Geology and Geochronology of Precambrian Rocks in the Central Interior Region of the United States

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EVA B. KISVARSANYI

CORRELATION OF PRECAMBRIAN ROCKS OF THE
UNITED STATES AND MEXICO

Edited by JACK E. HARRISON *and* ZELL E. PETERMAN

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Lithology, distribution, correlation, and isotope ages of Precambrian terrane for five subareas between the Appalachians and the Rocky Mountains

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GEOLOGY AND GEOCHRONOLOGY OF PRECAMBRIAN ROCKS IN THE CENTRAL INTERIOR REGION OF THE UNITED STATES

By RODGER E. DENISON,[1] E. G. LIDIAK,[2] M. E. BICKFORD,[3] and EVA B. KISVARSANYI[4]

ABSTRACT

Rocks of the buried Precambrian crust in the Central Interior region range from more than 2,700 to less than 1,000 million years in age and from granite and granulitic gneiss to gabbro and basalt in rock type. The oldest rocks occur in the Dakotas and clearly are buried portions of the Canadian Shield; they are mostly older than 2,700 million years, and some may be as old as 3,600 million years. The central part of this region, including Nebraska, northern Missouri, and northern Kansas, is underlain by diverse igneous and metamorphic rocks whose ages are mostly 1,600 to 1,800 million years; scattered anorogenic granitic plutons whose ages are about 1,400–1,500 million years are also known in this terrane.

The most distinctive feature of the Continental Interior is the great terrane of felsic igneous rocks that makes up the basement from Ohio and Wisconsin across southern Missouri and Kansas and into the Texas Panhandle and far western Texas. These rocks, which include abundant rhyolite and mesozonal and epizonal granitic bodies, range in age from 1,500 to 1,200 million years, and the general tendency is for ages to decrease from northeast to southwest; older rocks are not known anywhere within this terrane. Toward the east in Ohio, eastern Kentucky, and eastern Tennessee, and toward the south in central Texas, the basement terrane consists of medium-grade metamorphic rocks and associated granitic plutons that formed mainly 1,000–1,100 million years ago.

A belt of basalt, interflow arkosic sandstone and siltstone, and related mafic intrusive rocks can be traced with the aid of geophysical data from the Lake Superior region southward into central Kansas. This feature, the Central North American rift system, is widely believed to be an abortive continental rift that formed about 1,100 million years ago. Geophysical data suggest that other areas in the eastern part of the interior are also underlain by rift basalts and related rocks.

The Central Interior region was dominated by eugeosynclinal sedimentation and orogenic tectonics prior to about 1,600 million years ago. After that time the region apparently stabilized, and the sedimentation was characterized by the deposition of sheets of quartzose sandstone about 1,600 million years ago. Subsequent igneous activity, sedimentation, and tectonics have been dominantly anorogenic except along the margins of the stable interior.

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INTRODUCTION

Our understanding of the Precambrian in the Central Interior region is based upon widely separated outcrop areas and samples from irregularly distributed but numerous wells drilled largely in search of oil and gas. Flawn (1956) showed that it was possible to make a map of the buried Precambrian terrane based on drill-hole samples, and the larger scale study of Muehlberger and others (1967) led to publication of the basement rock map of the United States (Bayley and Muehlberger, 1968). These works remain the foundation of our present understanding. The geology and geochronology of the scattered surface exposures are now better known, but the geochronology of the subsurface has received little attention, and the basic reference work is the series of reports by Goldich and his coworkers (1966).

The rocks in the Central Interior region are here divided into four general types: (1) deep-seated granitic and metamorphic rocks similar to those exposed in the shield areas; (2) anorogenic mesozonal and epizonal granite; (3) rhyolite and epizonal granite; and (4) basalt and gabbro of "rift" type.

The first type is typical of rocks exposed in the Precambrian shields. These are diverse and strongly deformed rocks together with undeformed massive plutons that are characteristically older than about 1,600 m.y. (million years). The marked density and magnetic contrasts of these rocks allow extrapolation by geophysical methods in areas where drill control is lacking. About 18 percent of the Central Interior region is underlain by rocks of this type.

The second type is characterized by anorogenic mesozonal to epizonal granitic plutons, formed 1,300 to 1,500 m.y. ago, and associated with relatively minor metasedimentary and metaigneous rocks. Silver and others (1977) and Emslie (1978) have discussed the importance of these rocks, which form a discontinuous band from northeastern New Mexico to central Missouri and probably eastward to the Grenville Front in the Central Interior region. We estimate that 13 percent of the Continental Interior is underlain by these rocks.

The third type is characterized by large tracts of rhyolite and associated epizonal granite. After these tracts were recognized in the subsurface (Muehlberger and others, 1966; Muehlberger and others, 1967), additional drilling showed that much of the area east of the Mississippi River and west of the southward extension of the Grenville province is underlain by similar rocks. Although the origin of the epizonal granite-rhyolite terrane remains unclear, certain conclusions may be drawn from our present understanding:

(1) The rocks are preserved in structural depressions; surrounding rocks represent deeper crustal levels of emplacement.

(2) The rhyolites are invariably associated with coeval hypersolvus granites that commonly display micrographic quartz-perthite intergrowths.

(3) The rhyolites are not known to be associated with any significant volume of other volcanic or sedimentary rocks.

(4) The rhyolites are essentially undeformed and only locally recrystallized.

(5) The several tracts of rhyolite-granite are similar but not the same in age; the ages show no simple pattern of variation.

The rhyolite-epizonal granite association underlies an estimated 52 percent of the Continental Interior, although much of this area is east of the Mississippi River where drill-hole control is poor. The abundance of these rocks is the major difference between the buried Precambrian of the Continental Interior and the exposed shield areas. Gravity and magnetic observations are of limited value in extrapolating these rocks into areas where drill control is poor.

The extension of Keweenawan basaltic and gabbroic rocks from the Lake Superior region into the Central Interior region along the Central North American rift system has yielded the fourth major rock association. Basaltic rocks and related arkose can be traced as far as east-central Kansas on the basis of scattered well samples and gravity and magnetic data. That smaller areas east of the Mississippi River are also underlain by similar mafic igneous rocks can be inferred from geophysical measurements. These rocks are possibly time correlative with the Keweenawan associations. We estimate that about 10 percent of the interior is underlain by rocks of this type.

