain (fig. 2) and near the top of Stegall Mountain. This tuff is the most deeply eroded lithologic unit on the mountains, and its relationship to the ash-flow tuff and rhyolite could not be determined.

The distinction between the ash-flow tuff and the rhyolite porphyry is based on petrographic and textural differences. The ash-flow tuff is distinguished by presence of compaction foliation, collapsed pumice, iron-stained feldspar phenocrysts, absence of quartz phenocrysts, completely altered ferro-magnesian minerals, and eutaxitic textures. The rhyolite porphyry is more crystal-rich and has both quartz and feldspar phenocrysts; it has flow banding, snowflake texture, and spherulitic devitrification textures.

ASH-FLOW TUFF

The lower unit of the volcanic section is a dark-maroon to purple, rhyolitic ash-flow tuff containing orange-brown feldspar phenocrysts. It is exposed on the western and southern slopes of the mountains (fig. 2).

The ash-flow tuff contains fiamme and has eutaxitic structure. Extreme distortion and compaction of shards and pumice produced a nearly parallel, discontinuous banding in the rock (pl. 1, n. 1, 2, 3). The strike and dip components of compaction foliation are northwest and northeast, respectively. Dip values range from 70° to nearly 90°. Locally, the foliation is contorted and changes directions

abruptly within a few feet. In some outcrops an E-W strike is observed. The upper part of the unit is brecciated and contains abundant lithic fragments.

Due to the scarcity of outcrops and heavy vegetation, a good exposed section of this rock unit could not be found, and it was not possible to establish ash-flow cooling units as described in the literature of younger volcanic regions.

PETROGRAPHIC DESCRIPTION

Phenocrysts make up from 6 percent to 20 percent of the ash-flow tuff by volume, with an average amount of 11 percent. They are mostly euhedral to subhedral or broken alkali feldspar. They are generally untwinned, but a few are twinned according to the Carlsbad law. Alteration to sericite and clay minerals and absence of twinning make it difficult to determine the composition of the feldspar by optical means alone. At the time of formation it was probably sanidine, but sanidine would not have remained stable in the rock. A rather constant amount of hematite "dust" nearly always colors the feldspars to dull orange-brown in hand specimen and causes them to be turbid and cloudy in thin sections.

Magnetite and hematite make up from 2 percent to 10 percent of the rock by volume. Their grain size varies from indistinct, submicroscopic, opaque granules to crystals up to 2 mm in diameter. Iron oxides have the following modes of occurrence in the ash-flow tuff:

a. Euhedral-subhedral magnetite phenocrysts, 0.1 to 1.0 mm in size, showing partial to complete alteration to hematite. These magnetites are early-formed primary crystals.

b. Submicroscopic, dust-like inclusions in alkali feldspar phenocrysts and groundmass, imparting the diffuse coloration to the rock.

c. Very small (0.02 mm) cubic and needle-shaped magnetite crystals associated with vapor-phase crystallization, representing gas-fluxed devitrification products (pl. 1, n. 4).

d. Massive, coarse-grained hematite replacing former ferromagnesian minerals and feldspars.
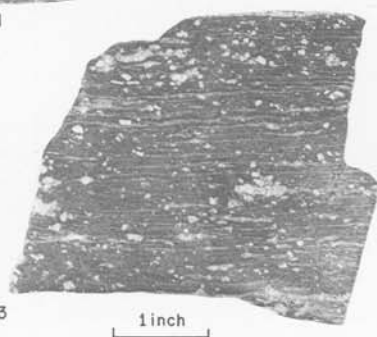
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PLATE 1

Types of rocks from the Stegall Mountain area.
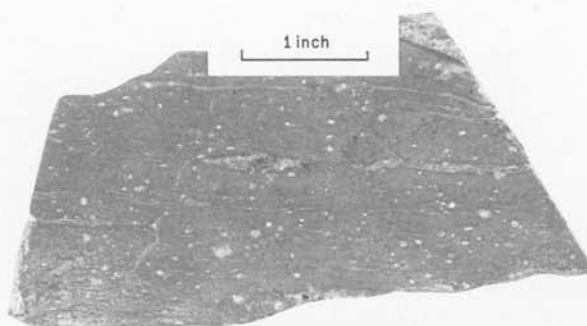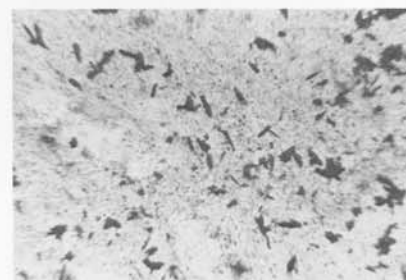

No. 1
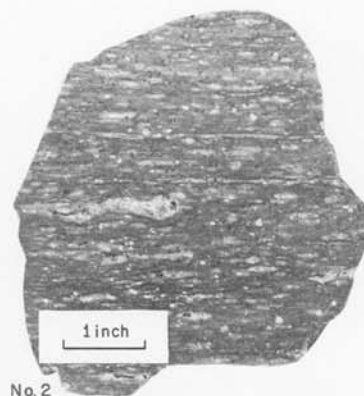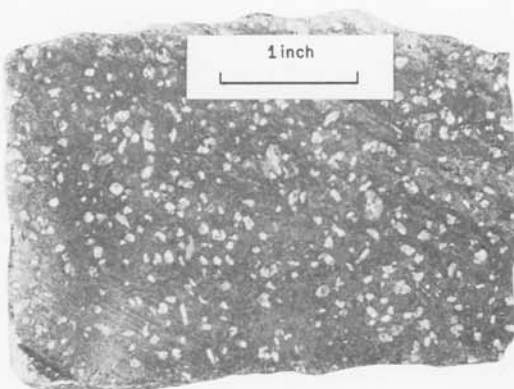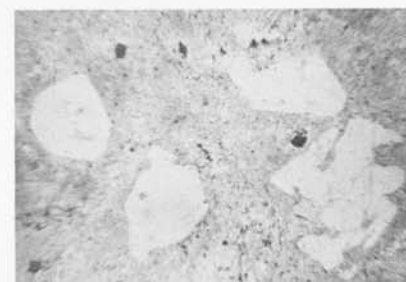

No. 2

No. 3

No. 4

No. 5

No. 6

No. 7

No. 8

Quartz phenocrysts are practically absent in the ash-flow tuff. In the lower, exposed part of the unit, however, euhedral phenocrysts of a former ferro-magnesian mineral, believed to have been fayalite or possibly an iron pyroxene, have been noted (pl. 1, n. 5). The mineral is completely replaced by hematite, calcite, sericite, and epidote. The form and typical olivine-type cross-fractures in the mineral suggest fayalite.

Fluorite and zircon are accessory minerals in the ash-flow tuff. Fluorite and calcite are usually vapor-phase products and fill vugs and fractures.

The groundmass of the ash-flow tuff is fine-grained to cryptocrystalline and consists of quartz, feldspar, and iron oxide. Relict pumice fragments and glass shards are visible in plain light under the microscope and show compaction, especially around phenocrysts (pl. 1, n. 6). Collapsed pumice is seen as lenticular pods filled by a coarser-grained aggregate of quartz, feldspar, and iron oxide. Very small, lenticular pods that are aligned in the groundmass are believed to be devitrification products.

Nos. 1, 2, and 3. Ash-flow tuff showing eutaxitic structure and compaction foliation.

No. 4. Photomicrograph of ash-flow tuff showing tiny needle-shaped magnetites formed as a result of gas-fluxed devitrification.

No. 5. Photomicrograph of relict fayalite phenocryst in ash-flow tuff. The mineral is completely replaced by calcite, sericite, and epidote; hematite fills cross-fractures and is concentrated along crystal outlines.

No. 6. Photomicrograph of ash-flow tuff showing compaction foliation of shards around alkali-feldspar phenocryst.

No. 7. Rhyolite porphyry showing abundant phenocrysts of feldspar (light-gray); quartz phenocrysts are not prominent against the dark background of the groundmass.

No. 8. Photomicrograph of rhyolite porphyry showing euhedral alkali feldspar and partially resorbed quartz phenocryst (lower-right corner) in devitrified felsic groundmass.

Photos by B.N. Sinha

RHYOLITE PORPHYRY FLOW

Rhyolite porphyry is the dominant rock type in outcrop, covering approximately 70 percent of the study area (fig. 2). It is exposed near the top and on the northern slopes of the mountains, and along creek beds.

The rhyolite is a dark-purple, flow-laminated, flow-folded, and contorted body of rock. The axial azimuth of flowage folds is E-W. The general strike of flow bands is N 45° W and they dip 30° northeast. Strike and dip are more irregular on the northern slopes near the base of the Precambrian exposures. Locally, flow lines change from an E-W strike and a dip of 20° N to a N-S strike and a vertical dip.

PETROGRAPHIC DESCRIPTION

The rhyolite porphyry consists of quartz, alkali feldspar, and magnetite-hematite phenocrysts, in a fine-grained to cryptocrystalline matrix. Accessory minerals are apatite, zircon, fluorite, and ilmenite(?).

Phenocrysts are more abundant in the rhyolite than in the ash-flow tuff and make up from 14 percent to 30 percent of the rock by volume (pl. 1, n. 7).

Alkali feldspar constitutes approximately two-thirds of the phenocrysts. It is usually perthitic, euhedral to subhedral, and is moderately altered to sericite and clay minerals; a few crystals have undergone calcification. Quartz makes up about one-fourth of the phenocrysts. It commonly occurs in the form of hexagonal dipyramids with short prism faces, but

is usually deeply embayed and resorbed (pl. 1, n. 8). The balance of phenocrysts is made up by magnetite-hematite.

The groundmass is a cryptocrystalline aggregate of quartz, feldspar, and iron oxides. Snowflake texture and spherulitic devitrification textures are common. Snowflake texture results from the devitrification of the groundmass of volcanic rocks, and is more commonly observed in the rhyolite than in the ash-flow tuff.

SUMMARY

As a result of this study the occurrence of ash-flow tuffs in the Eminence area has been confirmed. Although radiometric dating of the Eminence-area Precambrian rocks has not yet been done, our study indicates that the volcanic rocks are similar in every respect to those of the St. Francois Mountains and are representatives of the same Precambrian terrane, thus supporting the ideas of previous investigators.

Correlation between the volcanic rocks of the two principal outcrop areas is not yet possible. The stratigraphy of the volcanic rocks in the Eminence area should be defined first on the basis of more detailed mapping of the entire area at the 1:24,000 scale. Our study and reconnaissance mapping in the area by G. Kisvarsanyi, however, suggest that

the Stegall-Mule Mountains section may be correlated with that observed on Jerktail Mountain, about 10 mi northwest of the study area. The correlation is based on lithologic similarities and sequence analogy between these knobs.

Petrographic modal analyses and chemical analyses based on systematic sampling will have to be employed to a far greater extent than in the past to aid in this work, because the Precambrian outcrops are more restricted and isolated, and because structural relationships will be more difficult to determine in the field. Lithologic similarities between the volcanic rocks of the Eminence area and those of the St. Francois Mountains are not sufficient criteria for precise regional correlation of units in a volcano-stratigraphic sequence.

ACKNOWLEDGMENTS

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PRECAMBRIAN ALGAL STROMATOLITES AND STROMATOLITIC LIMESTONES IN THE ST. FRANCOIS MOUNTAINS OF SOUTHEAST MISSOURI

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INTRODUCTION

Exposed Precambrian rocks in south-central United States are mainly igneous, with ash-flow tuffs, rhyolites, and granitic intrusive rocks predominating. Metamorphic sequences, abundantly represented farther north, in the Canadian Shield, are nearly absent as surface exposures in the Ozarks. Sedimentary rock sequences also are rare in the Precambrian of Missouri.

The Precambrian core of the Ozark Uplift, exposed in the St. Francois Mountains of southeast Missouri, consists of a several-thousand-foot section of bedded and welded tuffs and rhyolites that were intruded by comagmatic granites. Pumpelly (1873) mentions a limestone interbedded with bedded tuffs on Cuthbertson Mountain. Grawe (1943), and Tolman and Robertson (1969), also refer to this occurrence. However, no additional data have been presented other than Pumpelly's inference that the limestone beds might be a lake or fresh-water deposit.

Grawe (1943) considered that the limestone was altered by intrusion; however, Tolman and Robertson (1969) disagree with this interpretation. No evidence of alteration or metamorphism can be detected in the material collected or observed on outcrop. The limestone is aphanitic and is similar to unaltered Precambrian limestones common in the Belt Series of the Central Cordillera.

The predominance of pyroclastic rocks in the Precambrian volcanic sequence of Missouri makes the limestone occurrence on Cuthbertson Mountain

especially interesting because no other such rock has been reported from exposed Precambrian within a 700-mile radius. Presumed Precambrian algal lime-

stones in northern Alabama (Butts, 1926) and Precambrian limestones of the southern Canadian Shield are the closest similar material in outcrop.

LOCATION

The stromatolites and stromatolitic limestones are exposed on the southern slope of Cuthbertson Mountain, south of Arcadia, Iron County, Missouri. Manganese mining in the vicinity temporarily obscured the limited exposures referred to by Pumpelly. Subsequent mining operations and stream runoff have re-exposed and enlarged outcrop areas. The stromatolitic limestones occur near a small draw through the upper part of the main manganese diggings on the south slope of Cuthbertson Mountain (fig. 1). Large boulders of stromatolitic limestone also occur along the eastern side of the diggings. Distinctive algal stromatolites occur farther down-stream on the north side of a tributary downhill from the manganese diggings. The manganese diggings are in SE¼ NW¼ sec. 19, and the distinctive algal stromatolites in the NE¼ NW¼ sec. 19, T. 33 N., R. 4 E. (fig. 1).
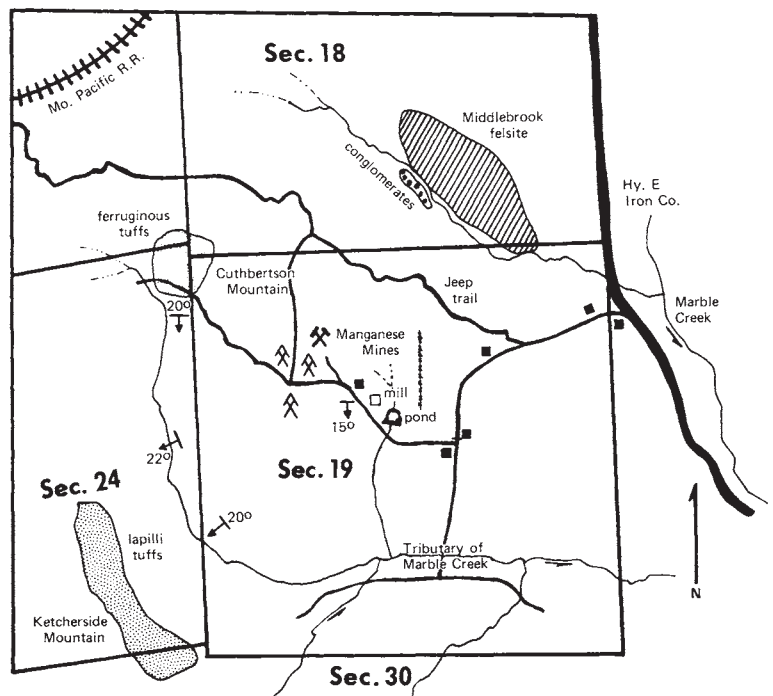

Figure 1

Location of manganese mines and typical Precambrian outcrops in the general area of Cuthbertson Mountain, Iron County, Missouri.

DESCRIPTION OF THE LIMESTONES

The limestones exposed on Cuthbertson Mountain are variable and exhibit various kinds of stromatolites, massive aphanitic limestone, and limestone interbedded with tuff. Two separate occurrences are known on Cuthbertson Mountain (fig. 2). One is massive limestone, 1 to 1.15 m thick, pigmented red with hematite. It is exposed at a number of places in the manganese diggings and is probably the limestone mentioned by Pumpelly. Red to red-brown

tuffs that contain fragments of laminar and digitate stromatolites, limestone, and oncolites overlie the massive limestone. Limestone and stromatolite fragments are angular, but usually have been removed by weathering. This material is red-brown, soft, manganese-stained tuff, full of numerous cavities caused by solution of the limestone clasts. A residue of Fe and Mn oxides frequently occupies freshly broken cavities. Freshly broken pieces of this rock

reveal an unweathered interior in which limestone clasts are still intact. Pockets of black, powdery manganese dioxide mixed with ferric oxide are often associated with these rocks.

The manganese-rich materials are identical to residual materials left by solution of limestone clasts in the reddish tuffs, and they are believed to represent residual material from the weathering and solution of an unknown thickness of massive

limestone. The residual materials are approximately 4 to 5 m thick and may represent the remains of a limestone sequence of possibly twice that thickness.

The stratigraphically lower, stromatolitic limestone (fig. 2) consists of thin bands or beds of stromatolite interbedded with greenish, bedded tuffs. Solution of the limestone layer is also extensive here; however, the predominance of tuffs over limestone at this location has protected the thin limestone bands to a greater extent. A powdery, black, manganiferous residue occupies solution cavities of stromatolites, as in the stratigraphically higher occurrence. These zones can be observed in outcrop on the side of a small intermittent stream (fig. 2).
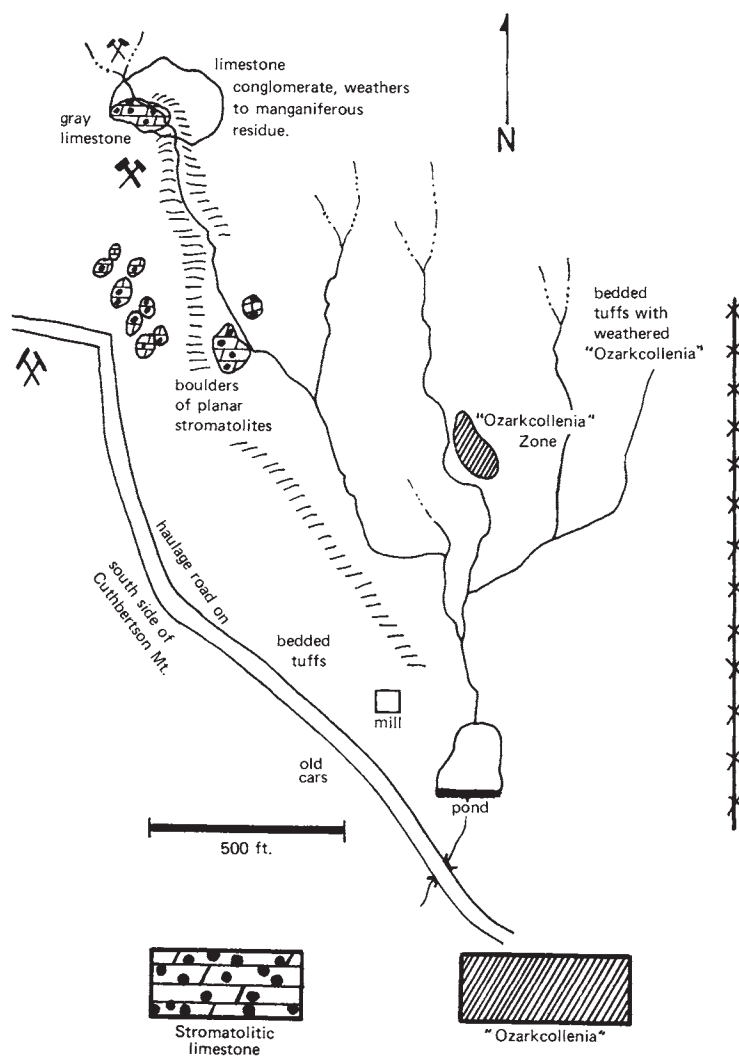

Figure 2

Location of stromatolitic-limestone outcrops in the vicinity of the manganese diggings on the southern slope of Cuthbertson Mountain.

STROMATOLITIC STRUCTURES

Four types of stromatolitic structures were identified in the limestones; there are also mixtures of the first three types.

TYPE I: DOMAL STROMATOLITES

Poorly formed, domal stromatolites occur in ferruginous limestone that has irregular bedding and is interbedded with ferruginous tuffs. Limestone layers are 2 to 5 mm thick and have a sharp contact with underlying ferruginous tuffs; they grade into overlying ferruginous tuffs or iron formation. The upper parts of limestone layers exhibit a serrated appearance which, under low magnification, reveals a series of small, domal, algal stromatolites (pl. 1, n. 7),suggesting an algal mat.

Algal limestones incorporating Type I structures exhibit the following variations:

I-A: BRECCIATED STROMATOLITES. Unsorted, angular breccia, in which limestone clasts range in size from 2 mm to 1.5 cm (pl. 1, n. 1). These bedded clasts are set in a ferruginous, siliceous matrix which contains silt-sized particles of probable pyroclastic origin.

PLATE 1

Stromatolite morphology in Precambrian limestones from Cuthbertson Mountain, Iron County, Missouri.
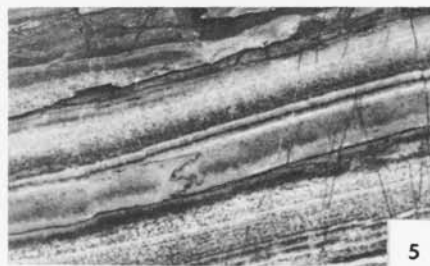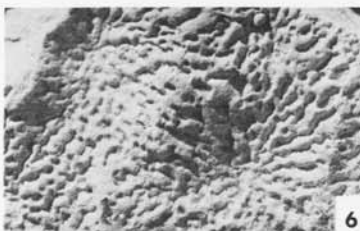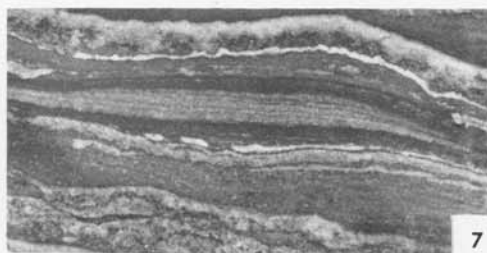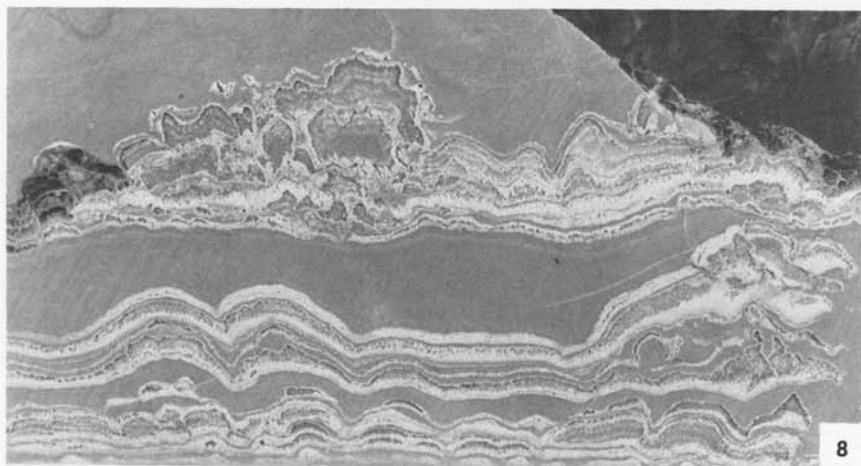

No. 1. Brecciated stromatolites (Type I-A). Breccia clasts are Type I stromatolitic limestone; matrix is ferruginous tuff.

No. 2. Group of domal stromatolites (Type I-B) spaced between laminated stromatolites.

No. 3. Laterally linked hemispheroids (Type I-C) shown as light, serrated lines.

No. 4. Oncolites (Type III). Indistinct concentric banding is visible.

No. 5. Planar stromatolites (Type II). Dark specks are hematite.

No. 6. Impression of upper surface of "Ozarkcollenia" mat. Two domes or hemispheroidal structures are visible; linear pits radiate outward from domes.

No. 7. Domal stromatolite (Type I). Limestone laminae are light; dark layers consist of ferruginous tuff. White band at top consists of small domal stromatolites above ferruginous limestone.

No. 8. Cross section of "Ozarkcollenia" (Type IV) shows series of domes. Two main periods of growth activity are represented, separated by dark, homogeneous tuff. Stromatolite in the younger layer is beginning to take on digitate appearance.

0   3 cm

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I-B: DOMAL STROMATOLITES. Domal stromatolites are generally small and poorly formed (pl. 1, n. 2). They occur as slender columns of stacked hemispheroids of the type LLH-S of Logan et al. (1964). Distinct, well-formed structures of this type are rare; however, sections of digitate stromatolites are a component of the clasts in the breccias. Stromatolitic development is also present above the clasts, in which case the clasts apparently acted as a substratum.

I-C: LATERALLY LINKED HEMISPHEROIDS. Stromatolitic development parallels a layer of limestone and produces a small series of laterally linked hemispheroids, 2 to 3 mm in diameter (pl. 1, n. 3). These are generally small structures and appear as undulating surfaces or, in plane section, as serrated lines. They might be described as a diminutive form of LLH-S/LLH-C (Logan et al., 1964). This type of small stromatolite is generally adjacent to or covered by a layer of ferruginous pyroclastic material. The stromatolitic bands are not more than 2 mm thick and are interbedded with pyroclastic and clastic layers that are 1 to 3 cm thick. Deeply weathered bedding surfaces of Type I-C, where the limestone has been dissolved, exhibit a characteristic undulating surface. The problematic forms of *Eoclathrus* Squinabol, 1887, or *Rivularites* Fliche, 1905, both in Hantzschel (1962), are suggested by this pattern that is also well represented in the Type IV specimens.

TYPE II: PLANAR STROMATOLITES

Planar stromatolites consist of many thin layers of alternating pink and gray limestone (pl. 1, n. 5). Granules or specks of hematite are embedded in the limestone. The planar stromatolite extends over a 1 to 7 m^2 area or occurs as small patches 10 to 30 cm in diameter. Small planar stromatolites commonly occur as clasts in limestone breccia.

Planar stromatolitic masses grade into massive, gray to pink limestone which shows little other structure. Such a mass is exposed near the middle of the manganese diggings, just south of a small stream that exposes many of the limestone types (fig. 2).

TYPE III: ONCOLITES

Oncolites are locally concentrated in the stromatolitic breccias (pl. 1, n. 4). The oncolites are small, from 0.3 to 1.0 cm in diameter, and their concentric layers are poorly developed and indistinct. They occur sporadically in the limestones and are locally concentrated in pockets.

TYPE IV: "OZARKCOLLENIA"

This is a term used informally here to describe a distinct series of laminar, undulating stromatolites that are interbedded with fine-grained tuffs (pl. 1, n. 8). The stromatolitic layers consist of buff to pink limestone, 0.5 to 5.0 mm thick. Limestone laminae occur in succession and develop a typical undulating surface of spaced, laterally linked hemispheroids (LLH-S of Logan et al., 1964). These stromatolites are developed on plane surfaces of bedded tuffs and alternate with them; the tuff beds appear to be cyclic and more frequent than in Types I or II. Where thickness of tuff beds exceeds 2 or 3 cm, they exhibit graded bedding; the finer grain sizes occur stratigraphically above coarser tuffs.

Stromatolites of this type may extend laterally for 2 m or more as a thin bed of limestone between layers of green or gray, thin-bedded tuffs, in contrast to the rather limited lateral extent of stromatolite Types I, II, and III. The laterally linked hemispheroids of "Ozarkcollenia" are often arranged in plan view in a somewhat circular pattern.

Cross sections of "Ozarkcollenia" are quite intricate and regular. The surface of stromatolitic mats consists of more or less regularly spaced series of small domes that make a distinct pattern of shallow impressions in the overlying tuff beds. Sometimes a set of larger domes or depressions (depending upon whether one is looking at the top of the algal mat or its mold in fine tuffs) is superimposed on the small set of depressions in a circular pattern as illustrated in pl. 1, n. 6. Individual domes occur with their arched surfaces uppermost, and extend above a continuous layer of banded calcium carbonate, 1 to 5 mm thick. The circular arrangement of domes is not always evident, and domes may be spaced randomly (mode S of Logan et al., 1964).

The domes and underlying layers of limestone are formed of indistinct laminae. Their upper surfaces are abruptly terminated by a layer of tuff. Vertical cross sections of the structure show a regular sequence of intricate limestone laminae alternating with tuffs.

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The tops of limestone layers where domes have been intersected have a sinuous pattern.

The upper surface of this form is difficult to separate from overlying tuff beds, as no separation takes place along the stromatolite-tuff interface in unweathered specimens. Deeply weathered tuff that occurs as float on the hillside shows impressions of stromatolitic domes and resembles some of the problematic algal structures described from the Belt Series, like *Camasia* sp. Walcott, 1914.

The Type IV structure is similar to Walcott's description of the form-genus *Collenia*, consisting of a somewhat irregular series of dome-shaped, laminated carbonate structures which grew with the arched surface uppermost. "Ozarkcollenia" differs from the form-genus *Collenia* in its small size, in the strongly arched position of the digitate parts of the structure that rise above the plane of calcareous material, and in the spatial relationships between individual hemispheroids and digitate structures. The structure probably represents a normal mat of blue-green algae that, if allowed to continue to grow and accumulate sediment, most likely would have produced *Collenia*-type stromatolites, or laminar stromatolites of Type II. The frequency with which blankets of volcanic ash covered the algal mats and abruptly terminated their growth is probably the explanation for this stromatolite morphology.

"Ozarkcollenia", in its lack of distinct laminae within thin limestone layers, somewhat suggests a thrombolite; however, the form exhibits more distinct laminae than the type thrombolites described by Aitken (1967).

MICROSCOPIC OBSERVATIONS

Under 200X magnification, the various types of stromatolites show uniform intergrowth of calcite crystals 0.05 to 0.2 mm in length. Margins of oncolites have an increased amount of clastic material and reddish grains, probably hematite. Limestones of Type I exhibit a greater concentration of pyroclastic particles than Types II or III.

Reddish-brown or brown-black bodies, considerably smaller than the calcite crystals, occur in the planar stromatolites and oncolites. These do not show constant morphology and usually occur at crystal contacts. A small and somewhat consistent size is typical of these bodies, and they may be interpreted as macerated and crushed organic, or former organic matter, stained red by ferric iron. They conceivably represent remains or sites of existence of iron-oxidizing bacteria.

Under high optical magnification of 1000X, the stromatolites exhibit a crystalline aggregate of calcite crystals. Indistinct, colorless, linear structures in the 2- to 5-micron range are seen in some thin sections, although these are vague and difficult to photograph.

Good preservation of algal filaments or trichomes would not be expected in a carbonate of this nature, where individual calcite crystals are now larger than the trichomes. The considerable range of lithologic types in the different limestones and algal structures might permit local preservation of the morphology of micro-organisms.

STRATIGRAPHIC RELATIONSHIPS

The limestones on Cuthbertson Mountain are underlain by bedded, water-laid tuffs and overlain by massive ash-flow tuff of Precambrian age. Contacts between various limestone types and overlying and underlying tuff beds are not exposed in all cases, but a general stratigraphic section can be constructed, as shown in figure 3. Tolman and Robertson (1969) assigned the bedded tuffs to the Ketcherside Tuff, which they considered a stratigraphic marker between an underlying older series of extrusive rocks (Middlebrook Group) and an overlying younger series of extrusive rocks (Van East Group). The Middlebrook Group may rest unconformably on older igneous and metamorphic rocks discovered by drilling in other parts of Missouri. The tuff and rhyolite sequence is intruded by granites.
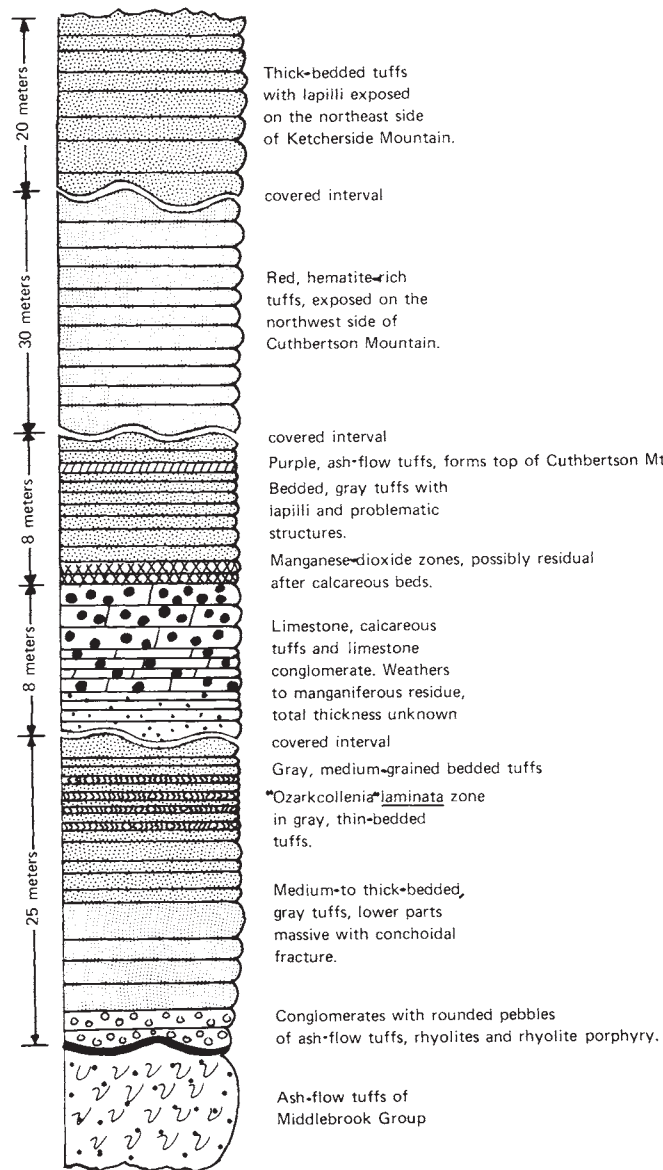
Figure 3

Composite stratigraphic section exposed on Cuthbertson and Ketcherside Mountains, Iron County, Missouri.

The stromatolitic limestone occurs near the middle of the Ketcherside Tuff. Rock ages obtained by Rb-Sr isotope analyses of the volcanic rocks cluster around 1,410 m.y. (Anderson et al., 1969), generally establishing the time of formation of the limestone. Pb-U dates

of zircons give ages of 1,500 m.y. (Bickford and Mose, 1975).

Stratigraphic relationships of the Ozark Precambrian are difficult to determine. Ash-flow tuffs of the Middlebrook Group underlie the Ketcherside Tuff unconformably. Coarse conglomerates containing well-rounded pebbles of purple ash-flow tuff and felsite occur just above massive felsites in a stream valley due north of Cuthbertson Mountain. The conglomerates are considered to be a basal unit of the Ketcherside Tuff, and the apparent unconformity represents an unknown span of time (fig. 3). Apparently overlying the Ketcherside Tuff is an extensive sequence of felsites, ash-flow tuffs, and rhyolites whose stratigraphic and structural relationships are not yet satisfactorily resolved.

Associated with the Ketcherside Tuff on Ketcherside Mountain, 2.1 miles southwest of Cuthbertson Mountain, is an occurrence of tuffaceous, banded iron-formation. It is a banded sequence of jasper, hematite, and tuff, lithologically similar to early or mid-Precambrian banded iron-formation. Exact stratigraphic relationships with the bedded tuffs on Cuthbertson Mountain are not evident; however, the iron-formation appears conformable with bedded tuffs in the immediate vicinity and was mapped with the Ketcherside Tuff by Tolman and Robertson (1969).

PALEOENVIRONMENTS OF THE STRUCTURES

DOMAL STROMATOLITES

These structures are characteristic of algal mats and algal-bound sediments in semiprotected locations. A marine, intertidal, mud-flat environment or sublittoral conditions are suggested. Growth of algal mats was locally terminated by ash falls, and the new surface of pyroclastic materials became a substratum for growth of a new algal mat. Scarcity of large domal stromatolites, that often occur in Precambrian limestones of algal origin, may be due to the repeated

infall of pyroclastic material that terminated algal growth before lateral expansion of the mat could occur. Limestone clasts of Type I-A represent supratidal conditions, where stromatolitic mats were desiccated, broken off, and reincorporated into the main mass.

PLANAR STROMATOLITES

These structures are considered to represent a deeper-water environment than the Type I structures. Planar stromatolites may have formed a base upon which the algal mats and algal-bound sediments of Type I structures have grown. Wave action in some cases was extensive enough to break off parts of the planar stromatolites and produce clasts or pebbles of the structures.

ONCOLITES

The oncolites in the limestones probably represent sublittoral conditions. Fragments of Type I or II structures may have been moved around and agitated, forming a nucleus on which the concentric bands of oncolites developed. Waters of high energy with considerable agitation are suggested.

"OZARKCOLLENIA"

These algal stromatolites are best explained as products of photosynthetic activity by recurring algal mats that grew upon a relatively smooth substratum of previously deposited pyroclastic material. Where algal growth and stromatolite formation were restricted, limestone beds are essentially parallel with the tuff beds. When a period of algal growth was uninterrupted by pyroclastic deposition, development of the raised domes and even digitate-type structures occurred. Development of domes in the algal mats may be attributed to growth of the mat, because domes are not evident on the substratum of the algal mat.

Wave action in the region of growth of Type IV structures was generally less than in that of Types I and III, as few clasts of these stromatolites are seen, and the algal limestone layers are generally continuous. The associated tuff layers contain 1 to 2 percent iron that is present as green or gray ferrous-iron pigment. Possibly, the depositional environment of the tuffs

was deficient in oxidizing potential to oxidize the iron. The presence of a reducing agent, such as organic matter, might be a reason for the ferrous iron; however, tuffs associated with Types I, II, and III, where organic matter should have been present in greater amounts, have a brick-red color from ferric iron.

The ferrous state of iron in tuffs associated with Type IV stromatolites appears to be due to original iron content in the pyroclastic materials, and absence of free (presumably photosynthetic) oxygen. When algal mats flourished, sufficient photosynthetic, free oxygen was locally available to oxidize ferrous iron in solution to ferric iron and to produce the pink or red pigment characteristic of all these limestones. The ferric-oxide pigment may be ascribed to geologically recent weathering, but large masses of unweathered limestone have abundant ferric-oxide pigment distributed to the center of the mass. Abundant algal structures in the limestones suggest that photosynthetic oxygen oxidized the more soluble ferrous iron to a fine, insoluble precipitate of ferric oxide that was incorporated into the stromatolitic limestone.

Phanerozoic algal stromatolites, particularly laminar types, often exhibit evidence of burrowing activity and were described in Cambrian limestones of Missouri (Howe, 1968). Lack of evidence of burrowing organisms and the probable absence of metazoans of any type is consistent with the 1,400 m.y. minimum age of the structures, a time when there was an apparent absence of metazoan heterotrophs (Cloud and Gibor, 1970). If algal browsers or burrowing organisms of any type had been part of the ecosystem during deposition of the fine tuffs, some evidence of disturbance should be present in the fine pyroclastic and algal layers.

It is possible that these limestones are a lake deposit (Grawe, 1943); however, stromatolites and oncolites suggest an environment associated with extensive wave action and possible tidal disturbances typical of a marine environment. Volcanic eruptions and accumulation of thick ash-flow tuffs could have caused the formation of impounded bodies of water where water-laid tuffs formed. Mats of algae would thrive in such a setting between periods of volcanic activity. Stromatolites alternating with bedded tuffs, some of which have graded bedding, suggest such conditions.

Brecciated planar stromatolites and stromatolite frag-
ments, a normal product of extensive wave action,
are the features that suggest a marine environment.
A lacustrine environment is often too restricted in
area to result in conditions favoring extensive wave
action. The possibility exists, however, that wave
action was generated as a result of the volcanic
activity. Stromatolite brecciation could be caused by
seismicity and energy from local volcanic eruptions.

Another interesting possibility is that the limestones
resulted from algal growth near hot-spring activity.
Algal stromatolites readily form in waters of hot-
spring regions today, and it can be assumed that
such growth would be favored in similar situations
in the distant geologic past. The Cyanophyacea are
today one of the few groups of organisms that thrive
in waters of 75° to 80° C (Bold, 1957). A not-

unreasonable model comprises hot-spring activity
feeding into a volcanically formed lake that accumu-
lated layers of volcanic tuff and that allowed the
growth of a mat of the blue-green algae over the
newly deposited pyroclastic layer during periods
of diminished volcanic activity.

The local extent of the limestone is probably more
apparent than real. Favorable topographic conditions,
fairly easy accessibility, and manganese mining
exposed it. Tuff sequences exposed in rugged areas
to the south of Cuthbertson Mountain also contain
this or similar limestones (E.B. Kisvarsanyi, pers.
commun., 1975). The relative nonresistance of the
carbonate rocks to weathering, as compared with
the siliceous tuffs, and their tendency to be
masked by tuff and rhyolite boulders might make
them difficult to locate in natural exposures.

SUMMARY

The scarcity of sedimentary rocks in the Missouri
Precambrian outcrops and the similarity between
the stromatolitic limestones and some Cambrian
carbonate rocks, particularly the red "Taum Sauk
marble", might suggest that the stromatolitic lime-
stones are Cambrian in age. The following observa-
tions negate this possibility:

a. Field relationships show that the limestones are
conformable with underlying bedded tuffs. Over-
lying ash-flow tuffs are also conformable and are
interbedded with the thick Ketcherside Tuff sequence
that is unquestionably Precambrian in age.

b. The stromatolitic limestone, although similar in
some aspects to Cambrian strata, is also quite unique
in its iron content, dense appearance, lack of burrow-
ing, and alternating beds of pyroclastic materials.

c. The variety of different types of stromatolites in
even a small sample of this limestone is greater than
in most Cambrian carbonate rocks of the Ozarks.

d. Banded iron-formation is found interbedded with
the Ketcherside Tuff a few miles from the algal
stromatolite occurrence; iron-formation is not a
Paleozoic lithologic type.

ACKNOWLEDGMENTS

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PETROLOGY OF THE MUDLICK DELLENITE, ST. FRANCOIS MOUNTAINS, MISSOURI

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INTRODUCTION

The Mudlick Dellenite is exposed in the southern-most part of the main area of exposed Precambrian rocks in southeast Missouri (fig. 1), in Iron and Wayne Counties. It is one of the mapped units of the St. Francois Mountains igneous complex, about which relatively little is known. Haworth (1894) first described it as a porphyry. In the late 1950's Tolman and Robertson named it the Mudlick latite from exposures on Mudlick Mountain in Wayne County, and grouped it with the granites (Hayes, 1961). They revised the name to dellenite, a synonym for quartz latite, and assigned the rock to the felsites in their 1969 publication. Three chemical analyses of the rock indicated petrochemical similarities to the Musco group of granites (E.B. Kisvarsanyi, 1972).

Tolman and Robertson (1969) described the Mudlick Dellenite as a sill-like mass striking about N 50° W and dipping not more than 5° to the north. This conclusion was based on observation of intrusive relationships to underlying tuffs and absence of distinctive extrusive and pyroclastic characteristics. They observed linear features and vertical zoning, with plagioclase phenocrysts more abundant near the bottom, and orthoclase phenocrysts more abundant near the top of the igneous body.

The petrographic and chemical characteristics of the Mudlick Dellenite were determined on the basis of detailed sampling from its outcrop area and 18 new chemical analyses (Malkames, 1974). This report is a concise summary of the results of that investigation.

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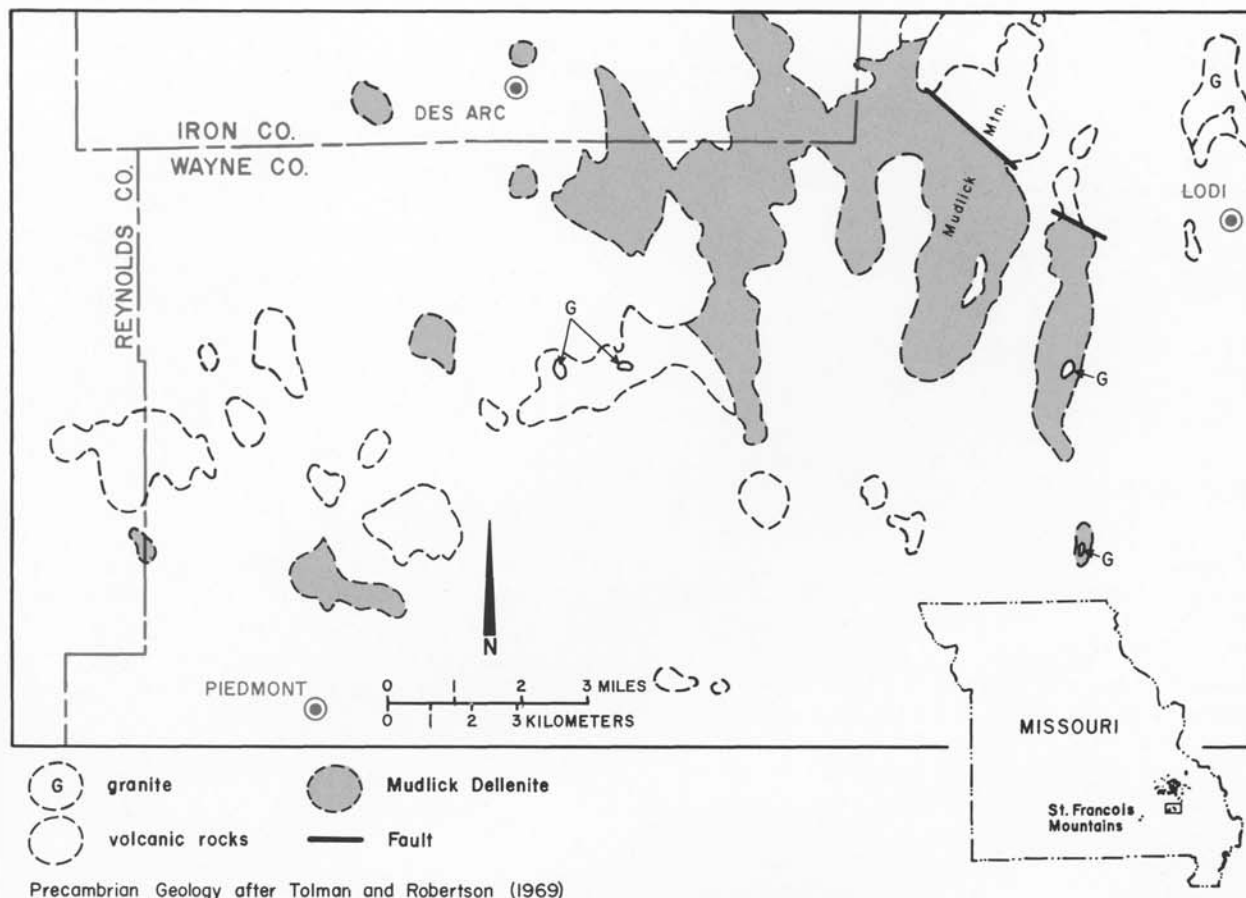
Precambrian Geology after Tolman and Robertson (1969)

Figure 1

Outcrops of Mudlick Dellenite in Iron and Wayne Counties.

PETROGRAPHIC DESCRIPTION

The Mudlick Dellenite is a blue-gray, fine-grained, porphyritic rock, commonly known in the area as "blue granite", and locally used as a building stone. In hand specimens, the larger phenocrysts appear to be plagioclase and the smaller ones orthoclase. Thin sections show that the larger phenocrysts are altered plagioclase, sometimes rimmed with orthoclase. These phenocrysts are usually highly altered and it is impossible to determine their composition. Occasionally, large, square phenocrysts of microcline are present. Elongate, rectangular phenocrysts are most commonly orthoclase, and the small phenocrysts are fresh oligoclase. The presence of highly

altered, large plagioclase phenocrysts and essentially unaltered, small plagioclase phenocrysts implies that the phenocrysts are of two different compositions.

The groundmass is a very fine-grained, microgranular to micrographic intergrowth of quartz and orthoclase, coarsening to a poikilitic texture near the top of the rock mass. Epidote and clinozoisite are common in the groundmass, either alone or associated with magnetite-ilmenite grains. Chlorite is found occasionally and is associated with the epidote and clinozoisite, or contained within altered plagioclase phenocrysts. The alteration minerals give the rock a

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greenish cast. Crystals of apatite and zircon are sometimes found in conjunction with epidote and clinozoisite.

Alteration of the rock is primarily shown by alteration of plagioclase phenocrysts to sericite and chlorite, and by the presence of epidote and chlorite associated with magnetite-ilmenite grains or disseminated throughout the groundmass. Epidote also occurs with secondary quartz in fractures. Because

of the close clustering of normative feldspar compositions on Ab:An:Or diagrams and the similar compositions of plagioclase, as determined both by measurement of extinction angles in thin sections and by the normative Ab:An ratio, it appears that the overall chemistry of the rock has not been changed much. The alteration is of a type generally caused by hot solutions and is probably related to later igneous activity in the St. Francois Mountains complex.

PETROCHEMICAL DATA

Samples were taken from most outcrops visited and, in particular, a set of samples was taken from Mudlick Mountain, the area of thickest exposure of Mudlick Dellenite, at about 50-ft vertical intervals. The locations of the samples analyzed are given by Malkames (1974). Results of the Chemical analyses are shown in table 1.

Preparation of samples for analysis was done according to the methods of Shapiro and Brannock (1962). Determinations of MnO, Al_2O_3, MgO, TiO_2, NiO, and Cr_2O_3 were done by atomic-absorption spectrophotometry on a Perkin-Elmer Model 107 atomic-absorption unit by standard methods (Perkin-Elmer, 1973). Analyses for Na_2O and K_2O were done by flame emission on the same instrument. Because of complexing with Al and Si (Angino and Billings, 1967), the CaO values found by atomic absorption were anomalously low. Calcium determinations were redone by X-ray fluor-

escence, and these values were used. SiO_2 was determined by a colorimetric method (Rainwater and Thatcher, 1960). Reichen and Fahey's (1962) method was used to determine FeO. Total iron was determined by atomic absorption, and Fe_2O_3 was determined by the difference between total iron and FeO.

The normative mineralogy was calculated by use of a computer program (Malkames, 1974, tbl. 4 and app. 2). Niggli values were calculated from the chemical analyses by methods devised by Niggli (1954). They are the equivalent amounts of oxides calculated from the weight percentages. The calculated values show the same ratios to one another as the oxide molecules present in the sample. The equivalent units that are closely related can be added together in groups. Niggli values give a more convenient, graphical method of comparison of the various oxides than direct comparison; they are given in table 5 by Malkames (1974).