Perhaps the single most significant feature of the Precambrian rocks of the Central Interior region is the great preponderance of granite and related volcanic rocks. These rocks, which generally have petrographic features indicating that they were emplaced at shallow to intermediate crustal levels, make up about two-thirds of the Continental Interior. Mafic rocks occur mostly along the Central North American rift system. Igneous rocks of intermediate composition are exceptionally rare. The greenstone belts that so characterize the older shield areas are confined to the buried extensions of the shield in Area I, and thus make up only about 1 percent of the Central Interior region.

Sedimentary rocks are also notably rare. Shelf-type sedimentation evidently began about 1,700 m.y. ago, but the major deposits were of clean sandstone. Carbonate rocks are virtually unknown, and all the sedimentary rocks make up only an estimated 7 percent of this great region.

ACKNOWLEDGMENTS

The cooperation of the various State geological surveys, mining companies, and oil companies in providing access to samples has been essential to this report. James D. Hansink of Rocky Mountain Energy provided an opportunity for Denison and Lidiak to review the basement of the Continental Interior in 1976, and this work has been an important base for the results presented here. W. R. Muehlberger and W. R. Van Schmus reviewed the manuscript and gave many helpful comments. Financial support was provided by the U.S. Geological Survey and the U.S. Department of Energy. Lidiak is pleased to acknowledge support from NASA grant NSG–5270.

AREA I—NORTH AND SOUTH DAKOTA

Characterization of the buried basement complex in North and South Dakota is based on gravity and magnetic anomalies and on lithologic study of several hundred basement well samples (Muehlberger and others, 1967). Lithology and ages of rock units are shown on plate 1. These data indicate that the eastern Dakotas are mainly part of the subsurface extension of Archean rocks of the Canadian Shield. The western Dakotas are a continuation of mainly Proterozoic rocks of the Canadian Shield.

ARCHEAN TIME

GNEISS

Gneiss of Archean age is apparently widespread in eastern North and South Dakota. The oldest rocks (fig. 1) are granitic and granulitic gneisses that crop out in the Minnesota River valley (Goldich and others, 1961;

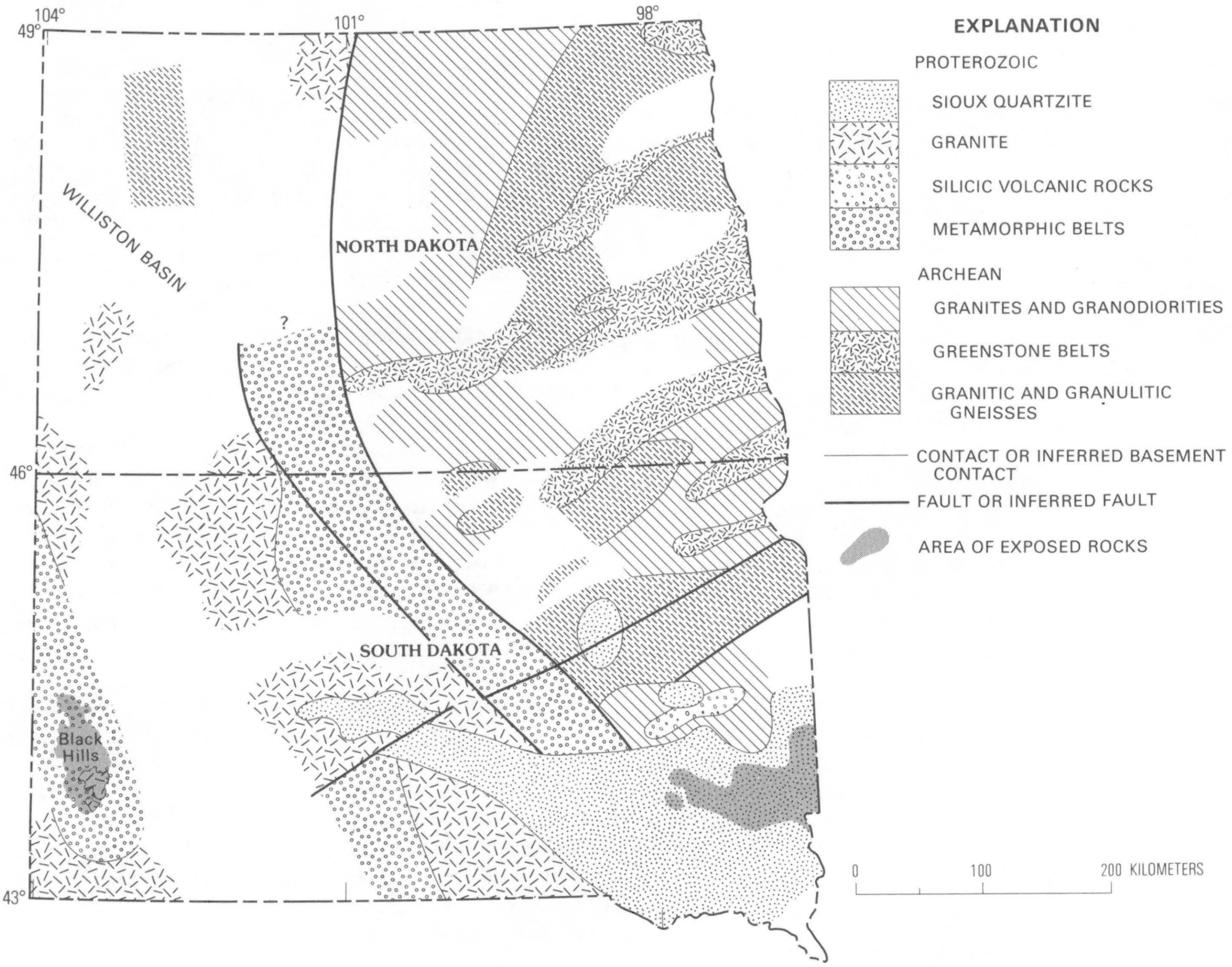

FIGURE 1.—Sketch geologic map of basement rocks in North and South Dakota. Unpatterned areas have no control.