DISCUSSION

NOMENCLATURE

Because of implication of extrusive characteristics by the name "dellenite", the writers considered the possibility of renaming the Mudlick "dellenite" using chemical and normative criteria. Normative mineral values of the samples were plotted on Streckeisen's (1967) Q-A-P diagram (fig. 2) in order to classify the

rock. The points fall in subfield 3b of the granite field. This field in plutonic rocks is called granite by Streckeisen. In the nomenclature for hypabyssal rocks, the rather cumbersome terms micromonzogranite or monzogranite porphyry correspond to this composition. In the volcanic rocks the Mudlick corresponds to rhyodacite, which is a synonym for quartz latite which, in turn, is a synonym for

TABLE 1
CHEMICAL ANALYSES OF MUDLICK DELLENITE
(in weight percent of oxides)

No.	9	14	15	19	41	46	48	50	64	65	67	70
SiO_2	67.91	68.53	68.21	66.51	62.97	65.43	68.02	67.14	64.83	62.91	69.93	65.12
Al_2O_3	15.34	15.27	15.59	15.59	15.59	15.30	15.49	15.74	15.54	16.26	15.56	15.14
Fe_2O_3	2.45	.67	2.03	.83	2.98	2.21	2.65	1.88	2.02	2.99	2.98	1.16
FeO	3.23	5.20	3.95	4.52	3.36	4.01	3.24	2.27	3.78	3.05	3.05	3.99
MgO	1.66	1.72	1.82	1.74	1.91	2.36	1.48	1.37	1.77	1.81	1.68	1.48
CaO	1.53	1.12	1.48	1.33	1.26	1.39	1.94	1.07	.85	.91	.96	1.15
Na_2O	3.50	3.45	3.84	4.08	2.99	3.94	3.57	3.10	3.91	3.40	3.40	2.99
K_2O	4.89	4.81	4.12	4.81	5.14	5.11	4.30	5.40	4.37	5.49	5.43	4.88
TiO_2	.79	.76	.73	.70	.67	.71	.70	.62	.72	.74	.76	.75
P_2O_5												
MnO	.08	.07	.07	.06	.07	.07	.07	.05	.04	.05	.06	.08
Zr_2O_3												
Cr_2O_3	.26	.30	.28	.27	.29	.25	.26	.28	.27	.29	.27	.25
NiO	.03	.02	.02	.02	.02	.02	.01	.02	.02	.02	.02	.02
Total	101.67	101.92	192.50	100.46	97.25	100.80	101.73	98.94	98.12	97.92	104.10	97.01

No.	91	92	104	105	171	172	29*	30*	31*	141**	198**	197**
SiO_2	66.71	66.35	66.51	65.26	65.54	66.91	69.23	68.61	68.38	68.36	69.48	69.95
Al_2O_3	15.53	16.02	16.34	16.21	15.78	15.87	13.83	14.84	13.94	13.24	13.88	14.78
Fe_2O_3	3.28	2.08	2.82	2.50	1.22	.57	1.50	1.48	2.20	1.29	2.67	1.54
FeO	3.06	3.93	3.57	3.34	4.23	5.23	3.31	5.40	3.14	3.39	1.53	1.75
MgO	1.73	1.73	1.86	1.79	1.50	1.86	.81	.63	.63	1.15	.71	1.05
CaO	1.03	1.44	.80	1.48	1.38	1.36	1.74	1.65	1.70	2.51	2.39	1.88
Na_2O	3.59	3.05	3.59	3.10	3.88	3.59	3.09	3.70	2.73	2.05	3.74	2.92
K_2O	4.58	4.84	5.06	4.77	4.22	4.87	4.49	2.28	5.12	5.34	4.44	4.16
TiO_2	.72	.67	.73	.75	.67	.69	.62	.00	.77			
P_2O_5							.16	.23	.21			
MnO	.06	.08	.08	.07	.05	.07	.09	.00	.10	.27	.15	.43
Zr_2O_3									.04			
Cr_2O_3	.29	.29	.23	.28	.25	.27						
NiO	.02	.00	.02	.02	.02	.02						
Total	100.60	100.48	101.61	99.57	98.74	102.31	98.94	95.82	98.96	97.60	98.99	98.43

*Analyses from E.B. Kisvarsanyi (1972).

**Analyses from Washington (1917).

dellenite. Because of the compositional similarity, the near-surface formation of the rock, and the fact that the name dellenite is already in the literature, the writers continue using the name "dellenite" without implication of an extrusive origin.

PETROCHEMICAL RELATIONSHIPS

Comparison of Niggli values calculated from the new chemical analyses with those of the other rock types of the St. Francois Mountains igneous complex (E.B. Kisvarsanyi, 1972) indicates that the Mudlick Dellenite is generally lower in silica (si values 258 to 303; Malkames, 1974) than the majority of the granites and rhyolites in the province. The dellenite is a calcium-poor rock (c values 3 to 8), but the majority of granites and rhyolites in the St. Francois Mountains are also calcium-poor and the Mudlick samples fall within the range of Musco and Bevos Group
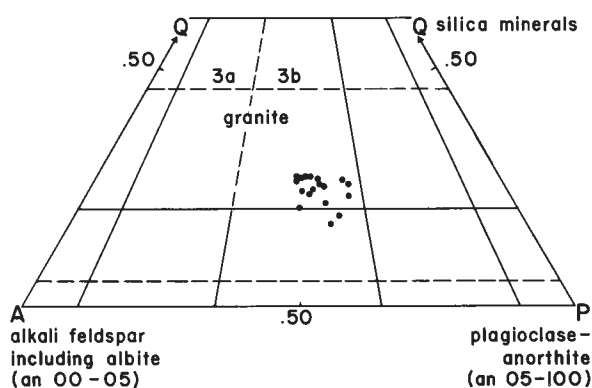
Figure 2

Normative quartz-alkali feldspar-plagioclase composition of Mudlick Dellenite (Q-A-P diagram after Streckeisen, 1967).

granites. The dellenite is generally higher in titanium (ti values 1.8 to 2.9) than other rocks of the province.

The Mudlick Dellenite is relatively more enriched in ferromagnesian constituents than the other rock types in the St. Francois Mountains. The ratio of alumina to alkalies indicates that the rock is subperalkalic, but is slightly lower in both alumina and alkalies than most of the other acidic rocks of the region. The Niggli k values indicate that K_2O is slightly in excess of Na_2O in all Mudlick Dellenite samples. The rock is higher in MgO (mg values) than most of the other rocks of the St. Francois igneous complex.

Both the normative mineralogy and the Niggli values suggest that the Mudlick Dellenite is more closely related to rocks of the Bevos and Van East Groups than to the other rocks of the igneous complex. Niggli values of the Van East Group correspond to those of the Mudlick most frequently in different comparisons (k, ti, al:fm, al:alk), although those of the Bevos Group better correspond to the Mudlick in some specific comparisons (c, k). The only exception is the Knoblick Granite of the Bevos Group, which is distinctly different from the dellenite in petrochemical comparisons in spite of the fact that petrographically it has been called a quartz monzonite (Tolman and Robertson, 1969).

CONDITIONS OF CRYSTALLIZATION

In order to estimate the conditions of crystallization, the normative feldspars and quartz were recalculated to 100 percent and compared with experimental data on crystallization of melts at various temperatures and pressures (Tuttle and Bowen, 1958). On the Ab:An:Or diagram (fig. 3), the Mudlick Dellenite plots on both sides of the curve separating the field of two feldspars from that of one feldspar on the liquidus surface representing volcanic conditions, or essentially 0 bars water-vapor pressure. Many of the Mudlick samples contain two feldspars as phenocrysts, which means that they must have begun to crystallize in the two-feldspar field. If the curve separating the one- and two-feldspar fields is redrawn to include all the Mudlick samples in the two-feldspar field, and the water-vapor pressure of this new boundary curve is estimated by its position relative to the experimentally determined 0-bars and 3,500-bars curves, it is found that the Mudlick Dellenite crystallized at a pressure of at least 500 bars, which is equivalent to a depth of at least 5,000 feet.

Textures observed in thin sections also suggest crystallization under low pressures. The groundmass of the Mudlick Dellenite has a very fine-grained, micrographic to poikilitic texture, indicating that it was quickly chilled. However, the distinctive lack of glass shards, flow structures, or other extrusive characteristics indicates that it was not a surface flow. The textural evidence, the low pressure and shallow depth of crystallization corroborate Tolman
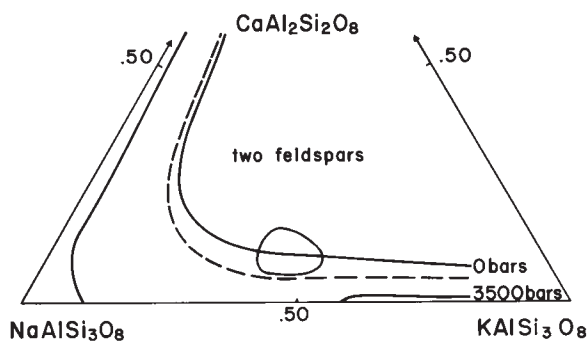

Figure 3

Mudlick Dellenite field compared to one- and two-feldspar field-boundary curves at various pressures (after Tuttle and Bowen, 1958).
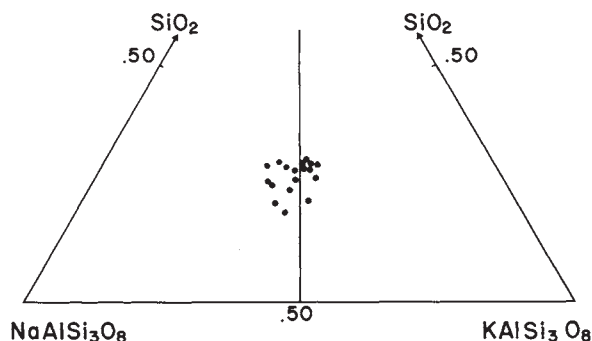
Figure 4

Normative quartz-albite-orthoclase composition of Mudlick Dellenite.

and Robertson's (1969) contention that the Mudlick Dellenite was emplaced as a shallow intrusive. Field evidence suggests that the Mudlick Dellenite is possibly a sill.

The temperature of crystallization was estimated by comparing the composition of normative minerals on the Qtz:Ab:Or diagram (fig. 4) with melting temperatures along a line from SiO_2 to $Ab_{50}Or_{50}$ (fig. 5) from Tuttle and Bowen (1958). Since the Mudlick points are clustered around the SiO_2-$Ab_{50}Or_{50}$ line on figure 4, it is reasonable to estimate, from figure 5, the temperature of formation at 795° to $830^{\circ}C$. This curve is plotted for 1,000 bars water-vapor pressure, so temperatures would be slightly higher at lower pressures, or lower at higher pressures. The slightly higher calcium content of the plagioclase might also raise the melting curve slightly, and the presence of other components might tend to lower it somewhat.

In summary, the Mudlick Dellenite appears to have crystallized at relatively near-surface conditions, with crystallization beginning at a depth of at least 5,000 feet, with pressures of about 500 bars or greater and at temperatures of perhaps 795° to $830^{\circ}C$.

VARIATION OF COMPOSITION IN A VERTICAL SECTION

Samples collected from a traverse across Mudlick Mountain in northwestern Wayne County (fig. 1)

represent a vertical section of about 800 ft in Mudlick Dellenite. These samples indicate a systematic increase in the amount of CaO from the bottom to the top of the section (fig. 6). Normative anorthite and Niggli c values show similar trends. Na_2O and albite have the lowest values near the center of the section and higher values at both the top and bottom. The Ab:An and Na_2O:CaO ratios generally decrease toward the top of the vertical section (fig. 7).

In the thin sections prepared from the Mudlick Mountain traverse two parameters were observed to change systematically. First, the grain size of the groundmass gradually increases towards the top to a micropoikilitic texture. Second, the anorthite content in plagioclase phenocrysts, as determined by measurement of extinction angles on twinned crystals and by the optic sign, increases slightly toward the top of the igneous body.

The significance of the textural and chemical variations observed in samples representing the vertical section on Mudlick Mountain is not clear. The increase in
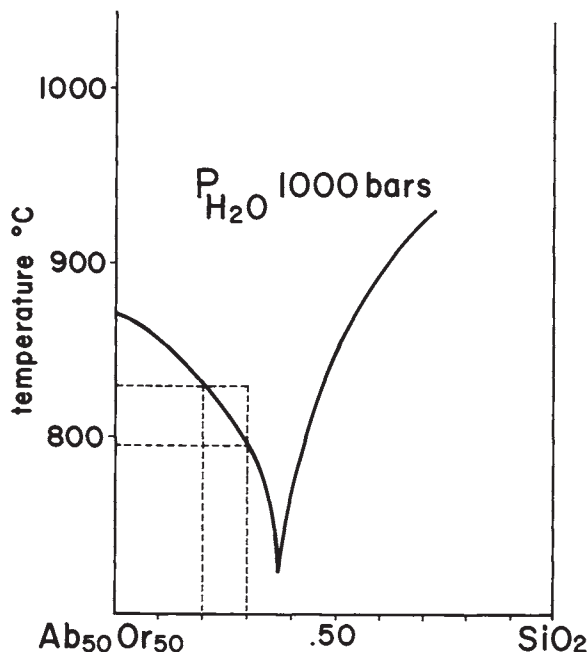

Figure 5

Melting temperatures along SiO_2-$Ab_{50}Or_{50}$ line at 1,000 bars water-vapor pressure (after Tuttle and Bowen, 1958).
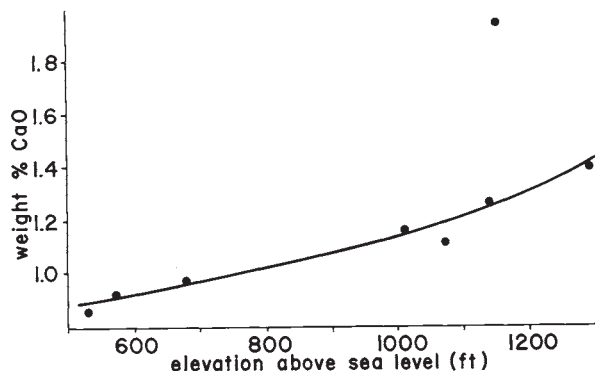
Figure 6

Variation in CaO content through Mudlick Mountain section.

grain size of the groundmass suggests that the emplacement conditions were more conducive to crystallization at a slower pace higher in the section, unlike the rapidly crystallizing crust of an extrusive rock. The slight concentration of Na_2O near the upper and lower parts of the section might have significance relative to the environment of crystallization of the body in combination with upward-decreasing $Na_2O:CaO$ ratios and increasing anorthite content of the phenocrysts.

Several models can be proposed to explain the coarsening of the groundmass near the top of the Mudlick Dellenite body. The first model invokes several successive intrusions, one on top of the other. Each intrusion heated the roof rock slightly, with the result that the later, higher stages of the intrusion had a warmer environment in which to crystallize and therefore crystallized more slowly and more coarsely.

The second model suggests that the gases in the magma rose through the intrusive body and as a result the upper levels were more fluid. Because of this, the upper part of the Mudlick Dellenite would have crystallized more coarsely.

In the third model, the entire body of the dellenite crystallized rapidly, with a fine-grained groundmass. The mass was then deeply buried and intruded by granite. The intrusion of granite could cause a recrystallization of the upper level of the dellenite body.

These three models give possible explanations for the coarsening of the groundmass toward the top of the Mudlick Dellenite, but only the first can reasonably explain the mineralogical and chemical variations. The reversed anorthite concentration in the Mudlick Dellenite body, and the upward-coarsening character of the groundmass suggest an intrusion in layers from a partially differentiated magma chamber.

In the earliest stage of intrusion, magma originates from the upper part of the magma chamber and contains less CaO and more Na_2O in phenocrysts. As magma is taken from lower levels in the magma chamber and is spread above previously intruded material, the amount of CaO increases and the Ab:An ratio decreases. As the lowest part of the magma chamber is emptied, the majority of phenocrysts are previously settled plagioclase, and phenocrysts are more abundant and richer in the anorthite component. This produces the higher concentration of CaO and Na_2O in the higher levels, with the CaO concentration high enough to produce the lowered Ab:An ratio. As each intrusion is injected above the preceding one, the anorthite content is increased and the roof rock is warmed to allow a more coarsely crystallized groundmass.
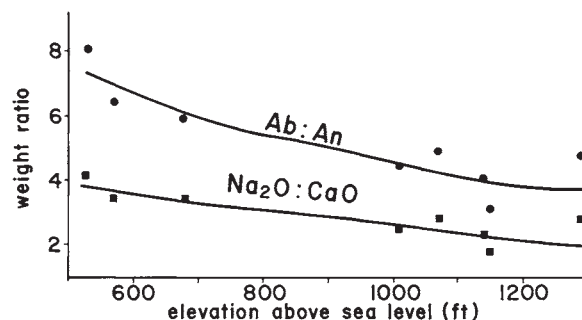

Figure 7

Variation in Ab:An and $Na_2O:CaO$ ratios through Mudlick Mountain section.

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PETROGRAPHY OF PRECAMBRIAN ROCKS IN THE HAWN STATE PARK AREA, STE. GENEVIEVE COUNTY, MISSOURI

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INTRODUCTION

The crystalline rocks which are the subject of this report are exposed in the drainages of Jonca and Pickle Creeks in the vicinity of Hawn State Park (T. 36 N., R. 7 E.) in Ste. Genevieve County, Missouri. These exposures of Precambrian rock are structurally situtated along the axis of the NW-SE-trending Farmington anticline (McCracken, 1971), which locally coincides with a drainage divide in the area.

The first published map to show the general distribution of Precambrian rock types in Ste. Genevieve County was that of Haworth (1895). Weller and St. Clair (1928) published very generalized descriptions of the Precambrian rocks of Ste. Genevieve County and indicated their distribution on an accompanying map. The unpublished thesis by Kidwell (1942) provided the best description, by far, of these Precambrian rocks.

GEOLOGIC RELATIONSHIPS

The Precambrian rocks in the Hawn State Park area are the northeasternmost exposure of the St. Francois Mountains igneous province. They are of particular petrologic interest because of recent suggestions that they may represent the deepest exposed level of a well-preserved volcanic-plutonic complex which has

been tilted to the west or southwest (Lowell, in press; Bickford and Mose, 1975).

Wheeler (1965) also discussed these rocks, in connection with his overthrust hypothesis, as representing the true (autochthonous) structural apex of the Ozark Dome. Whatever the tectonic interpretation, the crystalline rocks of the Hawn State Park area display a compositional and textural diversity not encountered elsewhere in the surface exposures of the Missouri Precambrian terrane. What follows is a general petrographic description of the major rock types exposed in the Hawn State Park vicinity. Mineral-composition data, major-element chemistry, and selected-trace-element data will appear in a subsequent paper (Lowell, Bickford, and Sides, in prep.).

METAMORPHIC ROCKS AND ASSOCIATED DIKES

GRANODIORITE GNEISS

The oldest rock exposed in the Hawn State Park area occurs along the footpath which follows Pickle Creek north from the park picnic grounds (NW¼ sec. 14, T. 36 N., R. 7 E.). Weller and St. Clair (1928) reported that "gray granite" is younger than "red granite" in this location, but this is not correct. In spite of very limited outcrop area and obscured contacts, it is easily shown that the opposite is true. Evidence for this contention consists of: (a) numerous inclusions of gray, foliated granodiorite in blocks ranging up to 5 ft in diameter which are enveloped by pink granite along Pickle Creek; (b) veinlets of posttectonic granitic material which cut across the foliation of the gray gneiss in boulders along Pickle Creek; and (c) float from a prospect pit along the inferred contact between the granite and the granodiorite gneiss which includes fragments of sericitized and epidotized granodiorite gneiss (epidote replacement zones cut foliation). Some confusion no doubt resulted from the convention of mapping all gray, acidic rocks in the area as "gray granite" (Kidwell, 1942). In the context of this paper that designation would include both the granodiorite gneiss (pre-granite age) in Pickle Creek and small, isolated intrusions of biotite-granodiorite porphyry (possibly of post-granite age) found along Jonca Creek and the upper reaches of Pickle Creek (fig. 1).

The granodiorite gneiss possesses a penetrative foliation which ranges from gneissic in coarse-grained samples to nearly schistose in fine-grained samples.

Mafic schlieren are numerous; some tend to parallel the foliation, others tend to disrupt it. Thin, pre-tectonic, aplitic veinlets are cut by the foliation. Microscopically, the general texture is decussate-granoblastic, and the average modal composition is about 60 percent plagioclase, 15 percent quartz, 15 percent hornblende and biotite, and 10 percent mesoperthite. Apatite, zircon, sphene, and opaques are the typical accessory minerals. Locally, the biotite-hornblende content may approach 40 percent.

The plagioclase appears to be of two generations. The pretectonic grains of plagioclase are larger and more altered than the syntectonic grains and display concentric zoning, twin-lamellae deformation, and some mortar structure. The less-abundant, syntectonic plagioclase appears mainly as rounded grains, with both Carlsbad and albite twinning, often poikiloblastically enclosed by hornblende or biotite. The plagioclase composition is in the range of calcic oligoclase to sodic andesine. Quartz is present as unaltered, rounded, interstitial grains with undulatory extinction, and as poikiloblastic inclusions in biotite and hornblende. Both brown (pretectonic?) and green (syntectonic?) biotite are present as ragged, kinked grains often displaying polysynthetic twinning. In some sections the biotite is riddled with inclusions of apatite, sphene, zircon, quartz, plagioclase, and opaque grains. The hornblende is frequently kinked and twinned, sometimes shows mortar structure. and contains inclusions of quartz and plagioclase. Microcline is present in small amounts as patchwise replacements of quartz and plagioclase which produce

"ice cake" texture. Minor pale-green muscovite was noted in a few sections. Myrmekite occurs along some microcline-plagioclase grain boundaries. Meso-perthite, showing excellent braid-and-ribbon texture, is present in small amounts.

Microscopic examination of the mafic schlieren indicates an assemblage of hornblende, green biotite, quartz, later plagioclase, and opaque grains with a granoblastic-elongate texture. Only a few remnant early-plagioclase grains persist in the schlieren and these possess distinct mortar structure.

Field and petrographic evidence suggest that the granodiorite gneiss is a piece of older basement crust which was transported surfaceward as a xenolith. U-Pb measurements on zircon separates, however, yield a probable crystallization age of 1,500 ± 30 m.y. (Bickford and Mose, 1975), which appears incompatible with the interpretation that the gneiss is older, unless the zircons have been completely reset.

BIOTITE-GRANITE PEGMATITE

The granodiorite gneiss contains a poorly exposed dike (?) of very coarse-grained biotite-granite pegmatite just off the footpath along Pickle Creek and north of the picnic grounds of Hawn State Park. According to Weller and St. Clair (1928), this deposit was once worked commercially for feldspar under the name "Niedringhaus Pegmatite Pit".

The rock is pink to red in color, has well-developed graphic texture, and contains books of bronzy, euhedral biotite up to 5 inches in length. The major components of the rock are very large (over 1 inch) crystals of pink microcline-microperthite (string perthite) with faint gridiron twinning, kink banding, and mortar structure along grain boundaries. Quartz is present as optically continuous, graphic inter-growths in microcline hosts and as ragged anhedra riddled with trains of fluid inclusions. It has undulatory extinction. A small amount of strongly sericitized euhedral to subhedral sodic plagioclase is present. Giant crystals of bronzy to green biotite replace both plagioclase and microcline-microperthite and exhibit abundant opaque grains (magnetite?) along cleavages. Quartz replaces plagioclase, fills the sheared grain boundaries around microcline, and

Precambrian rocks
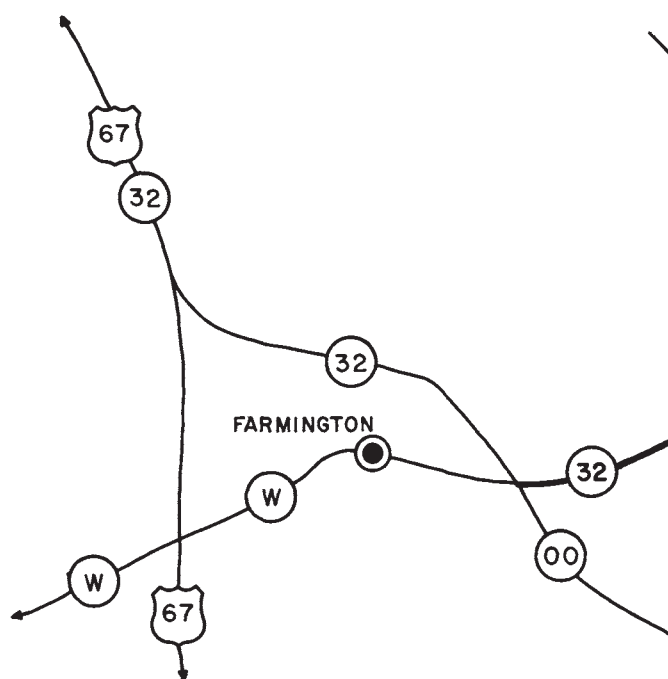
Plutonic rocks

g   Granite undifferentiated

Biotite granite
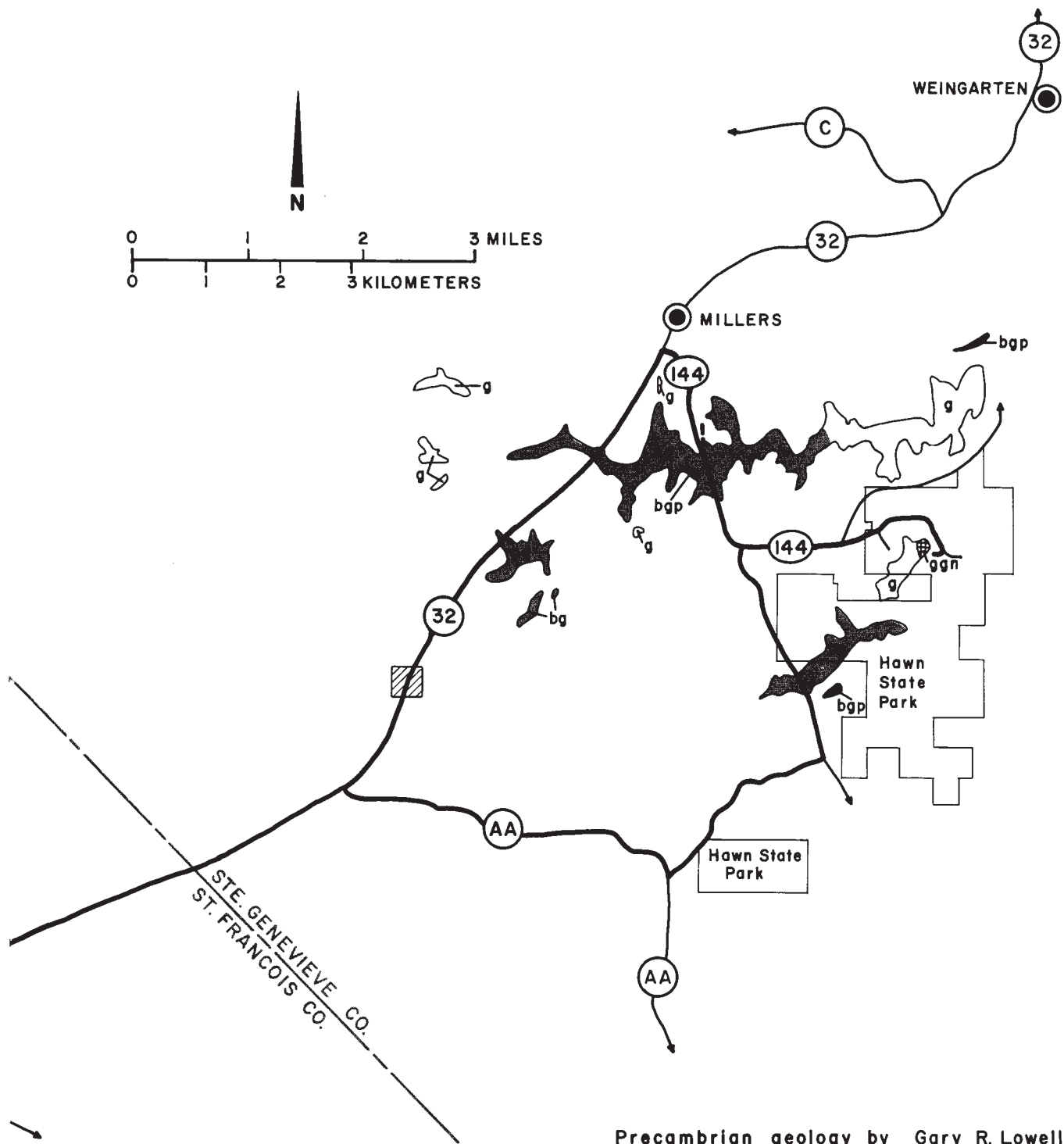
Biotite granodiorite porphyry

Metamorphic rocks

ggn   Granodiorite gneiss

Post-Devonian intrusive rocks

Ultramafic diatreme

- - - -   Fault, inferred

Precambrian geology by Gary R. Lowell

Figure 1

Map showing Precambrian rocks and post-Devonian intrusive rocks in Ste. Genevieve County.

partially envelopes biotite. Paragenetic relationships between quartz and biotite are not clear from the sections studied. Accessory minerals consist of zircon inclusions in microcline, plagioclase, and biotite, and apatite inclusions in plagioclase. The modal composi-

tion of the pegmatite is that of granite. To the author's knowledge, this type of pegmatite is unknown elsewhere in the St. Francois Mountains. Since it is apparently restricted to the granodiorite gneiss, it further contributes to the unique aspects of that body.

PLUTONIC ROCKS AND ASSOCIATED DIKES

A large number of textural variants of plutonic rocks can be mapped from the outcrops of igneous rock in the Hawn State Park area. However, the lack of a suitable base map for the western portion of the Weingarten 15-minute quadrangle (1907) and the absence of detailed chemical and isotopic data necessitate, for the present at least, rather broad groupings for these rocks. Accordingly, the following informal field designations are adopted for descriptive purposes in this paper. The order of presentation does not imply relative age relationships among the units. The dikes, of course, are younger than their hosts, but no other age relationships are known with certainty at present.

BIOTITE-GRANODIORITE PORPHYRY

Several small, isolated outcrops of biotite-granodiorite porphyry are found in the Hawn Park vicinity (fig. 1). The best-exposed of these is found in NW¼ sec. 22, T. 36 N., R. 7 E., where the rock weathers to prominent spheroidal boulders. Typically, the fresh rock is medium-grained, pinkish-gray, phaneritic-seriate to phanerophyric, and possesses numerous small clots of fresh, equant biotite grains. Microscopically, the texture is hypidiomorphic-granular; euhedral and subhedral grains are very sparse, however. The modal composition is estimated as 30 percent intermediate plagioclase, 25 percent quartz, 25 percent biotite, 15 percent microcline-microperthite, and 3 percent hornblende. Zircon, apatite, and opaque grains are present as accessory minerals, and muscovite, hematite, and clay are found as secondary minerals. At the locality along Jonca Creek (sec. 9) miarolitic cavities containing fluorite, quartz, and pyrite were observed in float samples.

The plagioclase phenocrysts are zoned, rounded, partially altered to clay, and twinned by both the Carlsbad and albite laws. Anhedral, microperthitic microcline commonly replaces and rims the corroded plagioclase phenocrysts, forming "anti-rapakivi" texture. Neither granophyric intergrowths nor myrmekite were present in any of the sections examined. Brown and green varieties of biotite are each present as subhedral grains; the green biotite contains inclusions of brown biotite. Biotite replaces twinned hornblende along its cleavages and embays it along grain boundaries. A few inclusions of feldspar and pyroxene(?) were observed in the hornblende. Anhedral quartz fills interstices and replaces plagioclase, biotite, and microcline. Only one generation of quartz is present, and this is fresh, free of mineral inclusions, and has undulatory extinction. The mineralogy and texture of the rock is that of biotite granodiorite, and the striking resemblance between this unit and the Knoblick Granite (chemically and petrographically also granodiorite) suggests a possible correlation. Chemical and isotopic data are being obtained to test this hypothesis.

BIOTITE GRANITE

Biotite granite occurs in the Hawn Park area as widespread, low, rounded outcrops which are typical of granite exposures in the St. Francois Mountains. The rock weathers to brownish-red, but is pinkish-gray when fresh. The texture is coarse to medium in grain size, hypidiomorphic-granular, and seriate. Locally, rapakivi texture can be recognized both in thin section and outcrop (particularly on weathered surfaces). Estimates of modal composition for a typical specimen are 20 percent sodic plagioclase, 10 percent to 30 percent microcline-microperthite,

10 percent to 30 percent orthoclase-microperthite, 30 percent quartz, 5 percent to 15 percent biotite, and 0 to 5 percent hornblende. Accessory minerals include apatite, zircon, pyrite, fluorite, and opaque minerals other than pyrite. The most distinctive feature of this rock is the presence of fresh, black biotite plates which exhibit a glomeroporphyritic tendency in some outcrops.

In thin section, subhedral plagioclase is concentrically zoned, with the grain cores invariably replaced by clay; the grains are twinned by both the Carlsbad and albite laws. Microcline, which may form very large grains, appears to replace orthoclase in all of the sections examined. Brown biotite, exhibiting kink bands and undulatory extinction, is slightly altered to chlorite in some sections, and may be replaced along its cleavages by quartz. Quartz is present as fractured grains which are replaced by microcline-orthoclase grains and have undulatory extinction, and as clear anhedra which replace all other mineral phases (two generations). Twinned hornblende was present in small quantities in some of the sections examined and absent in others. One very ragged pyroxene inclusion in a quartz grain was observed in a section of biotite granite from Jonca Creek (NW¼ sec. 10). It is probable that detailed mapping of the bodies designated as biotite granite would permit division of this unit into facies which (a) do or do not possess hornblende and (b) do or do not exhibit rapakivi texture. Except for the abundance of fresh biotite, the biotite granites of Hawn Park closely resemble the Butler Hill rapakivi granites described by Lowell and Sides (1973).

GRANITE UNDIFFERENTIATED

This designation includes those granitic bodies which have not yet been studied in detail. For the most part, these rocks are medium- to coarse-grained, pink leucogranites and leucocratic rapakivi granites (lacking hornblende and containing less than 5 percent biotite). Locally, they may contain swarms of xenoliths; some of these appear to be volcanic material. These bodies closely resemble the Butler Hill Granite, which is exposed approximately 15 mi southwest of the Hawn Park region (Tolman and Robertson, 1969). Efforts to determine whether these rocks are correlative with

the Butler Hill Granite are currently underway; the results of these studies will be reported in a subsequent paper.

RAPAKIVI-PORPHYRY DIKES

An extremely interesting dike rock is well exposed in the valley of Pickle Creek (NW¼ sec. 14, T. 36 N., R. 7 E.), just beyond the Niedringhaus Pegmatite Pit (fig. 1). The dike is vertical, strikes N 30° E, and cuts both granodiorite gneiss and undifferentiated granite. It is unconformably overlain, as are all the crystalline rocks of the area, by the Lamotte Sandstone. Weathered surfaces of the rock are dark-brown, while fresh exposures are distinctly pink. Kidwell (1942) described the rock as rhyolite porphyry.

The dike is cut by veinlets of quartz and black, fine-grained, opaque material and is distinctly aphanophyric. Phenocrysts of microperthite (up to 1 inch), sodic plagioclase, quartz, and biotite compose 50 percent of the rock; they are set in a matrix consisting mainly of granophyre and myrmekite. Pink, ovoidal orthoclase phenocrysts contain inclusions of quartz, plagioclase, and hornblende and are zonally replaced by microcline; twinning in the orthoclase-microperthite ovoids is by the Carlsbad and Baveno laws. Highly altered, multi-granular mantles of sodic plagioclase envelope and replace many of the ovoid orthoclase phenocrysts, producing rapakivi texture. The growth of the plagioclase mantles appears to have been controlled by the orthoclase cleavage. Large, embayed quartz phenocrysts indicate active resorption. The quartz grains have undulatory extinction, are shattered, and enclose biotite inclusions; fluid inclusions are very abundant along fractures. A small number of extremely ragged, green biotite grains are present as phenocrysts; these grains show kinked cleavage and are replaced by matrix material. Subhedral insets of kink-banded and altered sodic plagioclase are also present in small amounts.

Matrix material, mainly granophyre, with lesser amounts of myrmekite, replaces all of the phenocryst minerals and composes about 50 percent of the rock. Small, remnant grains of phenocrystic material are scattered throughout the matrix. Zircon, apatite, and opaque minerals are present in accessory amounts. Calcite, clay,

and sericite-muscovite are present as secondary minerals replacing phenocrysts.

The rock described above is a granophyre in the classic sense (Johannsen, 1931), but the mantled ovoids of orthoclase suggest kinship to the rapakivi porphyries of Finland described by Marmo (1971), hence the selection of the name given. The dike clearly carries an imprint of mechanical deformation. At one outcrop, orthoclase and quartz phenocrysts are definitely strung out into lensoidal pods defining a foliation somewhat divergent from the strike of the dike itself. Scattered float of this distinctive rock has been observed upstream from the dike exposure along Pickle Creek, but no other outcrop has been found.

GRANOPHYRE AND APLITE DIKES

A dike which cuts biotite granite about 400 ft north of Jonca Creek bridge (NW¼ sec. 9, T. 36 N., R. 7 E.) is a red granophyre. This dike is about 20 ft wide and is poorly exposed on the west side of the road; it was described by Kidwell (1942) as red granite porphyry. The fresh rock is pink, with weathered surfaces of mottled brown, and its texture is aphanophyric. Phenocrysts of orthoclase-microperthite, plagioclase, and quartz compose 50 percent

of the rock and are enveloped and corroded by a matrix composed largely of granophyric intergrowths of quartz and feldspars. No ferromagnesian minerals are present. Quartz phenocrysts form about 25 percent of the rock; they are rounded, clear, fractured, have undulatory extinction, and are replaced along the fractures by the groundmass. Large, euhedral phenocrysts of orthoclase-microperthite compose about 22 percent of the rock; microcline was not present in the sections studied from this locality. A small number of sodic-plagioclase phenocrysts, amounting to perhaps 5 percent of the total rock, are present; these show some vermicular intergrowths of quartz along grain boundaries and are sericitized and replaced by matrix granophyre. Zircon and opaque minerals are the only accessory minerals. The granophyric matrix contains a very small amount (2 percent) of pale-green muscovite.

Aplites are relatively rare in the exposures of plutonic rock in the Hawn Park area. The best-exposed aplite is in an abandoned quarry east of Highway 32 (C, SE¼ sec. 7, T. 36 N., R. 7 E.). A single dike (about 5 inches wide) can be traced over a distance of 60 ft. The aplite is hosted by biotite rapakivi granite which is represented by the only existing chemical analysis in the area (E.B. Kisvarsanyi, 1972, MGS No. 64).

MAFIC DIKES

Plutonism in the Hawn Park vicinity was succeeded by the emplacement of mafic dikes. Presumably, the latter event was part of a period of basic hypabyssal activity which affected both exposed and unexposed portions of the St. Francois Mountains igneous terrane (Tolman and Robertson, 1969; Amos and Desborough, 1970; E.B. Kisvarsanyi, 1974). The mafic rocks in the Hawn State Park area are very poorly exposed and are represented, for the most part, by scattered float boulders. Kidwell (1942) reported seeing a mafic dike in place in a tributary to Jonca Creek (NW¼ sec. 9, T. 36 N., R. 7 E.), and Weller and St. Clair (1928) reported one at Jonca Falls (Sec. 2, T. 36 N., R. 7 E.); the writer was unable to find either of these exposures. The writer did find a mafic dike

cutting biotite granite in the roadcut of Highway 144 about 400 ft north of Jonca Creek. This dike is adjacent and parallel(?) to the dike of granophyre described above. The dike is about 25 ft wide, and weathers to a buff to brown color. The fresh rock is black, aphanophyric, and carries distinctive, ragged clots of pyrite. In thin section the texture is subophitic.

Euhedral phenocrysts of zoned and altered plagioclase compose about 5 percent of the rock. A single quartz grain, very ragged and embayed, and possessing a reaction corona of fibrous muscovite(?) was observed. The matrix is composed mainly of unzoned plagioclase laths (50 percent) and pyroxene (35 percent)

which is partially interstitial to, and partially enveloping, the plagioclase. Opaque minerals, mainly pyrite, form an impressive 10 percent of the rock. Apatite is very abundant as an accessory (1 percent) and forms extremely long, slender crystals. Secondary clay replaces the pyroxene and plagioclase; the former replacement is very extensive.

Kidwell (1942) reported mafic float in NW¼ sec. 22, T. 36 N., R. 7 E. which the author was able to find and examine. The float has a linear distribution (N 40° E) which may be indicative of the trend of the dike. The writer's location of this material is topographically lower than that shown by Kidwell (1942) and is along the boundary between Sec. 15 and Sec. 22. The rock is buff to yellowish-brown on weathered surfaces and has a distinctive, "knotty" appearance which results from its glomeroporphyritic texture. Phenocrysts of altered euhedral plagioclase form clots composing 5 to 10 percent of the rock. The aphanitic matrix has an intergranular texture, with plagioclase interstices filled by altered pyroxene and opaque

minerals. A small amount (less than 1 percent) of quartz is present in this rock also, but it is fresh, equant, and lacks a reaction corona. The groundmass is composed of fresh, zoned, sharply twinned plagioclase laths which amount to about 60 percent of the rock volume. Matrix pyroxene forms an estimated 20 percent of the rock. Cubes of pyrite are very abundant (7 percent); criss-crossing opaque laths (ilmenite?) compose an additional 1 percent. Apatite is present mainly as inclusions in matrix plagioclase. The plagioclase phenocrysts are altered to clay and carbonate; the pyroxene is partially replaced by clay and chlorite.

Kidwell (1942) studied mafic dike rocks from localities different than those described above and noted that epidote was abundant and pyroxene lacking in all sections examined. The only extensive epidote mineralization noted by the present writer is along the contact between the granodiorite gneiss and granite above Pickle Creek, but no mafic dikes are present at that locality.

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GEOCHRONOLOGICAL STUDIES IN THE ST. FRANCOIS MOUNTAINS, MISSOURI

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INTRODUCTION

One of the most important results of the last 20 years of geochronological study has been the discovery that igneous activity, and probably also metamorphism and orogeny, are not random events. Rather, the ages of rock units show a definite episodicity. It is, therefore, important to determine accurately the ages of rocks which are studied, particularly in relatively isolated occurrences of Precambrian rocks such as the St. Francois Mountains; it is in this manner that rock-forming events may be seen as parts of regional or even continent-wide processes through which the continental crust has been formed and evolved.

REVIEW OF GEOCHRONOLOGICAL STUDIES IN THE ST. FRANCOIS MOUNTAINS

The first radiometric ages from the rocks of the St. Francois Mountains were reported by Allen et al. (1959), by Tilton et al. (1962), and by Muehlberger et al. (1966). These measurements were made on single mineral samples or single whole-rock samples by K-Ar, Rb-Sr, and U-Pb methods, and yielded ages ranging from 1,190 to 1,525 m.y. These early measurements indicated the approximate age range of the rocks, but they suffered from the uncertainties of working with single minerals (Wetherill and Bickford, 1965) and they were not systematic.

The first really systematic studies were done by Bickford and Odom (1968), who obtained Rb-Sr isochrons from whole-rock samples from several volcanic rock units and several plutons. The data obtained by these authors indicated two times of formation for both the volcanic rock units and the plutons. These ages, which were subsequently published in a paper by J.E. Anderson et al. (1969), were about 1,300 m.y. and about 1,400 m.y. As will be seen, these results were erroneous because the Rb-Sr system has not remained a closed chemical system in the rocks of the St. Francois Mountains. However, the data points yielded quite good isochrons and the results were good for the "state of the art" at the time.

Mose and Bickford (1972) published the results of further studies on Rb-Sr systematics in St. Francois Mountains igneous rocks, and concluded that the ages obtained by this method could be considered minimum ages only. It was further concluded that Rb-Sr ages in these rocks had been systematically lowered, probably by Sr loss, during an event which occurred somewhat more recently than 1,300 m.y. ago. It was evident that the two-event chronology of Bickford and Odom was fortuitous and resulted from the fact that relatively small numbers of whole-rock samples from each unit had been analyzed. Moreover, field studies had not yielded the evidence of structural or erosional uncon-

formities which a 100 m.y. interval between two periods of igneous activity would require.

Beginning in 1971-72, I began studying the U-Pb ages of zircon fractions separated from volcanic and plutonic rocks of the St. Francois Mountains. These data indicated that all of the rock units studied had been formed 1,500 ± 30 m.y. ago except for the Munger Granite Porphyry, which yielded a U-Pb zircon age of 1,400 m.y. The results of all of our geochronological studies have been recently published as Special Paper 165 of the Geological Society of America (Bickford and Mose, 1975b). This paper includes detailed descriptions of sampling localities, laboratory methods, reproducibility, and other aspects of methodology. The results of both the U-Pb and the Rb-Sr measurements are summarized on the next page.

It should be noted that U-Pb ages are available for most of the major plutons and for one major extrusive rock unit. There are no radiometric ages available for the basaltic dikes and sills which are abundant in many parts of the St. Francois Mountains (Amos and Desborough, 1970), because the chemistry and mineralogy of these rocks render them unsuitable for any of the currently practiced isotopic methods of age determination. These rocks are demonstrably pre-Upper Cambrian, but I am not aware of any field relationship which permits a more precise statement than that.

DISCORDANCE OF
THE Rb-Sr AND U-Pb RESULTS

It is clear from the foregoing and from the data in table 1 that there is a serious discrepancy between the reported Rb-Sr and U-Pb ages. In only one unit, the Butler Hill Granite, does the Rb-Sr age even overlap the zircon U-Pb age at 95 percent confidence levels (and then only barely) In all other units the zircon U-Pb age is greater. Although many workers have recently reported similar discrepancies between U-Pb zircon ages and Rb-Sr whole-rock isochron ages (e.g., Cormier, 1969; Zartman and Marvin, 1971), geologists frequently accept Rb-Sr whole-rock ages without question.

Questions of interest are: a. Which method, U-Pb or Rb-Sr, yields the closest approximation to the real

age of the rocks? b. What process or processes may have resulted in the altering of one or both isotopic systems? c. If one method yields the "true age", does the other record some other event or events, or is it without meaning?

I will discuss these questions briefly below:

a. It has been shown recently that both the Rb-Sr system in whole rocks and the U-Pb system in zircons can be altered by physical-chemical processes related to events in the history of the rock under study. In the case of the St. Francois Mountains rocks, it seems most likely that the U-Pb age of the zircons is the most reliable because: (1) there is much

TABLE 1

WHOLE-ROCK Rb-Sr ISOCHRON AND ZIRCON U-Pb AGES
FROM ROCKS OF THE ST. FRANCOIS MOUNTAINS BATHOLITH

Rock Unit	Rb-Sr Isochron Age*	Number of Samples	Maximum Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86} (initial)*	Zircon Fractions Analyzed	U-Pb Age**
Volcanic 690***	1331±44	19	24.46	0.7115 ±0.0072		
Volcanic 700***	1315±48	6	19.84	0.7081 ±0.0037		
Volcanic 810*** (includes Royal Gorge Rhyolite)	1346±31	23	71.93	0.7124 ±0.0055	4	1530±20
Stouts Creek Rhyolite	1327±27	53	101.32	0.7094 ±0.0058		
Breadtray Granite	1289±69	9	44.67	0.7070 ±0.0193	5	1500±20
Graniteville Granite	1273±92	9	110.84	0.7254 ±0.0847		
Slabtown Granite	1321±98	8	3.06	0.7045 ±0.0036		
Munger Granite Porphyry	1280±50	3	6.50	not precisely determined	3	1408±12
Butler Hill Granite	1408±72	8	8.38	0.7036 ±0.0066	3	1500±20
Silvermine Granite					3	1501±40
Foliated granodiorite of Hawn Park					4	1514±20

*Ages in m.y.; errors at 95-percent confidence level except for Munger Granite Porphyry, for which errors are an estimate.

**Ages in m.y.; errors at one standard deviation.

***Nomenclature of A.W. Berry (1970).

more analytical scatter in the Rb-Sr data when it is plotted on isochron diagrams than there is in the U-Pb data when it is plotted on concordia diagrams; (2) Mose and Bickford (1972) have shown that there is a significant positive correlation of the Rb-Sr ages of the volcanic rocks with Sr concentration, suggesting that the Rb-Sr ages have been lowered by Sr loss; and (3) the U-Pb results are much more consistent than are the Rb-Sr ages, yielding essentially the same age for all of the rock units studied except the Munger Granite Porphyry. It appears that most of the rocks of the St. Francois Mountains were formed about 1,500 m.y. ago, a conclusion that is consistent with observable field relations and with the suggestion of Hamilton and Myers (1967) that the exposed terrane is a composite batholith consisting of an eruptive roof of volcanic rocks intruded by residual magmas of essentially the same bulk composition. The Munger Granite Porphyry may represent a younger period of igneous activity.

b. It follows from the discussion above that the ages yielded by the Rb-Sr system must have been systematically lowered. The process or processes which caused this are not clear at this time. However, as argued above, the result was apparently loss of Sr. Those rocks which had the smallest concentration of Sr initially apparently had their ages lowered the most. It has been shown by other investigators (e.g.,

Lanphere and others, 1964) that Sr can be redistributed between minerals and even over small distances between total rock masses. However, since the effects described here have affected large whole-rock samples from essentially all of the major rock masses of the batholith, it seems unlikely that Sr was only redistributed. Rather, there seems to have been wholesale loss of Sr from most of the rocks. Such a loss could presumably have been affected by a fluid medium which permeated the rocks at some time subsequent to their formation; such an event is strongly indicated by the oxygen and hydrogen isotopic data of Wenner and Taylor (1972), who found that the feldspars from most of the rocks of the batholith had undergone extensive isotopic exchange with an O^{18}-rich fluid.

c. As indicated in table 1, the Rb-Sr ages cluster around 1,300 m.y. If Sr loss were associated with devitrification or unmixing of alkali feldspars, it would seem that these events would occur within a relatively short time after the emplacement of the rocks. It therefore seems likely that the 1,300 m.y. Rb-Sr ages record a real event in the history of the rocks during which Sr was lost from them. Rocks which had, initially, very little Sr had their Rb-Sr "ages" almost completely reset during this event. Rocks with more initial Sr, like the Butler Hill Granite, had their "ages" lowered from 1,500 m.y. toward 1,300 m.y.

Sr ISOTOPES AND PETROGENESIS

Initial Sr isotopic composition, specifically the ratio Sr^{87}/Sr^{86}, has been widely used in studies of magmatic origin and evolution. Table 1 indicates wide variation in initial Sr^{87}/Sr^{86} ratios as determined by regression of Rb-Sr whole-rock isochrons to their intercept on the ordinate and also large errors associated with these values. It is clear from these data and from the foregoing discussion that little information of petrogenetic value can be obtained from whole-rock Rb-Sr analyses because the Rb-Sr system has been disturbed. If

initial Sr^{87}/Sr^{86} ratios are to be measured, the measurements will have to be made on minerals that have resisted the mobilization of Rb and Sr which is evident in the total-rock samples. Apatite and fluorite are possibly such minerals, and Sr isotopic analyses of these minerals are now in progress in our laboratory at the University of Kansas. These data are of great potential importance, for the origin of large volumes of silicic and alkalic magma in a continental setting poses a major petrogenetic problem.

THE RELATIONSHIP OF THE ST. FRANCOIS MOUNTAINS TO OTHER 1,450-1,500-M.Y.-OLD IGNEOUS ROCKS

As mentioned in the introduction to this paper, one of the principal goals of geochronology is to associate local occurrences of igneous or metamorphic rocks with other rocks which have formed at the same time. It is of great interest that there are many bodies of igneous rocks known in North America which were formed between 1,450 and 1,500 m.y. ago. Rocks of this age are known in eastern North America, but many more are reported from western and southwestern parts of the continent. Results from our laboratory indicate that numerous plutons of this age lie buried beneath sedimentary rocks across the great mid-continent area.