Goldich and others, 1970) and extend along a series of prominent gravity and magnetic anomalies from near Duluth, Minn., west-southwestward to east-central South Dakota (Lidiak, 1971; Morey and Sims, 1976). Detailed radiometric studies of the Minnesota River valley rocks (Goldich and others, 1970; Goldich and Hedge, 1974) have shown that they are at least 3,500 m.y. old and that one phase appears to be 3,700 m.y. old. Metamorphism and granite emplacement about 2,700 m.y. ago and a thermal event about 1,800 m.y. ago have partly obliterated the earlier geologic history of the gneisses.

Granitic gneiss is shown on figure 1 as the predominant rock type in five other areas of northeastern South Dakota and in a large area of northeastern North Dakota. The belts in South Dakota are associated with west-southwest-trending gravity lows and magnetic highs; five wells to basement encountered granitic and gneissic rocks. In North Dakota the gravity anomalies are less distinct, but 22 wells to basement demonstrate the granitic and gneissic character of the terrane. Mineral assemblages in the gneisses indicate widespread metamorphism to the amphibolite facies.

Sparse radiometric data indicate that the gneisses are of probable Archean age (Burwash and others, 1962). A further indication of age is the continuation of geophysical anomalies associated with Archean gneisses of the Canadian Shield into the eastern Dakotas. The higher grade of metamorphism in the gneisses compared to Archean greenstones suggests that at least some of the gneisses predate the 2,700-m.y.-old Algoman orogeny.

Rocks of Archean age are also present in the Black Hills (Zartman and Stern, 1967; Ratté and Zartman, 1970; Kleinkopf and Redden, 1975). Two granulites from near the center of the Williston Basin may also be Archean in age because they occur along a prominent linear gravity high, which can be traced northward to the Nelson River high of Innes (1960). The Nelson River high has been correlated with Archean granulitic gneisses that were involved in both the Kenoran and Hudsonian orogenies (Patterson, 1963; Bell, 1966; Gibb, 1968; Kornik, 1969).

GREENSTONE

Belts of greenstone and related rocks are extensive in the basement of the eastern Dakotas. Seven belts are shown on figure 1; they are characterized by gravity highs and less pronounced but linear magnetic highs. Study of 18 samples indicates that amphibole schists and gneisses are dominant; serpentinite is present in one basement well. Modal compositions suggest mafic and ultramafic igneous antecedents. A staurolite schist in northeastern South Dakota indicates that metasedimentary rocks are associated with the greenstones. The rocks are characterized by metamorphism to the greenschist or lower amphibolite facies.

No age determinations have been published for any of the supracrustal rocks in the Dakotas. They are regarded as being of Archean age because the associated gravity and magnetic anomalies continue into northern Minnesota, where they coincide with greenstone and iron-formation of the Keewatin Group, dated at about 2,700 m.y. (Hart and Davis, 1969).

GRANITE AND GRANODIORITE

Coarse-grained, two-feldspar granite (21 wells) is interpreted as the principal rock type in large areas of the eastern Dakotas (fig. 1). Granodiorite and trondhjemite (seven wells) and amphibolite-grade gneiss (seven wells) are also present but are apparently subordinate to granite. These rocks lie in the subsurface extension of the Superior province of Canada and are characterized by gravity and magnetic lows. The granite and related rocks in the eastern part of the area of figure 1 have the same general trend as the greenstones and are interpreted as being part of an Archean greenstone-granite terrane that was involved in the Algoman orogeny. K-Ar (potassium-argon) and Rb-Sr (rubidium-strontium) ages on minerals from both granite and gneiss reflect mainly the widespread igneous activity and metamorphism that occurred during this orogeny (Burwash and others, 1962; Peterman and Hedge, 1964; Goldich and others, 1966).

PROTEROZOIC TIME (INTERVAL OCCURRING 1,600–2,500 M.Y. AGO)

METAMORPHIC ROCKS

The east-northeast-trending anomalies of the Superior province are terminated in the central Dakotas by northwest-trending anomalies of the Churchill province (Muehlberger and others, 1967; Lidiak, 1971). The alinement of gravity and magnetic anomalies implies a northwest structural trend of the basement rocks. Three metamorphic belts are inferred. The belt in the central Dakotas is marked by magnetic highs and both highs and lows in gravity. The few wells to basement suggest that the area is underlain by mafic and silicic schist and gneiss. The belt in south-central South Dakota continues into Nebraska and coincides with magnetic and gravity lows. The rocks are dominantly silicic schists (Lidiak, 1972). The third metamorphic belt trends through the Black Hills and continues into Montana. This belt also coincides with a magnetic low. The rocks are mainly medium grade metasedimentary rocks, locally intruded by granite. Gough and Camfield (1972) suggested that graphitic schist may be abundant.

The presence of Archean granitoid rocks in the Black Hills suggests that these metamorphic belts probably developed on a sialic crust within a craton rather than along a continental margin. The time of deposition is inferred to have been about 1,900–2,100 m.y. ago.

Goldich and others (1966) concluded that the rocks in the western Dakotas were involved in orogeny 1,700–1,900 m.y. ago. Most of the ages are of minerals from metamorphic rocks. The basement may include older rocks whose ages were reset by younger metamorphism as well as rocks formed at that time. The metamorphic belts possibly date from earlier Proterozoic time, but this dating can be demonstrated only in the Black Hills, where Archean granite gneiss (Zartman and Stern, 1967) is unconformably overlain by a thick metasedimentary succession that was folded, metamorphosed, and intruded by granite 1,700–1,900 m.y. ago during the Black Hills orogeny (Goldich and others, 1966).

GRANITES

Granite (11 wells) occurs at scattered localities in the western Dakotas. Apparent radiometric ages on minerals and whole rock samples are in the range 1,660–1,810 m.y. (Goldich and others, 1966). The granites probably formed during the major period of orogeny in the western Dakotas.