Most reported occurrences of rocks of this age are plutons of granitic to quartz-monzonitic composition which have been emplaced in an anorogenic setting. In certain aspects the batholith of the St. Francois Mountains fits this model, for there are no deep-seated plutonic or metamorphic rocks known in this area. However, it has also been noted by several authors (e.g., Muehlberger et al., 1966; Bickford and Van Schmus, 1973; Bickford and Mose, 1975a and 1975b) that the St. Francois Mountains is clearly part of a great, crudely arcuate terrane of similar rocks which can be traced in the subsurface from northern Ohio at least to the Texas Panhandle. This terrane is bounded to the north by older rocks with ages mostly greater than 1,600 m.y., and to the south by younger rocks of "Grenville" age (about 1,100 m.y. old). Thus, it seems possible that the St. Francois Mountains batholith and the other rocks of this terrane were formed on the edge of a pre-existing continent and may thus represent the orogenic phase of the 1,450-1,500-m.y.-old igneous event.

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GEOLOGY OF
THE PILOT KNOB MAGNETITE DEPOSIT,
SOUTHEAST MISSOURI

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INTRODUCTION

The Pilot Knob mine is in Iron County, Missouri, just
south of the village of Pilot Knob, in Sec. 30, T. 34 N.,
R. 4 E. (fig. 1). The surface facilities and main shaft
are situated at the base of the western flank of Pilot
Knob near the same location where once stood the
mill that processed hematite ore mined from the
top of the knob in the mid-1800's.

The first diamond drillhole, to test a moderate-sized
aeromagnetic anomaly and overlapping gravity
anomaly, was completed in May, 1957. This hole
proved to be just to the east of the updip edge of the
orebody, but a second hole intercepted magnetite ore
and 178 holes have subsequently been completed to
outline the orebody.

Construction of the concentrator and pelletizer along
with sinking of the three-compartment main shaft
and open-vent shaft began in February, 1965, and
the first pellets were shipped to Granite City, Illinois,
in June, 1968. As part of a recent expansion program,
the vent shaft has been deepened and fitted with
hoisting equipment to bring total designed hoist
capacity from both shafts to 3.7×10^6 tons per year.

The mining method is a combination of room-and-
pillar and sublevel stoping. The broken ore is pulled
from drawpoints by rubber-tired loaders and dumped
into the ore raise, which feeds the underground
crusher. After crushing to a minus-6-inch size, the
ore is hoisted to the surface in two balanced 10-ton
skips powered by a Koepe friction hoist. The ore is
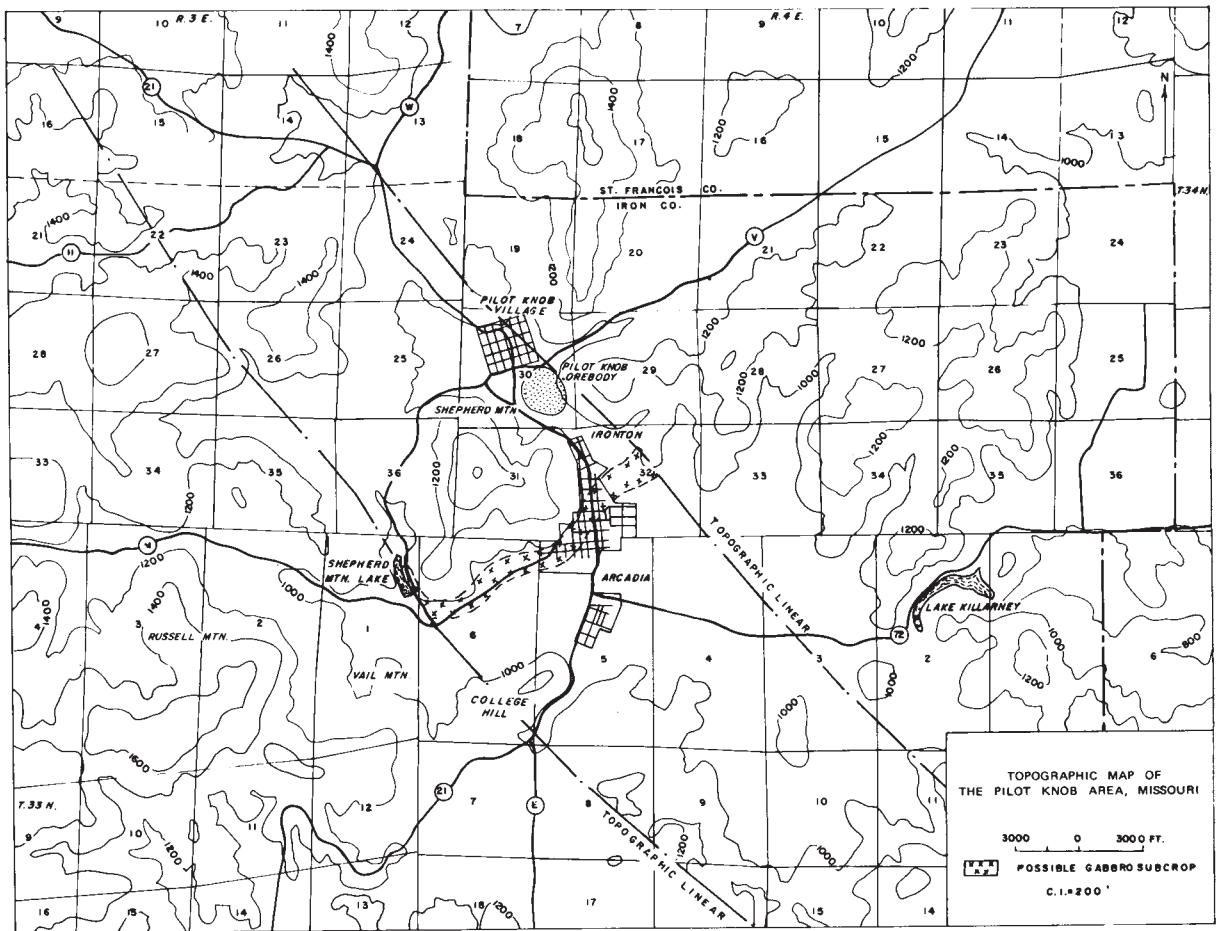crushed at the surface to minus-1-inch, then passed

Figure 1

Topographic map of the Pilot Knob area, Missouri showing location of the Pilot Knob orebody.

over a magnetic pulley which cobs out 5 percent to 12 percent of the feed as nonmagnetic waste. After beneficiation and pelletizing the total pellet produc-

tion is shipped by the Missouri Pacific Railroad to National Steel Company's facilities in Granite City, Illinois.

GEOLOGIC SETTING

The Pilot Knob magnetite deposit occurs in, and is apparently conformable with, a sequence of south-west-dipping Precambrian ash-flow tuffs and rhyolitic flows similar to those exposed elsewhere in the St. Francois Mountains of Missouri. The deposit lies at the south end of the Southeast Missouri Iron

Metallogenic Province, an area approximately 70 mi long and 40 mi wide (G. Kisvarsanyi, 1966).

The hangingwall rock is thought to be an ash-flow tuff from the presence of fiamme (collapsed pumice fragments) and eutaxitic and snowflake texture.

The unit probably lies near the base of Berry's volcanic stratigraphic section and is similar to his unit 700 (Berry, 1970). Banding (fiamme) in the hangingwall rocks appears to be parallel to the irregular surface of the orebody, although the possibility exists that the orebody cuts the volcanic strata at a low angle.

The footwall rocks are predominantly red, fragmental tuffs and subordinate massive, pink to dull-red tuffs and felsites. It is not known if this unit is exposed at the surface, although very similar rocks form outcrops near the crest and on the west flank of Pilot Knob.

DESCRIPTION OF THE OREBODY

The Pilot Knob orebody is a roughly tabular mass of magnetite shaped as a synform with an axial trace of N 25° E plunging to the southwest (fig. 2). The arcuate updip edge of the orebody subcrops beneath 380 to 400 ft of Cambrian limestone and sandstone and Quaternary alluvium. The southern flank of the orebody strikes N 30° W and the northern flank strikes E-W. Flank dips vary from 10° to 60°, but normally range from 45° to 55° to the south and southwest. Total strike length of the arcuate subcrop of the orebody at the Precambrian surface is nearly 2,800 ft, but the total mineralized zone may be nearly a mile in length. The orebody will be developed to a depth of 1,480 ft below the surface.

MINERALOGY

Magnetite makes up from 35 percent to 85 percent of the ore. Quartz accounts for 50 percent to 75 percent of the gangue and alkali feldspar makes up the balance. Accessory minerals rarely exceed 10 percent of the rock. The most abundant are chlorite, secondary quartz, dolomite, fluorite, barite, pyrite, and orthoclase, with lesser amounts of actinolite, chalcopyrite, apatite, sphene, and tourmaline. Apatite, common in many magmatic iron deposits, is very rare at Pilot Knob.

ORE TYPES

The ore is a fine- to medium-grained crystalline mixture of magnetite, quartz, and feldspar and is divisible into three crudely stratified zones (fig. 3). The classification of the ore into separate types is based both on megascopic physical features and on metallurgical characteristics (Cameron, 1965).
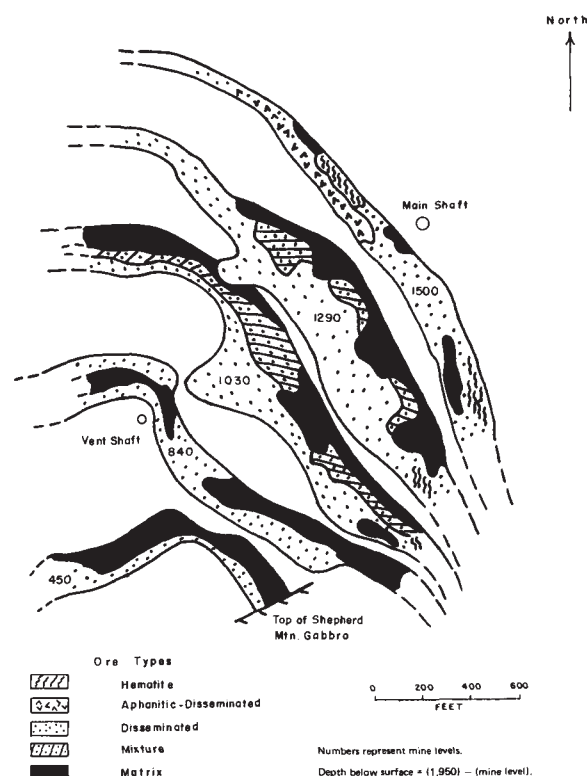
Figure 2

Generalized mine-level plans (selected levels).

The amounts of magnetic iron and silica in Davis Tube concentrates at a standard −325-mesh grind are the important metallurgical variables used in ore classification. The importance of the iron is self-evident, while the amount of silica provides information on the expected grindability and liberation characteristics of the ore. The following chart shows the ore types and their general magnetic iron and silica compositions in −325-mesh Davis Tube concentrate (D.T.C.).

ORE TYPE	MAGNETIC IRON IN D.T.C.	SILICA IN D.T.C.
Disseminated	30% to 40%	3.5% to 13.0%
Matrix	40% to 60%	0.8% to 4.0%
Mixture	30% to 50%	2.5% to 5.5%

DISSEMINATED ORE

Disseminated ore is predominantly medium- to fine-grained, massive or fragmental, and rarely banded. It is best distinguished underground by its purplish-black color. The disseminated ore can contain a wide range of small (1 to 10 mm), angular felsite fragments. A subtype of this ore is called aphanitic-disseminated and is characterized by its very fine-grained (porcelaneous) nature, a high silica content in a Davis Tube concentrate (8 percent to 13 percent), and subconchoidal fracture. This aphanitic-disseminated ore is, for the most part, restricted to the updip edge of the orebody. The disseminated ore commonly occurs along the hangingwall, or upper side of the orebody, but can occur anywhere from footwall to hangingwall.

The proportion of disseminated ore to other ore types decreases with depth.

MATRIX ORE

The matrix ore is dull-black in color, medium- to coarse-grained and may contain rounded quartz eyes (0.5 to 1 mm). It usually contains very few rock fragments and is notable for its scattered, irregular masses of barite. A loose, almost sandy variety of this type is called friable matrix and is very rare. Matrix ore is the highest-grade and coarsest-grained ore in the mine. It is restricted for the most part to a very irregular sheet along the footwall, but, as with the disseminated ore, may locally be found in any position within the orebody.
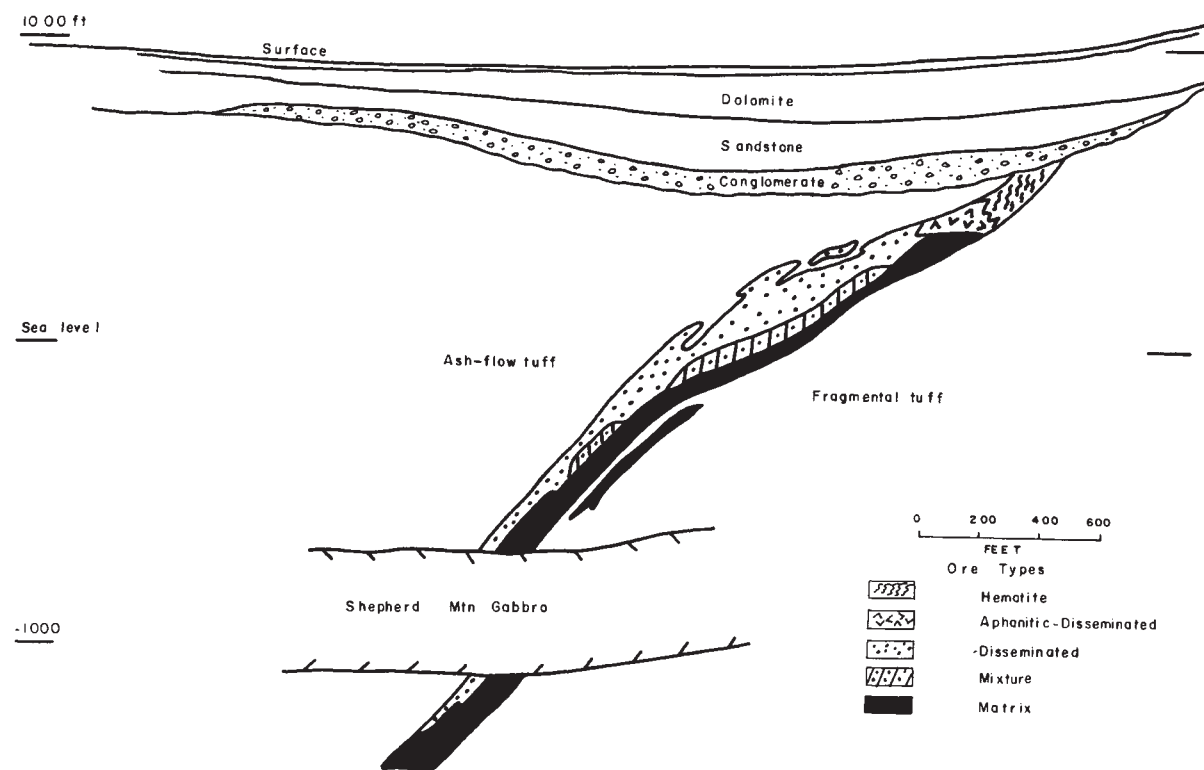

Figure 3

Generalized cross section (looking north).

MIXTURE ORE

Mixture ore is, as its name suggests, composed of angular to subangular fragments of disseminated ore suspended in matrix-type ore. It is gradational with the other ore types, and is the most difficult of the three types to identify underground. It is usually found in irregular zones in the interior of the orebody, between disseminated and matrix horizons, but is not uncommon in other stratigraphic positions.

HEMATITE

Hematite occurs in the orebody as a cap on the updip edge, as irregular, usually roughly planar zones within the orebody, and at the terminus of the south flank where the entire magnetite orebody apparently grades into hematite. Other Missouri magnetite bodies, such as Pea Ridge and Camel's Hump, also have hematite caps at the updip edge. The plant is not designed to handle hematite, and it is rejected with the waste rock at the magnetic cobber pulley. The hematite in the mine has previously been considered to be younger than the magnetite and to have formed as a weathering or oxidation product while exposed to the pre-Paleozoic atmosphere. Preliminary results from a study currently underway at Pilot Knob, however, suggest that the cap has not formed from surface oxidation. Instead, it appears to have a magmatic source, as indicated by lamellar twinning in the hematite and grain-boundary relationships with the magnetite suggesting simultaneous original deposition. Hematite-magnetite samples from the interior of the mine suggest a similar relationship, while some polished sections suggest replacement of hematite by magnetite (Mattson, 1976).

INTERNAL ROCK

Internal lenses of barren, brown-mottled felsite and red felsite make up approximately 15 percent of the orebody. These lenses usually have extremely complex three-dimensional shapes and may show evidence of replacement by magnetite along their irregular surfaces. Not uncommonly, lenses of these rocks can be traced through three or four mine levels (200 to 260 ft).

MAFIC AND INTERMEDIATE DIKES

Diabase, chlorite, and andesite dikes cut all the ore types and both wall rocks at Pilot Knob. Some of these dikes were emplaced before or during deposition of the magnetite and are now preserved as partially replaced remnants. Post-ore dikes are especially numerous in the north flank of the orebody, and drillhole data suggest they are for the most part restricted to the ore zone itself. They are commonly subparallel to the strike of the orebody, dip steeply at about 70° in either direction, and are often anastomosing. They range in thickness from a few inches to 30 ft, but are usually less than 10 ft thick.

CONTACT RELATIONSHIPS

There is no dramatic evidence of alteration at either the hangingwall or footwall contacts at Pilot Knob. This is similar to the ore-host contacts at Kiirunavaara in Sweden, and differs markedly from the well-developed hematite-quartz skarn envelope at the Pea Ridge deposit near Sullivan, Missouri (Emery, 1968). There are, of course, specific exceptions to this generality at Pilot Knob, particularly where the usually banded red hangingwall, and to a lesser extent, the maroon-red footwall, is bleached to a buff-white color. No well-developed contact alteration facies exist, however.

The contact of the footwall tuff and the ore is very similar to that described by Geijer (1931) as "ore breccia" in the footwall of the "Kiruna type" ore deposits. The term "ore breccia", as used in Sweden, describes a network of closely spaced ore veins which separate fragments of host rock, giving it a brecciated appearance. At Pilot Knob, the contact of footwall tuff and magnetite ore is completely gradational from unmineralized tuff, through tuff with veins and veinlets of magnetite, to massive ore with suspended tuff fragments of all sizes. Near the footwall, angular fragments of tuff completely surrounded by magnetite have obviously moved very little and can, in some cases, be put "visually" back to their original position. The fragments are angular and show little evidence of replacement, corrosion, or embayment by the magnetite ore. The footwall at the Kiirunavaara and Tuolluvaara deposits in northern Sweden, as described by Geijer and Odman (1974), appears to be nearly identical.

The ash-flow tuff of the hangingwall, on the other hand, occasionally shows evidence of replacement by

the adjacent magnetite ore. Replacement features are not widespread, however, and for the most part underground exposures of the hangingwall contact show it to be a rather sharp, but highly irregular surface, with tongues of ore reaching into the hangingwall at low angles to the main contact. Strong bleaching and replacement of the hangingwall banded ash-flow tuff seems to be limited to areas close to matrix ore, although there is almost always at least a narrow zone (about 10 ft) of disseminated ore sandwiched between the matrix ore and the banded tuff.

SHEPHERD MOUNTAIN GABBRO

The orebody is cut by a gently dipping, coarse-grained mafic dike, 400 ft thick, composed predominantly of olivine diabase and ophitic gabbro (Desborough, 1967). The diabase is exposed at the surface in a roadcut along the east side of Shepherd Mountain Lake, 1 mile west of Ironton, and has been cut by drillholes in the mine area. The dike strikes N 20⁰-30⁰ W and dips 12⁰ to 17⁰ to the north. Projection of these data suggests that the dike may subcrop at the Precambrian surface beneath Cambrian sedimentary rock and Quaternary valley fill in the valley between Shepherd Mountain and College Hill (fig. 1). The diabase is not exposed in the higher ground at either end of the valley and thus may be restricted between two northwest-trending topographic linears mapped as post-Cambrian faults 5 miles southeast of Shepherd Mountain by Amos and Desborough (1970). These faults cut another gabbro body exposed in the valley south of Grassy Mountain. The easternmost linear (fig. 1) is probably coincident with the Ironton fault named by Graves (1938) and later described as a segment of the Ironton lineament by Kisvarsanyi and Kisvarsanyi (1976).

The Shepherd Mountain gabbro cuts the south flank of the orebody approximately 1,230 ft below the surface (700 mine elevation). Because of its northerly dip, the gabbro cuts progressively lower into the orebody until it leaves the north-flank footwall at a depth of 1,630 ft (300 mine elevation).

Diamond drilling shows that the ore was offset by the gabbro sheet (fig. 3). The contact of the ore and gabbro shows little megascopically visible textural or mineralogical metamorphism in the orebody. The gabbro, however, has a chilled border facies of greenish-gray basalt. The gabbro is not presently exposed underground, but planned drifting in the lower levels of the mine should intersect the top of the gabbro early in 1977.

BRECCIA PIPES

A few roughly circular masses of breccia cut the orebody and may be traced for as much as 250 ft subparallel to the dip of the orebody. These features have tentatively been described as breccia pipes. To my knowledge, they are not present in the Swedish or other Missouri iron deposits. They contain fragments of ash-flow tuff (hangingwall), brown and red felsites (internal rock), disseminated-type ore, and dike fragments in a matrix of quartz, chlorite, carbonates, and barite that fills the interstices between the fragments. Matrix-type ore fragments have not been found in the pipes, although in a number of locations the pipes apparently cut or originate in matrix ore. Ash-flow-tuff fragments are very abundant in the pipes and apparently have collapsed in from the hangingwall. The pipes do not seem to have been intensely fluidized as the fragments are sharply angular, with little or no interstitial crushed rock or glassy felsite.

STRUCTURE

Although much of the orebody, including the internal rock, is highly fractured, no through-going faults of large displacement have been verified. Recent interpretations of underground mapping, however, suggest the presence of a few high-angle reverse faults with up to 50 ft displacement. Further work may verify these faults.

AGE OF MINERALIZATION

K-feldspar samples collected from veins cutting the Pilot Knob orebody were dated (Rb-Sr) by D.G. Mose and M.E. Bickford at 1,180 $\pm$ 35 m.y. (Bickford, pers. commun., 1976). This should be considered a minimum age, however, because regional geochronological studies indicate that most of the volcanic rocks which host the iron mineralization are 1,500 m.y. old (Pb-U) and that the Rb-Sr ages have been lowered by an event which occurred at 1,300 m.y. ago (Bickford and Mose, 1975). The age of the orebody is, therefore, in the interval of 1,180 to 1,500 m.y.

GENESIS

Cameron (1965) has offered three general theories of origin as a result of his studies of drillcores. These are: a. intrusive magnetite ore magma; b. magnetite flow; and c. hydrothermal replacement. Cameron favored the hydrothermal-replacement theory, which postulates the replacement of a lithic tuff or tuff breccia by iron-bearing solutions. The disseminated ore is a replacement of an original very fine-grained ash-flow tuff containing lithic fragments and occasional pumice fragments which have been replaced to form ill-defined magnetite-crystal aggregates. Matrix-type ore was thought to represent complete replacement of a fragmental lithic tuff, with quartz eyes forming from devitrification of collapsed pumice fragments. Cameron offered no theory for the formation of the mixture-type ore.

During the years following that report, most company geologists have generally favored a combination of Cameron's theories. Simply stated, this composite theory calls for an irregular, roughly tabular magnetite injection along the contact of the present footwall tuff and an overlying pyroclastic unit. Iron-rich fluids from the injected magnetite replaced the pyroclastic unit to form the disseminated and mixture ores. The magnetite injection cooled to form the present matrix ore. Murrie (1973) supports this general theory with the following conclusions based on his study of the trace elements in the magnetite:

a. Trace-element geochemistry indicates that the matrix and disseminated ores can be differentiated on the basis of their respective trace-element contents.

b. The distribution of selected trace elements between the two major ore types, based on predictions of Goldschmidt, Ringwood, and crystal field theory, imply that the matrix ore formed earlier than the disseminated ore.

c. Analyses of the titanium content of magnetite, as a geothermometer, places a minimal high temperature of formation for the matrix ore and the disseminated ore at 550°C and 470°C, respectively.

d. The matrix ore was injected as a quartz-magnetite fluid, and the disseminated ores are the result of replacement of a felsite.

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Murrie did not work on the mixture-type ore and therefore offered no theory for its formation. Pinchock (1975) generally supported these conclusions with his study of the accessory minerals at Pilot Knob, with one exception; since there are fragments of disseminated-type ore found in matrix ore (described and mapped as mixture-type ore), Pinchock feels that the disseminated ore formed first and fragments of it were incorporated into the later injection of matrix-type ore. This writer tends to agree with Pinchock, and studies are now underway at Pilot Knob to verify the hypothesis.

ACKNOWLEDGMENTS

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PRECAMBRIAN METALLOGENESIS IN THE ST. FRANCOIS MOUNTAINS IGNEOUS PROVINCE, SOUTHEAST MISSOURI

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INTRODUCTION

The metals that form ore deposits are widely distributed in trace amounts in the crust of the earth. To understand local, ore-grade concentration of metals one must investigate the processes of concentration, which in the case of magmatic and hydrothermal deposits are closely linked to the evolution of igneous rocks themselves.

The formation of the Precambrian ore deposits of southeast Missouri was a function of the petrochemical composition and original metal content of the magmas that formed the igneous rocks of the region. The emplacement and distribution of ore deposits within the igneous province were controlled by structural features. The ore deposits, the metallogenesis, and the resource potential of the Precambrian terrane should therefore be examined in the broad context of petrogenesis and tectogenesis.