SILICIC VOLCANIC ROCKS

Silicic volcanic rocks are present in eastern South Dakota. These rocks are essentially unmetamorphosed and apparently overlie the older plutonic complex. Three determinations yield ages of 1,680–1,700 m.y. (Goldich and others, 1966). Petrographically similar rhyolitic volcanic rocks occur in adjacent northwestern Iowa (included in undifferentiated felsic rocks on fig. 2).

PROTEROZOIC TIME (INTERVAL OCCURRING 900–1,600 M.Y. AGO)

GRANITE

Four Rb-Sr whole rock or feldspar ages on granite from southern South Dakota and adjacent Nebraska are in the range 1,480–1,510 m.y. (Goldich and others, 1966). These rocks are probably related to the anorogenic granites discussed in the following section on Nebraska, Iowa, and surrounding area.

MAFIC AND ULTRAMAFIC ROCKS

Diabase, diorite, gabbro, and pyroxenite occur in scattered wells in North and South Dakota. Except for deuteric alteration in the diabases, the rocks are unaltered and thus intrusive into the plutonic complex. Their age is unknown, but they probably reflect several intrusive episodes. They are tentatively regarded as postdating regional metamorphism and thus being less than 1,750 m.y. old.

SIOUX QUARTZITE

The Sioux Quartzite is a uniform, mildly folded, subhorizontal formation that is nonconformable on the underlying plutonic complex. It is extensively developed in the surface and subsurface of southeastern South Dakota and extends into adjacent Minnesota, Iowa, and Nebraska. The formation is composed mainly of silicified quartz sandstone that is conglomeratic near the base, and minor thin beds of red shale and argillite. The presence in the essentially undeformed quartzite of diaspore plus quartz and pyrophyllite plus quartz (Berg, 1938) suggests hydrothermal or burial metamorphism under static conditions.

Pebbles of iron-formation in the Sioux Quartzite indicate that the unit may be no older than about 1,900 m.y. (Goldich, 1973), and a Rb-Sr age determination on a rhyolite from Sioux County, Iowa, suggests that it may be at least 1,520 m.y. old (Lidiak, 1971). A nearby well is reported to have penetrated alternating layers of rhyolite and quartz sandstone (Beyer, 1893). Similar silicic volcanic rocks in South Dakota yield ages of 1,680–1,700 m.y.; the Baraboo Quartzite of Wisconsin, often considered to be correlative with the Sioux Quartzite, rests upon rhyolite whose U-Pb zircon age is 1,760 ± 10 m.y. (Van Schmus, 1978).

AREA II—NEBRASKA, IOWA, NORTHERN MISSOURI, NORTHERN KANSAS, AND EASTERN COLORADO

Basement rocks in Area II include a variety of igneous, metamorphic, and sedimentary rocks whose ages range from at least 1,800 m.y. to about 1,000 m.y. The distribution and petrography of these rocks have been determined primarily from study of cuttings and cores from deep drilling, but geophysical data have also been used to extend terranes mapped on the basis of well samples. Large numbers of well samples are available in Nebraska and Kansas because of oil and gas exploration; these have been studied by Lidiak (1972) in Nebraska and by Scott (1966) and Bickford and others (1979) in Kansas. The Missouri basement is reasonably well known because of drilling for minerals and has been studied by Kisvarsanyi (1974, 1975). Relatively little is known about the Precambrian rocks of Iowa and eastern Colorado, because a smaller number of wells have penetrated the basement there.

ARCHEAN TIME

No rocks of Archean age are known in Area II, although we infer such rocks to underlie parts of northern Iowa because of the proximity of the ancient rocks that are exposed in the Minnesota River valley (Goldich and others, 1970; Goldich and Hedge, 1974).

PROTEROZOIC TIME (INTERVAL OCCURRING 1,600–2,500 M.Y. AGO)

Only one radiometric age greater than 1,800 m.y. has been reported for any rocks from Area II, and most are 1,700 m.y. or less (Goldich and others, 1966). We have, however, indicated on the chronometric chart (pl. 1) that both sedimentary and volcanic rocks may have formed as early as 2,000 m.y. ago. This speculation is based upon the presence of silicic metavolcanic rocks and various metasedimentary rocks (schists, quartzites) in the basement of both Kansas and Nebraska. These are associated spatially with gneissoid granitic rocks that have yielded ages of about 1,700 m.y. If metamorphism occurred later than 1,700 m.y. ago, it

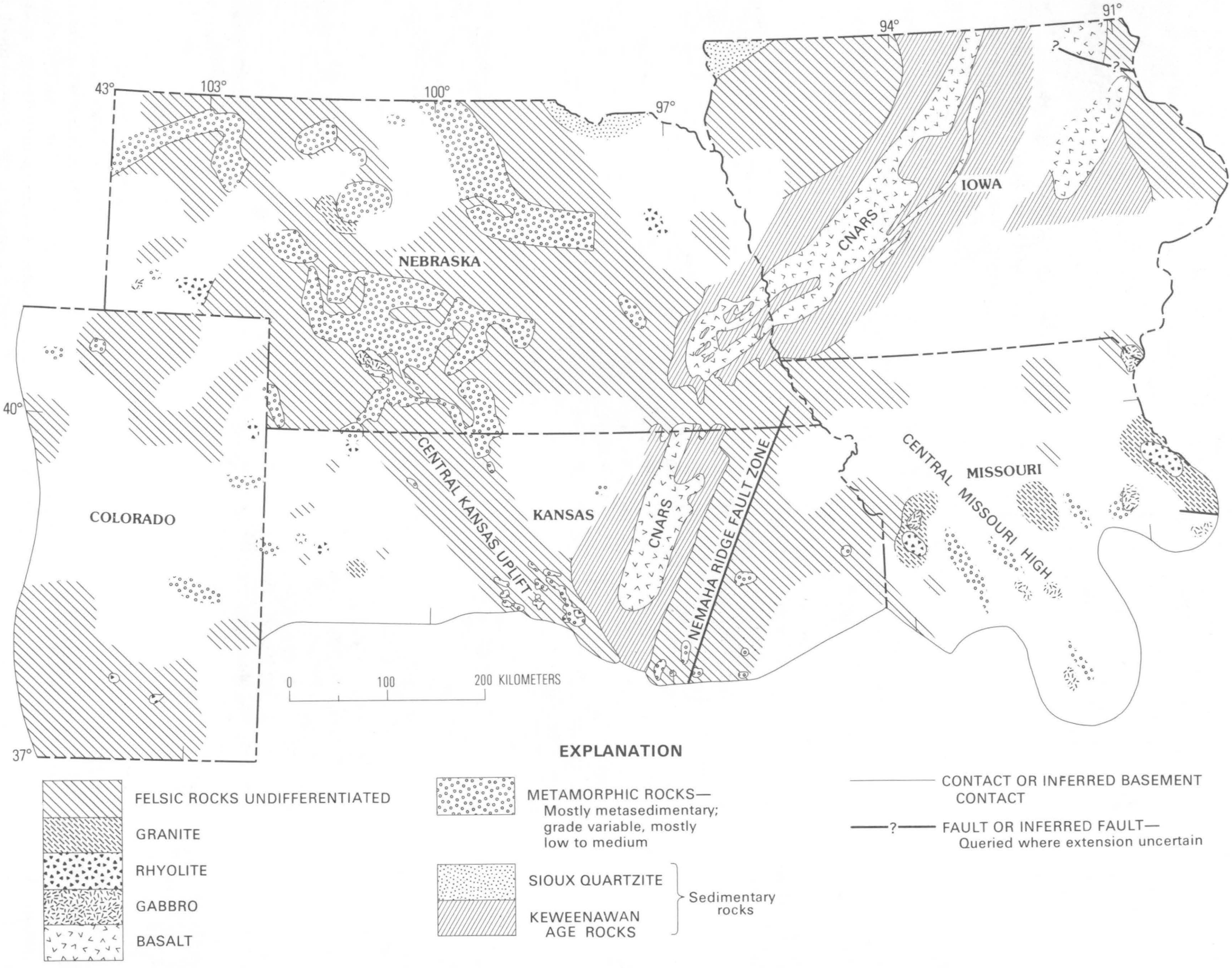

FIGURE 2.—Sketch geologic map of basement rocks in Nebraska, Iowa, and parts of Missouri, Kansas, and Colorado. Unpatterned areas have no well control. CNARS, Central North American rift system.

did not result in lowering of Rb-Sr whole-rock or feldspar ages of at least some of the gneissoid rocks, and we consider it more likely that metamorphism either preceded or accompanied the synkinematic emplacement of the granitic rocks about 1,700 m.y. ago. This event would thus be correlative with the Boulder Creek event, which has been well documented in the northern Front Range of Colorado (Peterman and Hedge, 1968; Stern and others, 1971).

METAVOLCANIC, METASEDIMENTARY, AND FOLIATED GRANITIC ROCKS FORMED 1,650–1,800 M.Y AGO

Much of Area II is underlain by the gneissoid granitic rocks (fig. 2) mentioned in the preceding section. Some of these rocks have been determined to be 1,600 to 1,800 m.y. old by either Rb-Sr or U-Pb (uranium-lead; zircon) methods (Goldich and others, 1966; Bickford and others, 1981). These rocks are commonly granitic to granodioritic in composition and are characterized by slightly to moderately developed foliation caused by pervasive shearing and cataclasis. Metasedimentary and metavolcanic rocks are distributed throughout the area either in fairly well defined belts or in small patches only a few kilometers in diameter. Metavolcanic rocks that were evidently originally rhyolitic to dacitic are known in western Kansas, north-central Missouri, and in northern and southwestern Nebraska, but they are not as widely distributed as metasedimentary rocks. Metamorphic rocks include fairly abundant muscovite and biotite schist, minor amphibolite, and abundant quartzite; the quartzite forms prominent basement-surface highs in southwestern Nebraska (Lidiak, 1972), to the south on the Central Kansas uplift (Walters, 1946), and on the Central Missouri high (Kisvarsanyi, 1974). The Sioux Quartzite (age and extent discussed previously) extends as far south as extreme northern Nebraska in the subsurface. It is known to rest nonconformably upon the underlying igneous-metamorphic complex, but it is not known whether the patches of metavolcanic and metasedimentary rocks that are known elsewhere throughout Area II lie upon the 1,600–1,800-m.y.-old granitic rocks or are older pendants and inclusions within them.

It seems clear that a widespread period of pervasive shearing and cataclasis occurred between 1,800 m.y. ago (the age of the oldest rocks dated) and about 1,480 m.y. ago, the oldest age determined from a widespread suite of nonfoliated anorogenic plutons that occur within the older terrane (Goldich and others, 1966; Harrower, 1977; Bickford and others, 1981). Because the age of the metavolcanic and metasedimentary rocks relative to that of the foliated granitic rocks is not known, it cannot be determined whether a single period of pervasive regional metamorphism, reaching amphibolite facies in parts of the area, affected all these rocks, or whether the metasedimentary and metavolcanic rocks were formed by a metamorphic episode earlier than the period of shearing and cataclasis that affected the granitic rocks.

PROTEROZOIC TIME (INTERVAL OCCURRING 900–1,600 M.Y. AGO)

ANOROGENIC PLUTONIC ROCKS FORMED ABOUT 1,450–1,480 M.Y. AGO

Granitic to tonalitic plutons having ages in the range 1,450–1,480 m.y. are known in Nebraska, northern Kansas, and northern Missouri. These rocks are generally not foliated and thus presumably were intruded into the older terrane after the pervasive shearing event. Because these rocks are not accompanied by associated volcanic rocks in this region, and because they are not deformed, they are assumed to have been emplaced anorogenically. These rocks are evidently a part of the great belt of anorogenic plutons of this age which are known from Labrador to California (Silver and others, 1977; Emslie, 1978). Where they have been well studied at the surface—for example, the Wolf River batholith, Wisconsin (Van Schmus and others, 1975; Anderson and Cullers, 1978) and the St. Francois Mountains batholith, Missouri (Bickford and Mose, 1975)—they are seen to be characterized by rapakivi texture and silicic-alkalic chemistry.