The Southeast Missouri Iron Metallogenic Province was defined by the writer (G. Kisvarsanyi, 1966; G. Kisvarsanyi and Proctor, 1967) on the basis of his study of the magmatic iron deposits of the region. This paper discusses the relationship of the Precambrian mineral deposits in general to the petrogenesis of the region.

EVOLUTION OF
THE ST. FRANCOIS TERRANE

TECTONIC ENVIRONMENT
AND MAGMA GENERATION

The exposed Precambrian rocks in southeast Missouri are part of an extensive terrane of volcanic and shallow-intrusive rocks that extends from Michigan and Ohio through Illinois, Missouri, and Oklahoma to as far southwest as Arizona (fig. 1). This terrane is located between the Churchill (1.7-b.y.-old) and Grenville (1.0-b.y.-old) provinces and is one of the least-known tectonic units of the ancient provinces of North America. It has variously been referred to as the Mazatzal or Central province; the writer calls it the St. Francois terrane when referring to it in a regional context, and the St. Francois Mountains igneous province when discussing its better-known and in part exposed portion in southeast Missouri (G. Kisvarsanyi, 1975).

The St. Francois terrane is 1.3 to 1.5 b.y. old (Muehlberger et al., 1966; Bickford and Mose, 1975) and may be an accretional belt which evolved on the margin of a middle Proterozoic continental platform that was bounded on the southeast by a sea. But the structure and composition of the rocks of this terrane are unlike those of the older shield provinces. Regional metamorphism, greenstone belts and corollary metasediments, and metamorphic envelopes of granite plutons are not known in this terrane. The petrology and mineralization of volcanic rocks in young mountain ranges on subduction zones are also different from those of the St. Francois terrane. Furthermore, direct evidence is lacking that the rocks of this terrane are related to a full-scale orogenesis including melting of geosynclinal sediments in an ultrametamorphic zone.

Preceding the evolution of the St. Francois terrane, magma generation in the mantle may have caused the formation of elongated arches in a relatively thin Precambrian crust. Faulting, primitive rifting, and general collapse of the arches would subsequently have triggered large-scale upward propulsion of magmas, resulting in intensive volcanic activity and the deposition of a volcanic pile thousands of feet thick. The volcanic pile was "floating" atop layers of intrusive sheets and cogenetic batholiths. This early evolutionary

epoch of the terrane was dominated by igneous processes and included differentiation and mixing of magmas, assimilation, generation of ore magmas, volcanic exhalations, and hydrothermal and fumarolic activity, producing the varied volcanic and intrusive rocks of the St. Francois Mountains and their unique mineral deposits that are without parallel in the United States. A Precambrian thermal event thus produced enormous amounts of magma which solidified, was added to the crust of the continent, and forms the present cratonic basement for the Paleozoic sediments.

CRUSTAL LAYERING

Geophysical data indicate that the upper 4 km of the terrane is dominated by high-silica rocks (Stewart, 1968); below this depth an inhomogeneous, possibly mixed layer is indicated, in which intermediate and basic rocks must be more abundant. Whether this mixed layer is an older, Archean series of igneous and metamorphic rocks or part of the St. Francois terrane is not known. Interpretation of seismic data places the depth of the Conrad discontinuity at approximately 20 to 24 km*, implying a gabbroic (sima) floor for these rocks.

The layered arrangement of rocks within the Precambrian terrane(s) is explained by the specific gravities of igneous rocks. The specific gravity of glasses made from plutonic rocks shows the following sequence (after Daly):

granite	2.38 - 2.45
diorite	2.68 - 2.71
gabbro	2.79
dunite	3.29

The differences between the "heavy" and "light" members of the series are enhanced by the fact that light, volatile constituents, such as H_2O, CO_2, F, and B, are concentrated in acidic magmas. The buoyancy of acidic magmas combined with the high specific gravity of basic magmas is responsible for the emplacement of high-silica rocks in the upper part of the crust and that of mafic rocks at greater depths.

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*Refer to Nuttli, p. 184, this volume, for seismological studies of Missouri crustal structure.
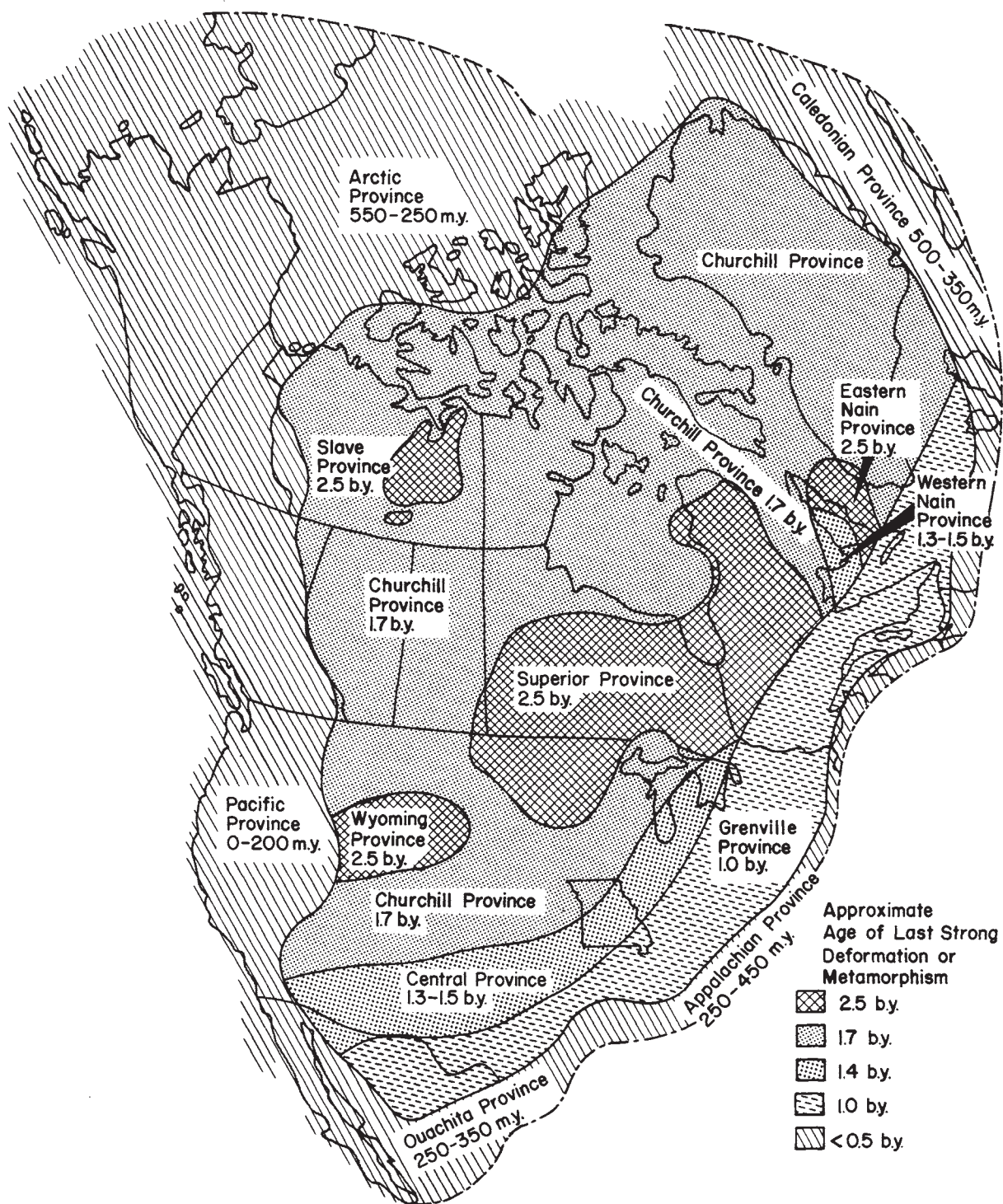
Figure 1

Tectonic provinces of North America (after Seyfert and Sirkin, 1973).

PETRO-METALLOGENESIS

MAJOR ELEMENTS AND "MINERALIZERS"

The relationship between mineral deposits and the chemistry of associated igneous rocks was recognized by several investigators (Geijer, 1910; Watson and Taber, 1910; Vogt, 1926; Lehman, 1941; and others). They found that many igneous rocks that contain genetically related ore deposits are particularly high in alkali metals, P, S, F, and other volatile constituents. Laboratory experiments conducted on the behavior and crystallization of metallic oxides and silicate melts (Bowen and others, 1930; Greig, 1927; Fischer, 1950; and others), and theoretical studies (Goldschmidt, 1954) made it increasingly evident that the petrochemistry and trace-element geochemistry of igneous provinces are important in understanding metallogenesis.

The St. Francois Mountains igneous province displays certain trends expected from a differentiated series of igneous rocks with a somewhat high alkali content. It is progressively enriched in Fe and combined alkalies at the expense of Mg and Ca in the high-silica members of the complex. Unsaturated alkalic rocks are not known to have been produced because of the high silica content of the magmas. The province as a whole is subalkalic and is transitional between the calc-alkalic and alkalic provinces (E.B. Kisvarsanyi, 1972).

Both in outcrop and in the subsurface the province is dominated by acidic igneous rocks: granite and rhyolite, latite and adamellite. Intermediate rocks (syenite and trachyte, diorite and andesite) occur in much smaller volume. Some rocks of the province correspond to alkali granite and alkali rhyolite when their chemical analyses are compared to world averages (Nockolds, 1954). Generally, K is the dominant alkali metal in the high-silica rocks, but locally Na may surpass it. Similarity of the amounts of alkalies and other major elements in certain spatially related extrusive and intrusive rocks supports their cogenetic nature. In certain rocks of the province enrichment in both Fe and alkalies is significant (fig. 2).

The metallogenic importance of these petrochemical characteristics is strongly expressed in the mineralogy
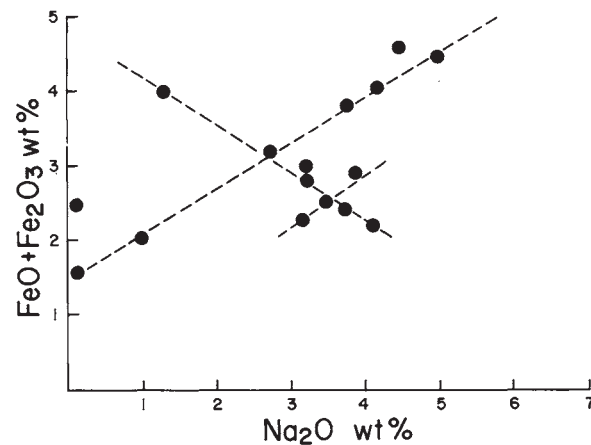
Figure 2

Relationship of total iron oxide and Na_2O content in selected high-silica rocks from southeast Missouri. Data from G. Kisvarsanyi (1966) and E.B. Kisvarsanyi (1972).

of both the igneous rocks and their associated mineral deposits. Absence of large-scale hydrous and argillaceous alteration indicates relatively small amounts of water in the magmas at the time of formation and a diminished capability to form residual pegmatitic liquids and hydrothermal fluids. Accordingly, mineral deposits do not have typical hydrothermally altered wall rocks.

Although water played a relatively minor role in forming mineral deposits, other volatile constituents, F, P_2O_5, CO_2, and B, were important in certain magmas, as indicated by the ubiquitous presence of fluorite, apatite, calcite, and tourmaline in the volcanic rocks and their associated iron deposits, and by their occurrence as common accessory minerals in the intrusive rocks.

Iron-oxide minerals (magnetite, hematite) are abundant in some rhyolites, trachytes, and andesites, but may be absent in others. The occurrence of iron silicates (fayalite) in some of the rhyolites may also be significant. Iron-rich lavas and ash flows locally produced vapor-phase iron-oxide (hematite) and possibly manganese exhalations that impregnated favorable, porous rocks.

The known Precambrian ore deposits of the province are those of iron-apatite-rare earths, iron-copper-cobalt, tungsten-lead-silver, and manganese (fig. 3). They are of magmatic origin in the form of ore
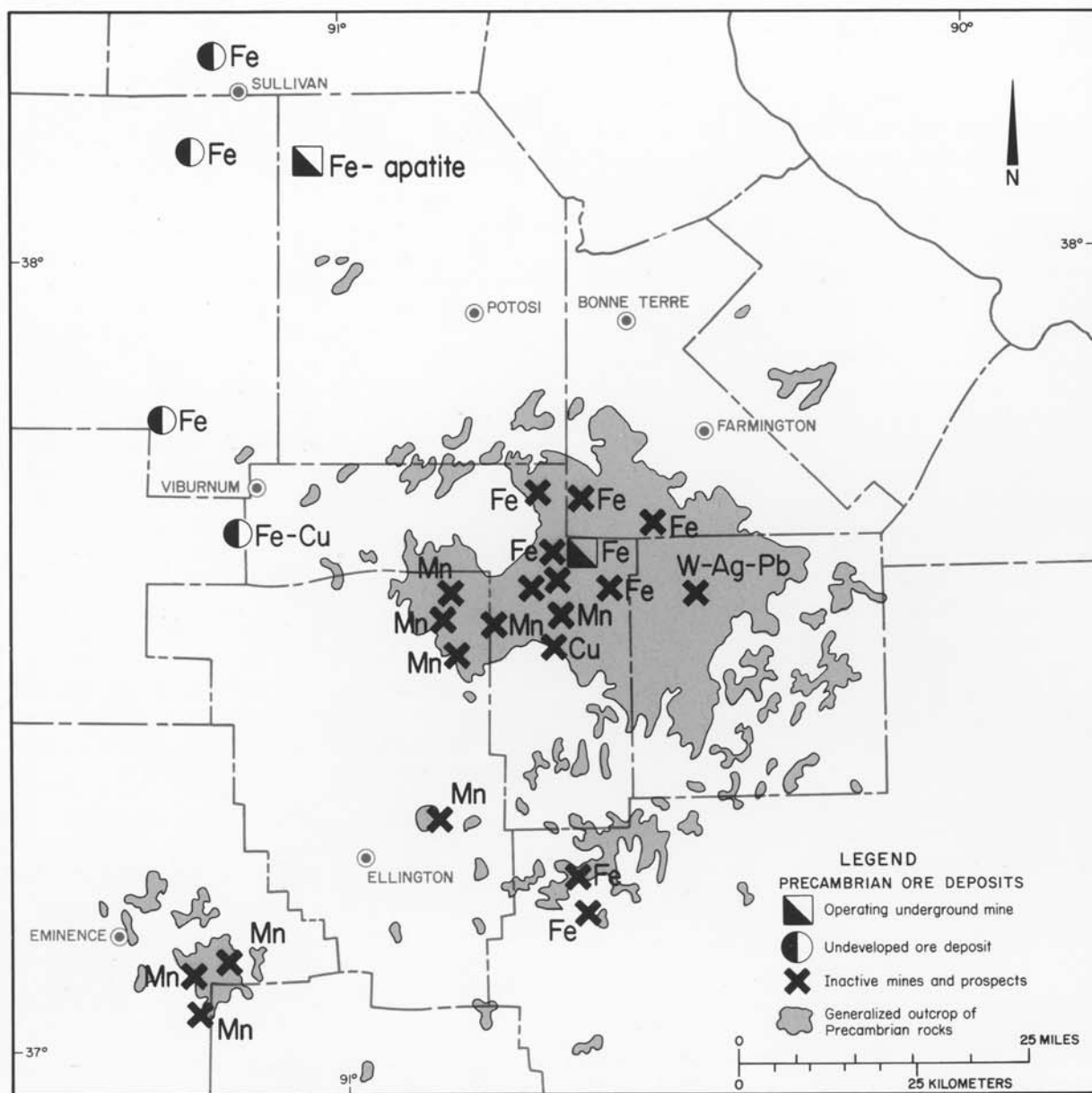
Figure 3

Precambrian ore deposits in southeast Missouri.

magma injections, volcanic exhalative deposits, and hypothermal bodies. All ore deposits are high-temperature formations. Meso-epithermal veins of the base and precious metals, commonly associated with igneous rocks of subduction zones, are not known to occur in the province. The general lack of large-scale propylitic and argillaceous alteration in the wall rocks is characteristic of the ore deposits of the province.

TRACE-ELEMENT GEOCHEMISTRY

The distribution of trace elements in the igneous rocks of the province and their local concentration in ore deposits point out the fundamental relationship between Precambrian magmatic evolution and metallogenesis. Geochemical data indicate that the igneous rocks of the province are enriched in a number of trace elements, particularly in some metals, relative to world averages of igneous rocks (E.B. Kisvarsanyi, 1961; G. Kisvarsanyi, 1966; Malan, 1972). Comparison of the trace-element content of selected rock samples from the St. Francois terrane with world averages for igneous rocks is shown in table 1.

The high-silica rocks are enriched in Fe, Co, Cu, Pb, Zn, Sn, U, and Th. They are generally deficient in or contain normal amounts of Ti, Mg, and Cr. The amount of Mo is near the world average for high-silica igneous rocks.

Intermediate rocks of the province, especially syenites, diorites, and andesites, are high in Mg, Fe, Ti, Cr, V, Mn, Co, Ni, Zn, Cu, and Mo. Some of these metals are more abundant in the intermediate rocks than in the more basic diabase and gabbro of the Skrainka type. Syenite intrusions with high volatile and metal contents were particularly capable of assimilating the intruded rocks. They deposited minerals in their contact zones, and caused extensive Ca, Si, K, and Fe metasomatism (G. Kisvarsanyi, 1966; Smith, 1968). Hornblende-diorite intrusive bodies are associated with some of the mineralization.

The late basic rocks of the province, diabase and gabbro of the Skrainka type, are relatively enriched in Cr, Cu, and Zn, are low in Ti, V, Mn, and Co, and are normal in Mo and Ni relative to world averages. Deep-seated basic intrusive bodies of gabbro and norite, discovered by drilling and known only from the subsurface (E.B. Kisvarsanyi, 1974), are quite different from those known in outcrops and contain Fe, Ni, and Cu minerals. However, trace-element studies of these rocks have not yet been done.

TABLE 1

ARITHMETIC MEANS OF TRACE ELEMENTS IN SELECTED PRECAMBRIAN ROCK SAMPLES FROM SOUTHEAST MISSOURI*
COMPARED TO WORLD AVERAGES OF IGNEOUS ROCKS**
(in parts per million)

Rock Type	No. of analyses	Ti	V	Cr	Mn	Co	Ni	Cu	Zn	Mo	Mg
Basalt, Missouri	2	5,350	117	465	1,116	23	148	165	240	1	10,000
Basalt, world		13,800	250	170	1,500	48	130	87	105	1.5	46,000
Diorite, Missouri	2	4,700	225	685	3,080	31	96	285	280	3	10,000
Andesite I, Missouri	2	4,225	204	465	4,700	55	62	330	265	1.5	———
Andesite II, Missouri	2	2,350	150	343	825	11	30	23.5	100	1	———
Diorite, world		3,400	88	22	540	7	15	30	60	1	———
Syenite, world		3,500	30	2	850	1	4	5	130	0.6	5,800
Granite, Missouri	3	673	28	1	883	17	1	19	216	1	1,176
Rhyolite I, Missouri	2	1,130	69	1	350	1	1.5	14	265	1	141
Rhyolite II, Missouri	4	665	17	1	9	1	2	15	100	2	585
Granite, world		1,200	44	4.1	390	1	4.5	10	39	1.3	1,600

* G. Kisvarsanyi (1966).
** Adapted from Turekian and Wedepohl (1961).

GEOLOGIC SEQUENCE
OF METALLOGENESIS

The rise and differentiation of magmas and the subsequent formation of the different igneous bodies transferred, recycled, and locally concentrated the metallic elements. The formation of mineral deposits was a function of various magmatic processes, including liquid immiscibility, separation of hydro-thermal fluids, and volcanic exhalation of metal-rich vapors.

Five major magmatic episodes, each complex in itself, are defined by the writer (G. Kisvarsanyi, 1973; 1975) in the evolution of the St. Francois terrane in south-east Missouri. The first three stages were the most important in metallogenesis.

FIRST STAGE

Regional high-silica volcanism, including emplacement of rhyolitic ash flows and lava flows, and accompanied by contemporaneous formation of granite porphyry and granite bodies, marked the onset of igneous activity. It was accompanied and followed in rapid succession by the intrusion of discordant, comagmatic granite. The initial magmatism was of long duration and yielded intermediate rocks in small volume. It was interrupted by periods of erosion during which volcanic detritus was locally redeposited into bedded tuffs. Lavas, ash-flows, and pyroclastics issued from several eruptive centers and from deep-reaching fractures and fissures. The large-scale volcanism substantially dehydrated magma sources below.

SECOND STAGE

The volcanic pile and its associated hypabyssal intrusive bodies of the first stage were intruded by a second stage of granites that represented deeper levels, more differentiation, and a later surge of granitic magma. Consolidation of this period is characterized by cauldron subsidence, collapse of volcanic strata, and ring-dike emplacement. During this stage, volcanism occurred at a reduced scale.

THIRD STAGE

Complex intermediate to acidic magmatism produced diorite, monzonite, and syenite intrusive plutons, stocks, and dikes, and shallow subvolcanic masses of andesite, trachyte, and dacite(?) during the third stage. The major iron-ore bodies of the province have been emplaced in the rhyolites and andesites in this stage or just preceding it, and it is probable that the magnetite-hematite-apatite ore bodies differentiated from these intermediate to granitic magmas (G. Kisvarsanyi, 1966).

The most important elements that were concentrated in the first stages of high-silica magmatism were Fe, Mn, W, Ag, Sn, Pb, Cu, Zn, U, Th, Ba, rare earths, P, and S. The intermediate magmatism was accompanied by Fe, Ti, Cu, Co, Pb, Zn, Mo, As, and S enrichments. P_2O_5, F, As, S, and CO_2 were important volatile constituents, whereas H_2O played a relatively smaller role than in other mineral districts. The syenite and other intermediate intrusions caused extensive Ca, Si, K, and Fe metasomatism, assimilation of intruded rocks, contact metamorphism, and Fe-Cu-Co mineralization with a unique assortment of ore minerals (G. Kisvarsanyi, 1966; Smith, 1968).

The formation of this new sialic crust moved large amounts of the radioactive elements upward. Some of the most radioactive (uraniferous) granites in North America are found in the St. Francois terrane (Malan, 1972). The province has a real potential for the existence of radioactive mineralization in some granites, especially in the later differentiates, which may in part have been recycled into the overlying sediments.

FOURTH STAGE

A third period of granitic intrusions is indicated only by major dikes within observable depth zones of the province. They cut all rocks of the first

three stages. This last upsurge of granite magma caused extensive hybridization in the intruded rocks. The hybrid rocks exhibit a remarkable mineralogy, especially when the intruded rock was of basic or intermediate composition. The mineralization potential of these late granites is not known, but is considered favorable for U-Th minerals and pegmatites, as they are apparently derived from more water-rich magmas.

Alteration of several types is observable in the igneous rocks of the province. Deuteric alteration affected the phenocrysts in volcanic and hypabyssal rocks and the essential minerals in the plutonic rocks to various extents. A widespread vapor-phase crystallization and locally intensive fumarolic activity deposited and rearranged some minerals, especially in the ash-flow tuffs and bedded tuffs. Iron oxides and manganese minerals may have formed locally during fumarolic activity; however, fumarolic steam and waters must have been essentially meteoric, as suggested by the oxygen-isotope composition of the rocks (Wenner and Taylor, 1972).

Hydrothermal alteration is not common in the rocks and is generally confined to the wall rocks of ore deposits (silicate skarn and greisen). Universal devitrification has probably caused changes in the groundmass of the volcanic rocks. In spite of these processes, the lithology of both the volcanic and intrusive rocks is preserved to a remarkable degree especially in non-mineralized areas.

FIFTH STAGE

The last major phase of Precambrian igneous activity was represented by highly mobile magma of basaltic composition. It formed gabbro and diabase dikes and sills, and probably basaltic flows that have since been removed by erosion. This stage is not known to be rich in ore minerals.

The deep-seated and probably layered mafic intrusive bodies that occur only in the buried part of Missouri's Precambrian basement complex, but within the general boundaries of the St. Francois terrane, are not well known. Their genesis, age, and tectonic relationships to the St. Francois terrane have not been established. They are likely to contain above-average concentrations of Cu, Ni, and possibly Fe, Ti, Pt, and Cr, and may represent potential resources for the future.

SUMMARY

Extrapolations and generalizations are not easy to render for the entire Central province from the known areas of the St. Francois terrane in southeast Missouri. The geologic, petrochemical, and tectonic characteristics of the terrane suggest that Meso-Tertiary type subduction did not play a role in its evolution. In subduction zones, serpentinized mafic rocks provided ample amounts of water to produce large volumes of andesitic volcanic and intrusive rocks. Meso-epithermal veins of the base and precious metals, with intensive hydrous alteration zones, are frequent in those provinces.

The metallogenesis and ore deposits of the St. Francois terrane are distinctly different. Intrusive contacts between volcanic and plutonic rocks are anhydrous; effects of water are generally confined and limited to contact aureoles of iron-ore bodies and to intrusive contacts of syenites. Metasomatic changes in the host rocks are well defined only around some of the iron-ore deposits, and small-scale greisen-type alteration is known only along W-Ag-Pb veins. Vapor-phase minerals of ash-flow tuffs are water-poor, while relatively large concentrations of F, CO_2, S, and P are present in many rocks and ore deposits. Fumarolic activity and devitrification produced slight general alteration in the volcanic rocks.

The Precambrian igneous rocks and ore deposits of the St. Francois terrane contain a distinctive assortment of metallic elements and mineralizers. Some of these, including F, Ba, alkali metals, and, marginally, Pb and Zn, suggest that the younger Illinois-Kentucky fluorspar district derived its elements from mobilized

and regenerated Precambrian material representing a later cycle of metallogenesis. The lead-isotope composition and Cu-Ni-Co enrichments in the ore deposits of the Lead Belt and Viburnum Trend of southeast Missouri may be manifestations of a Paleozoic epoch of metallogenesis that extracted and mobilized metals from the Precambrian basement.