In Nebraska the age of these plutons is known mainly from Rb-Sr measurements of total rock samples, but zircons separated from a core from southwestern Nebraska yielded a U-Pb age of 1,445±15 m.y., reported by Harrower (1977). Harrower also determined a similar age for zircons from a core in north-central Kansas.

As will be seen in the discussion of Area III, plutons of the anorogenic type occur to the south in southern Kansas, southern Missouri, and Oklahoma in association with extensive rhyolitic volcanic rocks. There, however, the age of the plutons is about 1,380 m.y., except in southeastern Missouri, where plutons and volcanic rocks are about 1,480 m.y. old (Bickford and Mose, 1975).

ANORTHOSITES IN SOUTHWESTERN NEBRASKA

A complex of anorthositic rocks occupies an area of about 400 km^2 in southwestern Nebraska (gabbro on fig. 2). The rocks, ranging in composition from anorthosite to anorthositic gabbro, have been subjected to cataclasis and to incipient greenschist facies metamorphism. No direct radiometric age measurement is available for these rocks, but Lidiak (1972) has inferred that they are younger than schists in the area because they lack metamorphism of amphibolite facies that may have occurred about 1,800 m.y. ago, and that they are older than a period of cataclasis and greenschist facies metamorphism that is inferred to have occurred about 1,200 m.y. ago.

MAFIC VOLCANIC AND HYPABYSSAL ROCKS AND RELATED ARKOSIC SEDIMENTARY ROCKS ASSOCIATED WITH THE CENTRAL NORTH AMERICAN RIFT SYSTEM

A major belt of mafic volcanic and hypabyssal igneous rocks coincides with pronounced positive magnetic and gravity anomalies in Kansas, Nebraska, and Iowa (King and Zietz, 1971; Woollard, 1943; Lyons, 1950; Thiel, 1956). Flanking basins containing immature sedimentary rocks are associated with negative anomalies on both sides of the belt of mafic rocks. This feature, the Central North American rift system (Ocola and Meyer, 1973; Chase and Gilmer, 1973), can be traced northwards into Minnesota where both the mafic volcanic rocks and the flanking arkosic sedimentary rocks appear at the surface in the Lake Superior region. There the age of the mafic volcanism has been determined to be about 1,100 m.y. (Goldich and others, 1961; Silver and Green, 1963, 1972; Goldich and others, 1966; Chaudhuri and Faure, 1967; Van Schmus, 1971); a well sample from Nebraska also yielded a K-Ar whole-rock age of 990 m.y. (Goldich and others, 1966). The continuity of these rocks in a belt more than 1,500 km long and about 65 km wide implies that they formed about the same time during a late Proterozoic rifting event.

In Nebraska the mafic igneous rocks include both hypabyssal types and extrusive basalts, and similar types have been observed in Kansas. The relatively small number of basement wells in Iowa precludes much detailed knowledge of these rocks there, but both mafic igneous rocks and arkosic sedimentary rocks have been encountered along the trend of the geophysical anomalies. Sedimentary rocks in both Kansas and Nebraska are mostly arkosic, but subarkose, argillaceous wackes, and red siltstones are also present. In Kansas, Scott (1966) called these rocks the Rice Formation.

METAMORPHISM

Lidiak (1972) noted the widespread occurrence of metamorphism in greenschist facies in rocks in the Nebraska basement, and inferred that this event occurred about 1,170 m.y. ago on the basis of numerous K-Ar and Rb-Sr ages of micas that fall within about ±100 m.y. of this age. That these mica ages record a metamorphic event is indicated by the fact that many of them are from rocks for which whole-rock or feldspar ages are significantly greater.

Lidiak (1972) also observed low-grade metamorphic mineral assemblages in the basaltic rocks of the Central North American rift system. These assemblages, including pumpellyite, laumontite, epidote, and chlorite, are indicative of metamorphism under conditions commonly attributed to simple burial metamorphism.

AREA III—SOUTHERN MISSOURI, SOUTHERN KANSAS, OKLAHOMA, AND NORTHWESTERN ARKANSAS

Area III (fig. 3) is underlain almost entirely by an extensive terrane of silicic volcanic rocks and associated epizonal and mesozonal granitic plutons. These rocks were formed in the interval 1,300–1,500 m.y. ago; rocks older than about 1,500 m.y. are not known anywhere in the area. Moreover, Precambrian mafic and intermediate igneous rocks are quite rare and, except for small areas in Missouri and Kansas, sedimentary or metasedimentary rocks are not known. The igneous rocks of the Wichita Mountains in south-central Oklahoma (fig. 3) include basalt, rhyolite, epizonal granite plutons, and a large body of gabbroic rocks (Ham and others, 1964). Most of these rocks yield K-Ar and Rb-Sr ages in the range 510–530 m.y. (Tilton and others, 1962; Muehlberger and others, 1966; Burke and others, 1969) and thus constitute an anomalously young part of the crystalline crust in this area.

PROTEROZOIC TIME (INTERVAL OCCURRING 900–1,600 M.Y. AGO)

FORMATION OF RHYOLITIC TO DACITIC VOLCANIC ROCKS AND ASSOCIATED EPIZONAL PLUTONS 1,485 TO 1,350 M.Y. AGO

One of the major events in the formation of the central part of the continent occurred during the interval 1,485–1,350 m.y. ago, when an extensive terrane of silicic volcanic and plutonic rocks formed. This terrane extends across the midcontinent region from western Ohio at least into the Oklahoma Panhandle; similar rocks occur in the Texas Panhandle and New Mexico, but these appear to be somewhat younger. This terrane is notable for its scarcity of intermediate to mafic rocks.