Exploration programs in the terrane should be carried out on the basis of extensive geological, petrochemical,

petrological, geochemical, and structural studies of the basement. Investigations should emphasize both the internal and the boundary relationships of the terrane and its floor rocks. Study of the isotope ratios in the rocks would be especially helpful to understand the genesis of the St. Francois terrane. The origin and chemical nature of these rocks have a direct bearing on their resource potential.

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STRUCTURAL LINEAMENTS AND MINERALIZATION IN SOUTHEAST MISSOURI

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INTRODUCTION

In an earlier report (Kisvarsanyi and Kisvarsanyi, 1976) we defined several major structural lineaments in southeast Missouri by integrating surface and subsurface geologic data, geophysical data, topographic features, and prominent airphoto linears. In that study, we used satellite remote-sensing imagery (LANDSAT-1) of the area only to supplement our data, to determine whether known structural features can be identified on the imagery, and to see if other features, not known to be of structural origin, can be recognized. The coincidence of structural lineaments with linear features on the imagery was found to be remarkably close, although many additional lineaments were indicated on the imagery. In addition to the major linear and curvilinear features confirmed or discovered in the course of that preliminary analysis of multispectral imagery, 24 major circular and arcuate features were also identified in southeast Missouri.

In a subsequent, NASA-supported investigation (Contract No. NAS5-20937) we analyzed the structural and ground patterns of the entire state with special emphasis on the Ozark Dome, utilizing both LANDSAT-1 and LANDSAT-2 imagery. The principal objectives of this investigation have been a) to assess the quality, characteristics, and overall value of satellite multispectral imagery in resources investigations in a structurally distinct unit of the Mid-continent platform, b) to evaluate and interpret the imagery for natural-resources detection, emphasiz-

ing the metallotects of the large mineralized districts present in the area, and c) to evaluate the imagery for gross rock-type recognition and identification as an aid for regional geologic mapping.

This paper is a brief summary of the results of our investigations, with special emphasis on the influence of the Precambrian basement on the distribution and local concentration of metallic minerals.

STATEWIDE PATTERN OF LINEAMENTS

LANDSAT-1 and LANDSAT-2 imagery indicates a distinct pattern of linear features throughout the state (fig. 1). The greatest frequency of lineaments occurs south of the 38th parallel north latitude, with the highest density occurring in southeast Missouri. Several major northwest-trending lineaments are 200 to 300 mi long and extend into northern Missouri. The most prominent of these is expressed on the ground as a geomorphic feature, namely, the valley of the Grand River in northwest Missouri, and continues on strike with a segment of the Missouri River in central Missouri. Northeast-trending lineaments are generally restricted to the southern half of the state; many of these extend into northern Arkansas.

Comparison of the lineament map (fig. 1) with the Structural Features Map of Missouri (McCracken, 1971) indicates that known and mapped structures (faults, synclines, anticlines) correlate very closely with the lineaments. Intersections of lineaments in several places coincide with structurally disturbed areas and cryptoexplosion structures. Geomorphic features, such as river courses and topographic escarpments, in hundreds of places across the state appear to be lineaments and may be expressions of fractures, faults or other geologic features.

A good correlation exists between lineaments and major magnetic anomalies (Magnetic Map of Missouri, 1943). In many places, deep drilling indicates that the magnetic anomalies are caused by mafic intrusive bodies in the Precambrian basement (E.B. Kisvarsanyi 1974). Coincidence of a string of magnetic anomalies

in northern Missouri with the Grand River lineament, and coincidence of another series of magnetic anomalies west of St. Louis with a major northeast-trending regional lineament strongly suggest deep-seated structural control. The distribution of Precambrian iron-ore deposits in southeast Missouri is also expressed by magnetic anomalies and shows correlation with lineaments identified from the imagery.

Aeromagnetic maps, where available, frequently display excellent magnetic lineaments. In central Missouri, a prominent aeromagnetic lineament corresponds closely with one of the major northwest-trending lineaments, identified from the imagery, which passes through the Decaturville structure. Recent mapping indicates that several faults in this area are along strike with this lineament (Ira Satterfield, pers. commun., 1976).

The greatest density of lineaments is observed in the area of exposed and shallow Precambrian basement in southeast Missouri. Both in southwest and central Missouri the relatively dense lineament pattern occurs over buried Precambrian highs as indicated on the contour map of the buried Precambrian surface (E.B. Kisvarsanyi, 1975). Lineament density in Missouri therefore appears to be inversely proportional to the depth of the Precambrian surface. The Precambrian basement, as a tectonic unit, must have exerted a profound influence over igneous activity, mineralization, and structural movements throughout the history of the region.
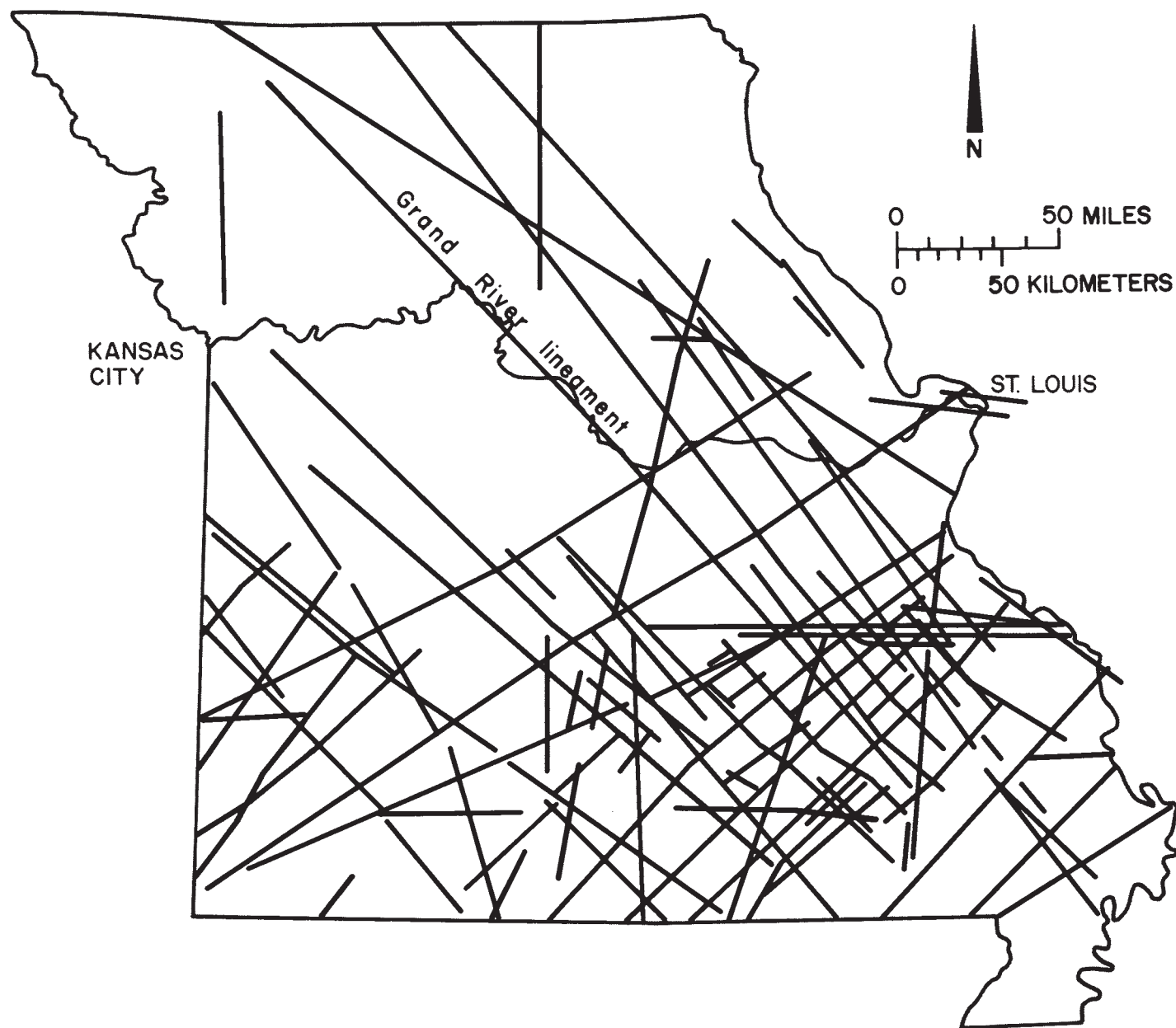
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Figure 1

Lineament map of Missouri based on LANDSAT-1 and LANDSAT-2 remote-sensing multi-spectral imagery.

RELATIONSHIPS OF LINEAMENTS, CIRCULAR FEATURES, AND MINERALIZATION IN SOUTHEAST MISSOURI

Comparison of the lineament map with the distribution of major mineral deposits in Missouri (E.B. Kisvarsanyi, 1965) shows a close geographical association. Mineralized areas in the southern part of the state are found on or along lineaments or near the intersection thereof. The frequency and distribution of lineaments is most regular and repetitive in the area of the Southeast Missouri Mining District (fig. 2). A definite lineament pattern is also associated with the formerly productive southwest Missouri part of the Tri-State Mining District and with the Central Missouri District. Along the Arkansas-Missouri border, several smaller mineral deposits occur near the intersections of lineaments in intensely brecciated rocks.

The spatial association of lineaments, as identified from the multispectral imagery, with the major iron and lead-zinc-copper deposits of the Southeast Missouri Mining District is illustrated in figure 2. The Precambrian outcrop area of the St. Francois Mountains is centered around the town of Ironton (fig. 2). The lead-zinc-copper deposits of the Viburnum Trend Mining District are located along an approximate north-south line, about 25 mi east of Salem.

Several of the lineaments shown in figure 2 correspond to faults or fault systems mapped in the Precambrian rocks and in the overlying sediments. The lineaments frequently extend on strike beyond the mapped length of faults. Many of the lineaments, however, are not associated with mapped faults. They may alternately be coincident along their strikes with drainage patterns, topographic escarpments, igneous-sedimentary contacts, mineralization, the intrusions of diabase dikes, and zones of brecciation. They are believed to be expressions of deep-seated fracture-fault systems in the Precambrian basement, and their width on the ground surface may be measured in hundreds or in thousands of feet.

Circular and arcuate features are particularly abundant in the area of exposed and shallow basement in southeast Missouri (fig. 3). They tend to be clustered in areas underlain by volcanic rocks. Where these rocks are exposed, as in the area of the Taum Sauk Caldera west of Ironton, and east of Eminence, the circular pattern is also visible on 1:24,000-scale topographic maps and on stereo images of airphotos. Circular features over buried basement are in part defined by curving segments of stream channels; others appear to encircle isolated small outcrops of volcanic rock around sediment-filled depressions. Some known cryptoexplosion structures also appear on the LANDSAT imagery as circular features. Several circular and arcuate features have been observed along the Viburnum Trend (fig. 3).

The circular features may be volcano-tectonic in nature, subsided cauldrons, or circular plugs, and appear to be related mostly to a mechanism of Precambrian magmatic activity. Some ignimbrite sheets may have issued from circular fractures and intrusive bodies may also exhibit cylinder-like circular patterns. Some circular features appear to be cut by others, or by faults, representing some age difference. It is possible that some circular features are of different origin and are genetically related to mineralization. Detailed ground-truth investigations are needed to determine the importance of these features in the evolution of the St. Francois terrane, and to determine their role, if any, in mineralization.

TECTONIC FEATURES OF THE METALLOGENIC PROVINCES OF SOUTHEAST MISSOURI

An important phase of structural analysis is the recognition of metallotects, particularly, the tectonic controls of ore deposits in metallogenic provinces. Southeast Missouri is the site of two major metallogenic provinces of North America. One of these is the Precambrian iron-copper-manganese province and the other is the
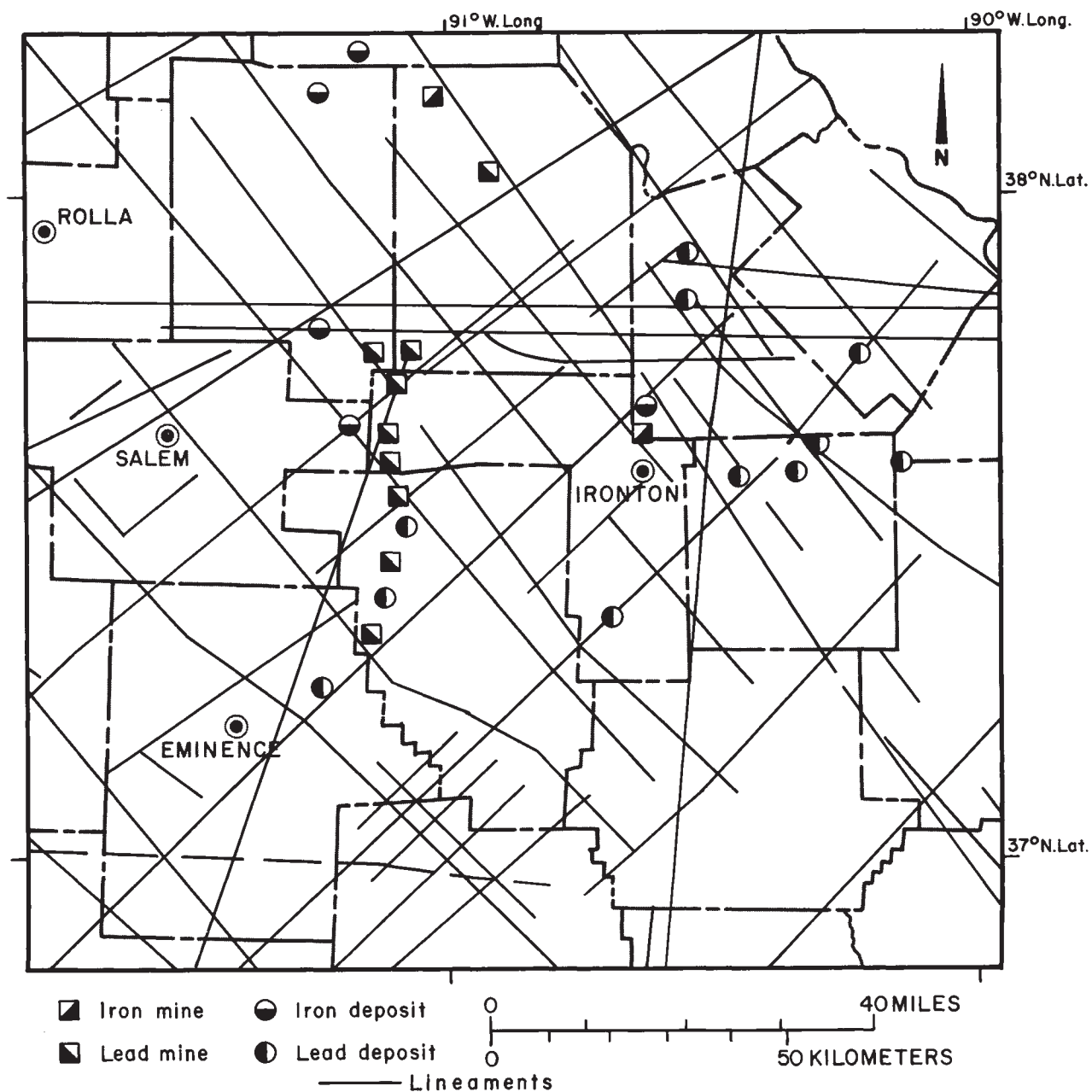
Figure 2

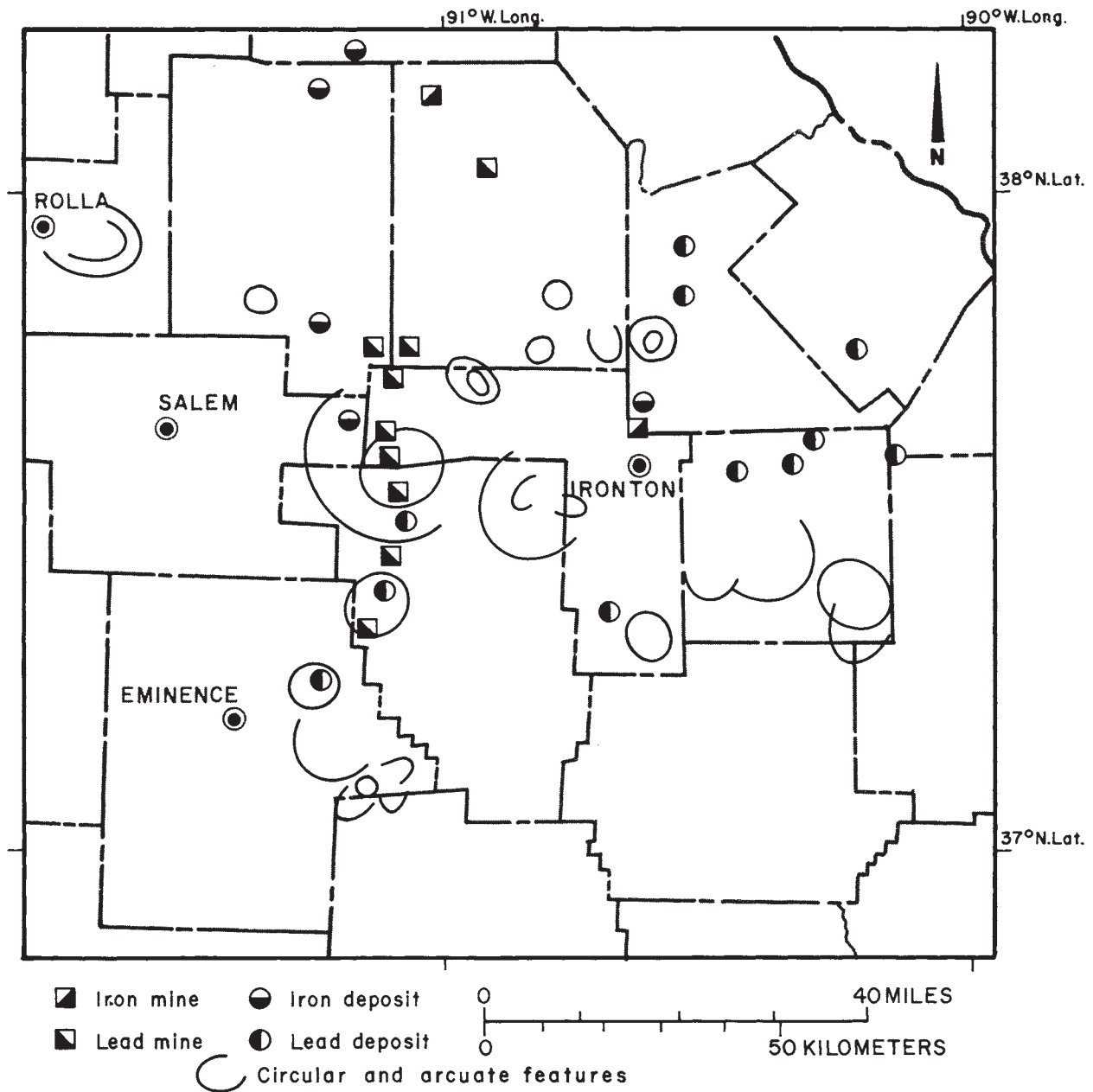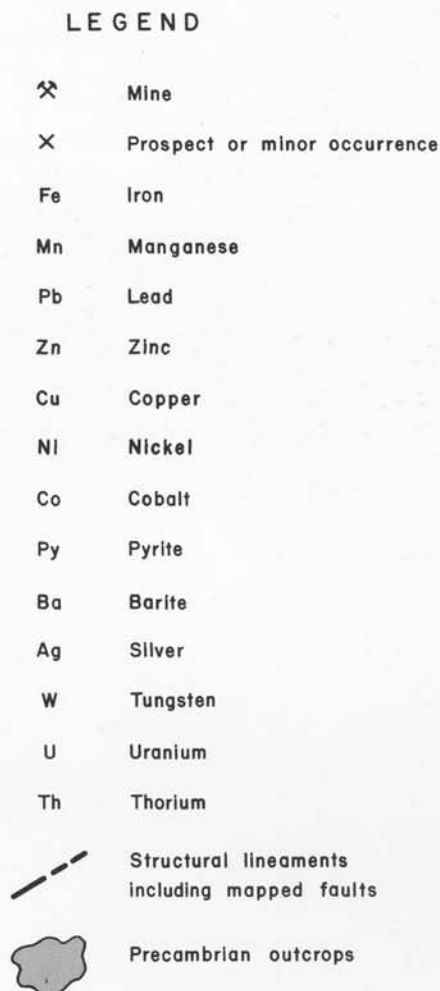*Lineaments in the Southeast Missouri Mining District.*

Figure 3
Circular and arcuate features in the Southeast Missouri Mining District.

Figure 4 *Precambrian outcrops, structural linea-*
ments, and mineralization in the South-
east Missouri Mining District.

LEGEND

⚒	Mine
×	Prospect or minor occurrence
Fe	Iron
Mn	Manganese
Pb	Lead
Zn	Zinc
Cu	Copper
Ni	Nickel
Co	Cobalt
Py	Pyrite
Ba	Barite
Ag	Silver
W	Tungsten
U	Uranium
Th	Thorium
╱ ╱	Structural lineaments including mapped faults
▨	Precambrian outcrops

Mississippi Valley-type lead-zinc-copper province in
the Paleozoic sediments. The Washington County
barite district, residual deposits of iron, and veins of
tin, tungsten, silver and lead are also within the area.

The ore deposits of the Precambrian igneous province
are localized along fractures and faults, and the strata-
bound lead-zinc-copper deposits are concentrated at
the hinge zones of Precambrian structural highs and
lows. The influence of the Precambrian basement on
the stratabound mineralization has been discussed by

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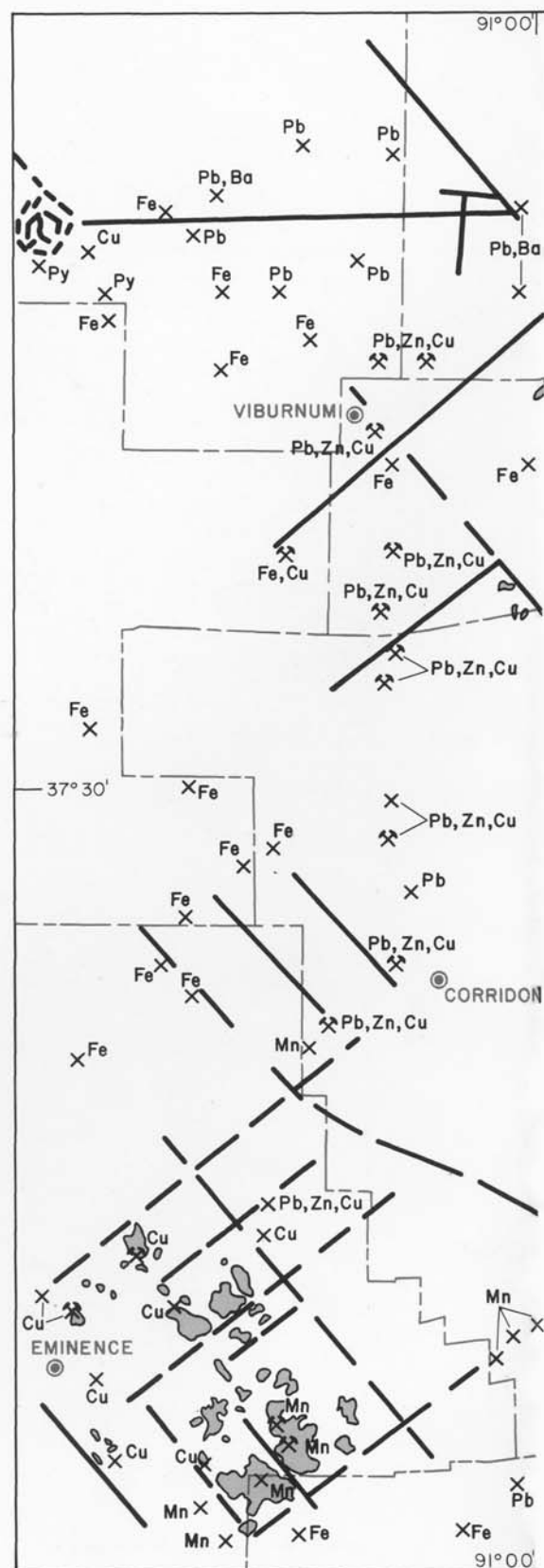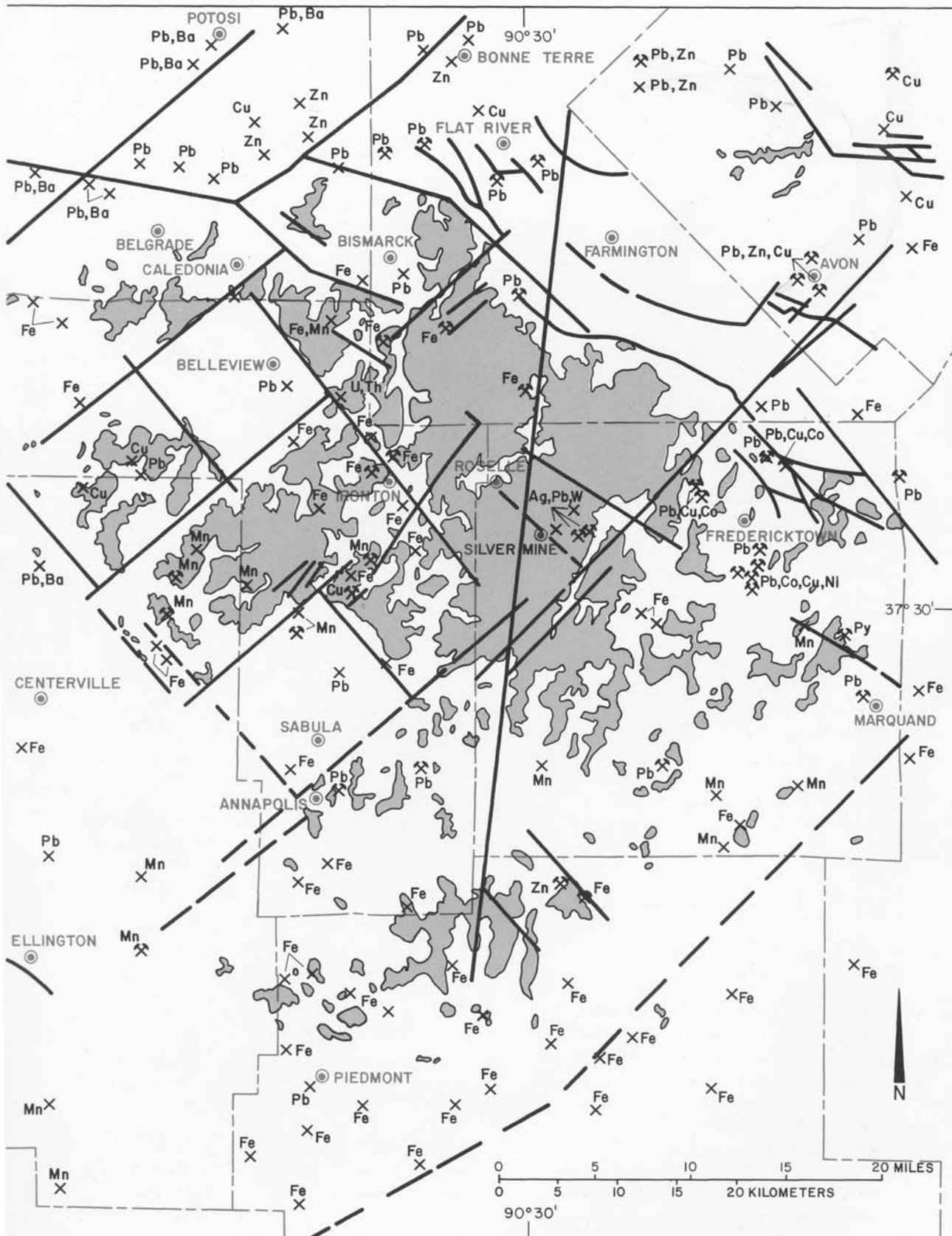
G. Kisvarsanyi (in prep.). Faults and fractures brecciated sedimentary rocks and controlled the movement of mineralizing solutions. The residual barite deposits are localized along fracture zones in the carbonate host rocks. A distinct relationship is recognized between the distribution of kimberlite-alnöite dikes and diatremes and the structural lineaments of the Avon area. Such a system of interrelationship between major structural lineaments and alkalic ultramafic complexes has been demonstrated in Angola and other parts of Africa (Reis, 1972).

Comparison of the pattern of structural lineaments (fig. 4) and the pattern of lineaments identified from the LANDSAT imagery (fig. 2) shows a basic similarity of strike directions and spacing. Precambrian outcrops in the St. Francois Mountains and Eminence areas have an orthogonal to polygonal distribution pattern. Within the outcrops, square-shaped basins and highs developed by differential tectonic movements. Structural lineaments form the boundaries of tectonic units such as the down-dropped blocks of the Belleview and Sabula "basins" and the uplifted Eminence block (fig. 4). A detailed description of the structural lineaments, many of which have been named, is given by Kisvarsanyi and Kisvarsanyi (1976).

In order to bring the interrelationship of tectonic elements and mineralization into sharper focus, minor concentrations of metals (prospects and "shows") in both the Precambrian and the Paleozoic rocks have been plotted on the structural-lineament map of southeast Missouri (fig. 4) along with the important mineral deposits. The distribution of mineralization shows a degree of coincidence with the structural lineaments of the region, which in turn appear to be a function of its Precambrian structure. The fracturing and faulting of the Precambrian basement have created an intricate plumbing system which provided avenues of access for metal-bearing solutions in Precambrian and later time. Such a system might permit ascending solutions to reach favorably prepared (fractured, brecciated, etc.) host rocks, lateral migration and redistribution of metals, and control of descending ore fluids along fractures produced by Precambrian and Paleozoic epeirogeny.

Local and regional structural elements had an important role in the formation and localization of the ore deposits of the region. Careful analysis of the individual lineaments and their pattern in the region should be a useful exploration tool.

Further investigations are needed to establish the interrelationship of ore deposits with the lineaments observed on the satellite imagery. Geographic association alone may not be meaningful if the genetic relationship of lineaments and ore emplacement is absent. Furthermore, the emplacement of ore deposits may be controlled by smaller structural elements which are not visible on satellite imagery. The association of lineaments and ore deposits may be closer, or better displayed in the Precambrian ore deposits than in the stratabound deposits. In the latter, factors other than structure, such as the Lamotte pinchout, permeability of sediments, chemical environment, etc., had also influenced ore deposition.

ACKNOWLEDGMENTS

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SEISMOLOGICAL STUDIES OF MISSOURI CRUSTAL STRUCTURE

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DEFINITIONS

The term "Earth's crust", as used by seismologists, refers to the part of the Earth above the Mohorovičić discontinuity, the latter being a surface across which the seismic body-wave velocities increase discontinuously from above to below, with the compressional-wave, or P-wave, velocity being about 8 km/sec below this discontinuity. Beneath the Mohorovičić discontinuity lies the Earth's mantle, which is believed to be chemically and mineralogically distinct from the crust. In continental regions the crust generally consists of a layer of sedimentary rocks, a layer of acidic igneous rocks, and a layer of more basic rocks. Each of the three layers may be subdivided into additional layers. The transition from acidic to basic rocks may occur gradually over a finite depth range or it may occur almost discontinuously. In the latter case the surface of discontinuity is called the Conrad discontinuity. In oceanic regions the layer of acidic rocks is missing, and the crust is correspondingly thinner than in continental regions. The average depth of the Mohorovičić discontinuity in continental areas is about 25 to 40 km, although it can vary from about 20 to 70 km.

The Earth's lithosphere includes the crust and a small part of the mantle which overlies the asthenosphere, the latter being a region of reduced rigidity and seismic body-wave velocities whose upper surface in continental areas is at a depth of about 50 to 150 km. The lower rigidity of the asthenosphere results from temperatures in that region being at or near the melting point of the rock or of some of its constituents. The depth to the bottom of the asthenosphere is variable and not well established, but is about 100 to 300 km.

METHODS

Seismological crustal studies normally are used for the determination of the thickness of the crustal layers and of the gross physical properties of the rocks contained in those layers. The seismological methods used to study crustal structure can be divided into four broad types: a) refraction methods, employing either explosion- or earthquake-generated body waves, b) reflection methods, usually employing explosion-generated P waves, c) surface-wave dispersion methods, and d) methods which make use of the spectra of earthquake-generated body waves. Although all four methods have been used in the study of Missouri crustal structure, the refraction method has provided the most definitive results.

Earthquake focal-mechanism determinations, although ordinarily not classified as crustal-structure studies, provide information about dynamic processes taking place in the crust. They yield, for example, information about the strike and dip of the fault plane, the direction of slip on the fault plane, and the orientation of the principal axes of regional compression and tension. Focal-mechanism solutions can be obtained from a study of the azimuthal variation of the amplitude spectra of surface waves, from the spatial distribution of the sense of the first P-wave motion (compression or dilatation) as recorded by seismographs distributed over the surface of the Earth, or by the polarization of shear, or S, waves as recorded at distant seismograph stations. The P-wave method is the only method that can be used for the relatively small-magnitude earthquakes that occur in the St. Francois Mountains region, because the long-period S and surface waves of these earthquakes have too-small an amplitude to be seen on the seismograms. Occasionally earthquakes occur in this region which are large enough to generate measurable surface waves, such as the earthquake of October 21, 1965, near Centerville, and of July 21, 1967, near Glover. In these cases, both P-wave and surface-wave data were used in the study, the combination giving focal-mechanism parameters with smaller uncertainty than if P-wave data were used alone.

RESULTS

An average crustal structure for the central United States, based principally on seismic-refraction data, is shown as figure 1. References to the sources of information used in constructing figure 1 are given in a paper by Nuttli et al. (1969). The quantities V_P and V_S are the P- and S-wave velocities, respectively. Only the gross properties of the crust and upper mantle are portrayed in figure 1. For example, the sedimentary layer is not included, and the velocities and thicknesses of the individual layers represent average values of those quantities. The P-wave-velocity discontinuity at 97 km depth, which is suggested by data from the 1968 south-central Illinois earthquake (Stauder and Nuttli, 1970), also has been found in the Canadian Shield at a depth of 84 km (Mereu and Hunter, 1969). As the bottom of the lithosphere or the top of the asthenosphere
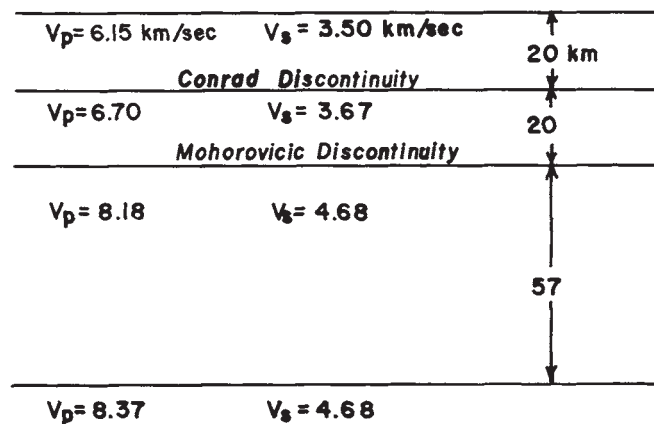

Figure 1

Average crustal structure of central United States (after Nuttli et al., 1969).

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is marked by a decrease in velocity from above to below, the asthenosphere in Missouri has to be at least 100 km deep, and probably is deeper.

Travel times of refracted waves from individual earthquakes show deviations from those predicted by the simple crustal model of figure 1. Thus, for the Mississippi Embayment, Stauder (1976) replaced the 20-km-thick upper crustal layer by four layers, having thicknesses of 1.0, 0.5, 0.5, and 18 km, and P-wave velocities of 2.8, 3.6, 5.6, and 6.15 km/sec, respectively. The upper two layers would correspond

to unconsolidated sediments, the third to competent sediments, and the fourth to acidic rocks of the basement. For the uplands to the northwest of the Mississippi Embayment, Stauder (1976) replaced the upper crustal layer of figure 1 by two layers, having thicknesses of 2 and 18 km, and P-wave velocities of 5.6 and 6.15 km/sec, respectively.

The most detailed crustal studies in Missouri were carried out by Stewart (1966, 1968) in cooperation with the U.S. Geological Survey. Figure 2 shows the locations of the two profiles, along with the shot points and the lines on which the seismic detectors
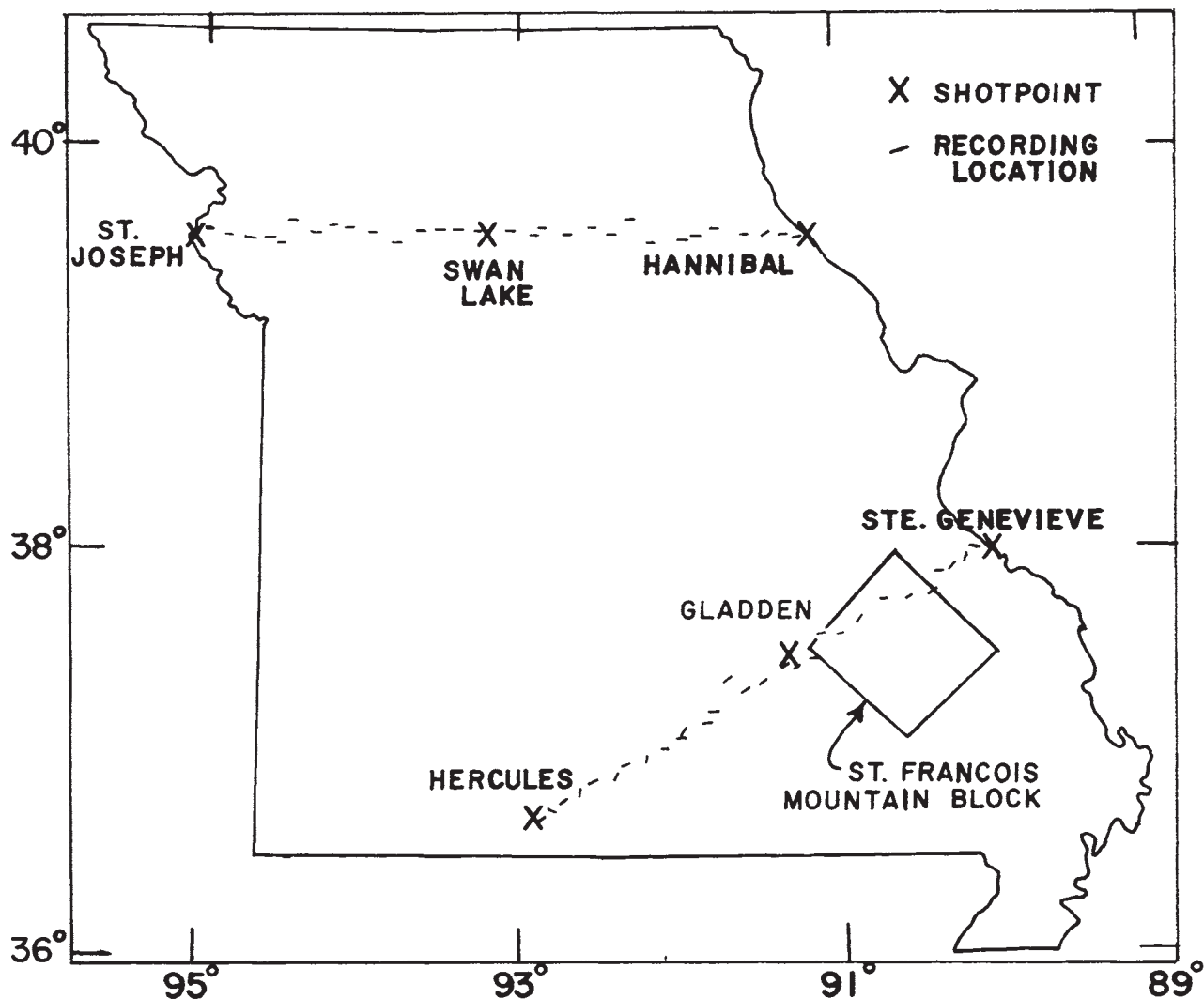

Figure 2

Location of refraction seismic profiles in Missouri (after Stewart, 1966, 1968). The outline of the St. Francois Mountain block is taken from Kisvarsanyi and Kisvarsanyi (1976).

were placed. Along the northern profile the explosive sources were located at Hannibal, Swan Lake, and St. Joseph, and on the southern profile at Ste. Genevieve, Gladden, and Hercules. X's in figure 2 indicate the locations of these shotpoints, and short lines the locations of the recorders. The St. Francois Mountain block, with boundaries as given by Kisvarsanyi and Kisvarsanyi (1976), is outlined in the figure.
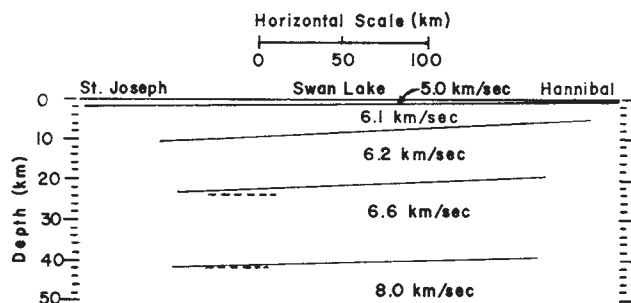

Figure 3

Crustal structure as determined from refraction profile from Hannibal to St. Joseph (after Stewart, 1966, 1968).

The results of Stewart's refraction study along the northern profile are shown in figure 3. The solid lines indicate boundaries as determined from refracted waves, and dashed lines indicate boundaries as determined from reflected waves. The P-wave velocities given for each of the layers represent values near the tops of these layers. Average velocity values for a layer will be somewhat higher, as was confirmed by the reflected-wave data. The upper boundary surface correlates well with the Precambrian surface as determined from drill data. The two layers of velocities 6.1 and 6.2 km/sec are presumed to be of acidic rock, with the Conrad discontinuity separating the layers of velocities 6.2 and 6.6 km/sec. All three crustal-discontinuity surfaces show a dip component of about 3/4 degree.

Stewart's (1966) refraction data for the southern-Missouri profile were not of as good quality as for the northern profile, because of poor signal-to-noise ratios. He explained the noise as due in part to the nature of the vegetation and the prevalence of

thunderstorms during the time of the field work, but perhaps to a greater extent to the existence of lateral inhomogeneities within the crust. As a consequence, there was more uncertainty in the interpretation of the data. For example, dip of the crustal-discontinuity surfaces could not be determined. Stewart had to resort to an assumption of horizontal boundaries, and to interpreting the data separately for the Gladden-to-Hercules profile and the Gladden-to-Ste. Genevieve profile. The results of his analysis are presented in figure 4. The figure should not be interpreted as indicating sudden changes in layer velocity and depth in the vicinity of Gladden, but rather as suggesting a dip of the boundary surfaces to the west from Ste. Genevieve to Hercules and also somewhat higher crustal velocities beneath the St. Francois Mountains.

Surface-wave dispersion can be used to estimate shear-wave velocities and layer thicknesses for the crust and upper mantle. McEvilly and Stauder (1965), using short-period surface waves from mining operations in southern Illinois and earthquakes in southeast Missouri, were able to estimate average sediment thickness and upper-crustal shear velocities for paths from the source regions to seismograph stations at St. Louis, Florissant, and Rolla, Missouri, and Bloomington, Indiana. The results agreed with what was known independently about the basement-surface topography, the data showing a thinning of the sediments for paths across the Ozarks and a thickening of sediments for paths across the Illinois basin. McEvilly (1964), using long-period surface
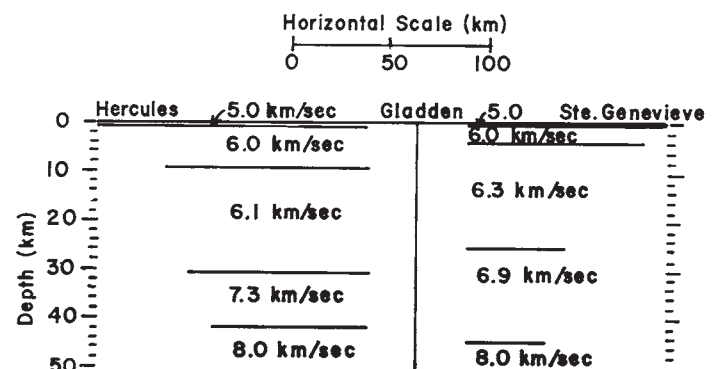

Figure 4

Crustal structure as determined from refraction profile from Ste. Genevieve to Hercules (after Stewart, 1966, 1968).
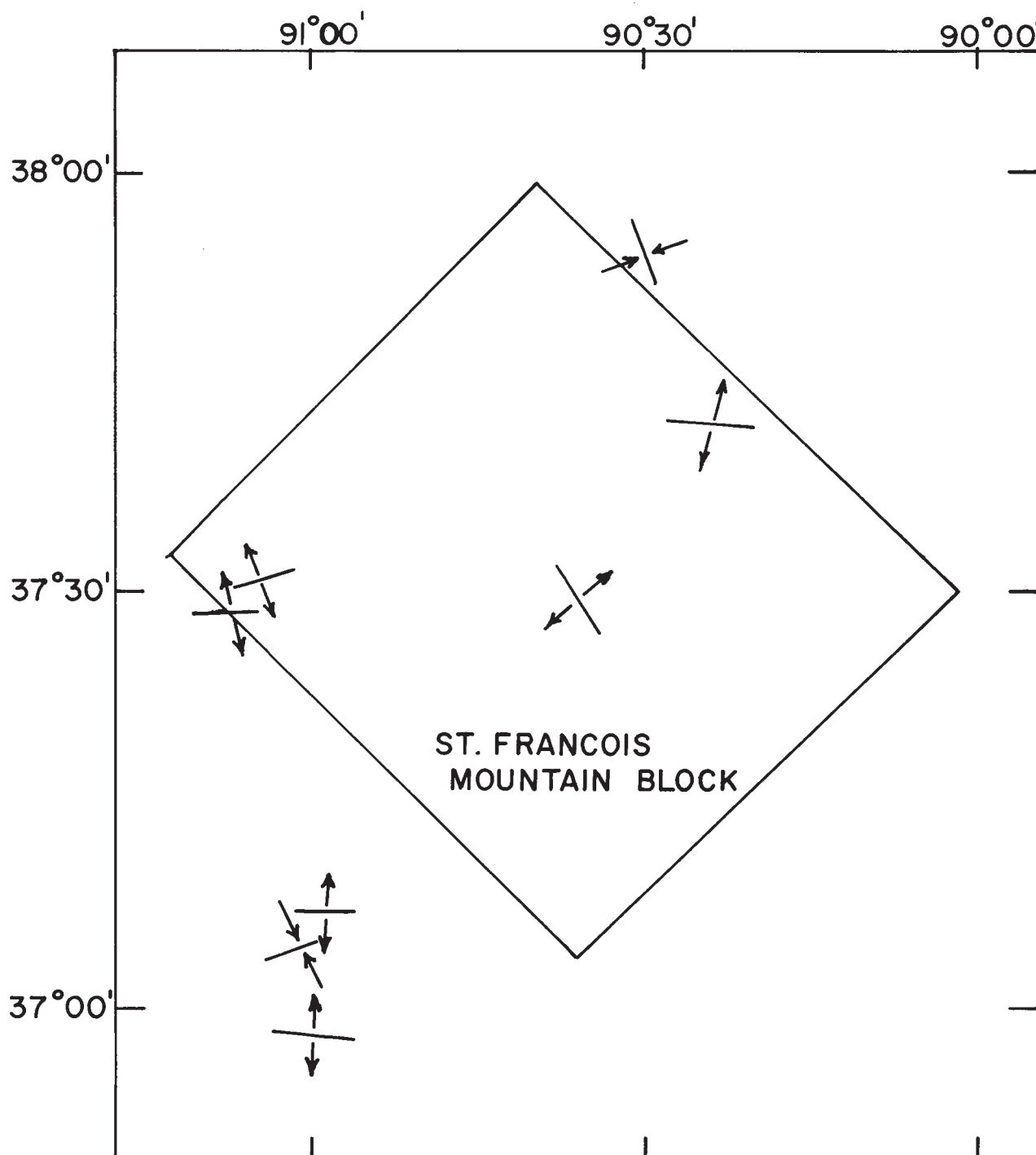
Figure 5

Strike direction of fault planes and trend of principal axes of tension or compression for recent earthquakes near the St. Francois Mountain block (after Street et al., 1974). The outline of the St. Francois Mountain block is taken from Kisvarsanyi and Kisvarsanyi (1976).

waves from distant earthquakes, obtained an average crustal structure for Missouri. The model crust consisted of three layers. The first had a P-wave velocity of 6.1 km/sec, an S-wave velocity of 3.5 km/sec, and a thickness of 11 km. Corresponding values for the second and third layers were 6.4 km/sec, 3.7 km/sec, 9 km, and 6.7 km/sec, 3.95 km/sec, and 18 km, respectively. The material below the Mohorovičić discontinuity had a P-wave velocity of 8.15 km/sec and an S-wave velocity of 4.75 km/sec.

The so-called crustal-transfer-ratio method utilizes the periods of maxima and minima in the spectra of earthquake P waves to estimate layer thickness and velocity for the crust and upper mantle, assuming that the geologic structure can be represented by a set of horizontal layers. Using the data from the seismograph station at Florissant, and assuming a two-layer crust, Fernandez and Careaga (1968) obtained thicknesses of 21 km for each of the two layers and P-wave velocities of 6.2 and 6.6 km/sec, with a sub-Mohorovičić-discontinuity velocity of 8.2 km/sec. Kurita (1973) found evidence of departures from horizontal layering and an average crustal thickness of about 47 km at Florissant. He also found that for the lower crust "a velocity of 7.4 km/sec is probable, implying an inclusion of ultramafic rocks".

Most of the earthquakes in the St. Francois Mountains region of southeast Missouri occur in the upper, or silicic, layer of the crust, at depths of less than 20 km. Focal-mechanism solutions (Mitchell, 1973; Street et al., 1974; Herrmann, 1974) for six of eight earthquakes in that region indicate normal faulting, and the remaining two thrust faulting. The strike-slip component is small for all of the earthquakes. In most cases the dip of the fault plane is approximately 45°. As the focal-mechanism data give two possible dip directions, i.e., to the north or to the south for a plane striking east-west, direction of dip of the fault plane is ambiguous by 180°. Figure 5 shows the locations of the eight earthquakes, the strikes of their fault planes, and the trends of the principal axes of tension (for normal faulting) and of the principal axes of compression (for reverse faulting). The figure demonstrates that the strike of the ongoing tectonic activity on the border of the St. Francois Mountains is approximately east-west, and that the regional stress field is predominantly tensional, with the principal axes of tension trending approximately north-south.

In summary, seismological studies in Missouri indicate that the crust is on the average about 40 km thick, and that it is divided into an upper half whose P-wave velocity is that of typical acidic continental rocks, and a lower half whose P-wave velocity is that of typical basic continental rocks. There is a suggestion that P-wave velocities are somewhat higher under the St. Francois Mountains. Most of the present-day earthquakes occur in the upper acidic layer, with those within or on the borders of the St. Francois Mountains block showing predominantly normal faulting, with an east-west strike and a north-south trend of the tensional stress axes.

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