In the St. Francois Mountains of southeast Missouri, about 900 km^2 of an extensive terrane of alkali rhyolitic ash-flow tuff, trachyte, trachyandesite, and a number of granitic plutons are exposed (Tolman and Robertson, 1969; Anderson, 1970; Berry and Bickford, 1972; Kisvarsanyi, 1972). This igneous terrane underlies an area of at least 40,000 km^2 in southeast Missouri (Kisvarsanyi, 1974). The exposed part of this terrane includes part of the volcanic roof that is several kilometers thick

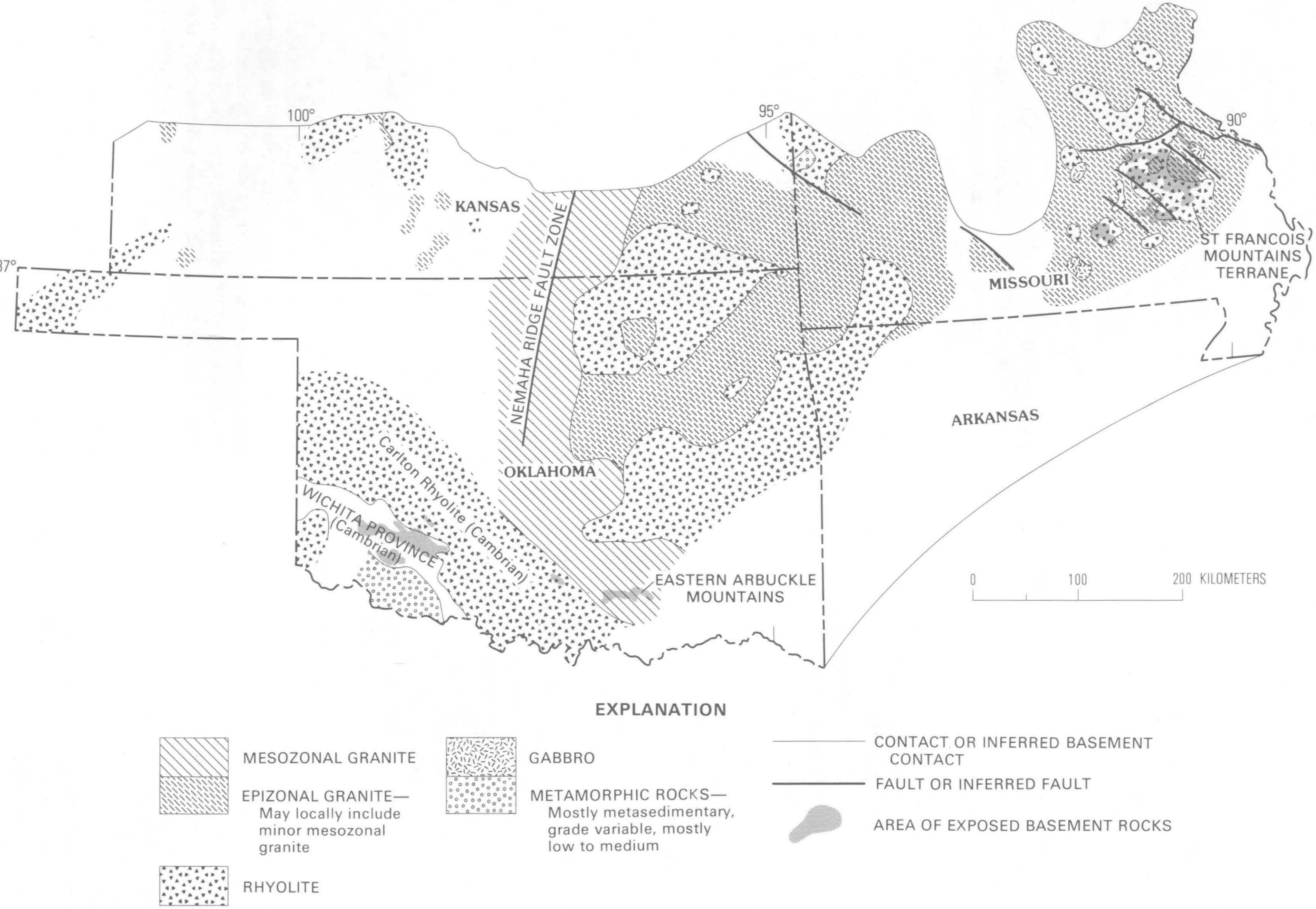

FIGURE 3.—Sketch geologic map of basement rocks in Oklahoma and parts of Kansas, Missouri, and Arkansas.

and a complex of subvolcanic and epizonal plutons. Plutonic rocks are exposed principally in the northeastern part of the area, whereas to the southwest, volcanic rocks are exposed, suggesting that some plutons are tilted to the southwest (Bickford and others, 1977). Contacts between the plutons and the volcanic roof, as well as chemical, mineralogical, and textural variations within the plutons, indicate that some of them are sheetlike. Some plutons, however, are cylindrical and like a cone-sheet in form, as suggested by subsurface and geophysical data (E. B. Kisvarsanyi, unpub. data, 1981). This terrane has clearly not been subjected to penetrative deformation.

The exposed rocks of the St. Francois terrane have been dated by Rb-Sr whole-rock and by U-Pb (zircon) methods by Bickford and Mose (1975). The Rb-Sr system has evidently been disturbed, for the ages reported range from about 1,380 m.y. to as low as 1,200 m.y., and the age data and field relations sometimes contradict each other. U-Pb measurements on zircons, however, yield consistent ages of about 1,485 m.y. for four major plutons and for one of the major volcanic units; one small sill or stock, the Munger Granite Porphyry, yields a U-Pb zircon age of about 1,385 m.y., which may indicate a younger igneous event in this area. A granite core from a buried part of the St. Francois terrane also yields a U-Pb age of 1,485 m.y. (Bickford and others, 1981).

Rocks entirely similar to those of the St. Francois terrane extend in the subsurface across southern Missouri and northern Arkansas into southern Kansas, Oklahoma, and the Texas Panhandle. Studies of these rocks, mainly from cuttings and cores returned from deep drilling, include those of Denison (1966) in northeastern Oklahoma, southeastern Kansas, and southwestern Missouri; Muehlberger and others (1967) over a large region including parts of Texas and New Mexico as well as the region considered here; Kisvarsanyi (1974) in Missouri; and Bickford and others (1979) in Kansas.

The ages of these rocks have been studied in northeastern Oklahoma and southwestern Missouri by Muehlberger and others (1966), Denison and others (1969), and Bickford and Lewis (1979), and in the Kansas basement by Bickford and others (1981). Zircons from the Spavinaw Granite, which is exposed in northeastern Oklahoma, and from a granite in the subsurface in southeastern Kansas (Bickford and others, 1981) yield U-Pb age determinations indicating that they are 1,375 m.y. old. These ages are in reasonable agreement with the Rb-Sr isochron age of about 1,300 m.y. determined by Denison and others (1969) from subsurface samples in northeastern Oklahoma.

MESOZONAL GRANITE ROCKS ALONG THE NEMAHA RIDGE IN KANSAS AND OKLAHOMA, AND IN THE EASTERN ARBUCKLE MOUNTAINS, OKLAHOMA

A terrane of mesozonal granitic rocks is known in southern Kansas along the northeast-southwest trend of the Nemaha Ridge (Bickford and others, 1979), and it extends southwesterly into Oklahoma at least as far as Oklahoma City (Denison, 1966). The age of these rocks is not well known, but their mesozonal character and their occurrence along the Nemaha Ridge suggest that they are somewhat deeper portions of the continental crust that were brought up by fault movements on the Nemaha structure and exposed by erosion prior to Late Cambrian sedimentation.

The only other place in Area III where more deep seated igneous rocks are known is in the eastern Arbuckle Mountains of southeastern Oklahoma (Ham and others, 1964). There, four extensive plutons are exposed in the core of the Tishomingo-Belton anticline (Denison, 1973). Rocks exposed include an unnamed granodiorite, the Troy Granite, the Tishomingo Granite, and the gneiss of Blue River, an informal name. The Troy Granite intrudes the unnamed granodiorite and is intruded by the Tishomingo Granite; the Blue River gneiss is intruded by the Tishomingo Granite, but its age relationships with the Troy Granite and the unnamed granodiorite are not known because the Tishomingo Granite separates it from those rock bodies. All these rocks are medium to coarse grained and have petrographic features suggesting mesozonal emplacement. Bickford and Lewis (1979) have determined the U-Pb ages of zircons from the Tishomingo Granite (1,374 ± 15 m.y.), the Troy Granite (1,399 ± 95 m.y.), and the gneiss of Blue River (1,396 ± 40 m.y.). The rocks are therefore the mesozonal age equivalents of the epizonal granophyres and rhyolites in southern Kansas and northeastern Oklahoma.

Several types of dikes intrude the granitic rocks of the eastern Arbuckle Mountains. The most common dikes are diabasic, whereas dikes of microgranite porphyry, granite, and rhyolite porphyry are less common. On the basis of unpublished age determinations, it appears that some of the diabase dikes and the granite and microgranite porphyry dikes are approximately the same age as their granitic host rocks, about 1,350–1,400 m.y.; the rhyolite porphyry dikes and the other diabase dikes are of Cambrian age. All the dikes have a strongly developed preferred strike direction near N. 60° W., which is parallel to the major Pennsylvanian deformational axes.

PHANEROZOIC TIME (PALEOZOIC ERA, CAMBRIAN PERIOD)

The igneous rocks of the Wichita Mountains consist of a bimodal suite of silicic and gabbroic rocks. The silicic rocks, consisting of epizonal granite plutons and rhyolite, and some of the gabbroic rocks have yielded ages in the range 510 to 530 m.y. (Tilton and others, 1962; Muehlberger and others, 1966). Paleomagnetic data (Roggenthen and others, 1976) and geologic considerations (Powell and Phelps, 1977) have suggested that the oldest rock unit, the layered series of the Raggedy Mountain Gabbro, is of Precambrian age. The K-Ar ages of these rocks, however, suggest a Cambrian age (Burke and others, 1969), and the age must be considered uncertain. The Raggedy Mountain Gabbro is the only large layered gabbroic mass exposed in the Continental Interior.

The geologic relations and structural framework for southern Oklahoma that were outlined by Ham and others (1964) appear to be essentially correct. However, the rhyolite terrane in extreme southwestern Oklahoma, which was considered to be of Cambrian age by Ham and others, is now thought to be an outlier of the Panhandle rhyolites of Precambrian age (see discussion of Area IV) on the basis of unpublished age determinations. The Tillman Metasedimentary Group is most probably Precambrian, as suggested by Muehlberger and others (1967), although parts of this unit may indeed be of Cambrian age as argued by Ham and others.

AREA IV—TEXAS AND EASTERN NEW MEXICO

This area, shown on figure 4, was the subject of the first successful study of the buried basement rocks of a large region. Flawn (1956) was able to show that consistently mappable units could be recognized over large areas by the petrographic study of well samples. Virtually no isotopic ages were available at that time, and the sequence of events and relative ages of the units were later modified when ages became available. The dating of both surface and subsurface samples by Wasserburg and others (1962) and Muehlberger and others (1966) made possible the determination of the sequence of events. Later, largely unpublished geochronological work on well samples has refined this timing of igneous and metamorphic activity, but no major modifications of the published data are justified at this time.

PROTEROZOIC TIME (INTERVAL OCCURRING 1,600–2,500 M.Y. AGO)

TORRANCE METAMORPHIC TERRANE AND "OLDER GRANITIC GNEISSES"

The oldest isotopic ages from the area shown on figure 4 have been reported from eastern New Mexico where Muehlberger and others (1966) determined Rb-Sr ages in excess of 1,600 m.y. for a whole-rock sample and for a feldspar from granitic gneisses. Micas from both of the rock samples studied yielded metamorphic ages of about 1,350 m.y. The granitic gneisses are associated with metasedimentary and metavolcanic rocks that are probably equivalent to the sequence found in outcrop along the Los Piños-Manzano trend (Stark and Dapples, 1946; Stark, 1956). Long (1972, p. 3425) reported ages of "about 1,600 m.y. or older" for metavolcanic rocks northward along this trend. The relationship between gneisses and the supracrustal rocks cannot be determined on the basis of the available information, but the mature character of the metasedimentary rocks suggests that they were originally shelf deposits upon sialic crust. These two units (the Torrance metamorphic terrane, and the "older granitic gneisses" of Muehlberger and others, 1967) have been extended by us with considerable trepidation in the subsurface on the basis of petrography.

PROTEROZOIC TIME (INTERVAL OCCURRING 900–1,600 M.Y. AGO)

ROCKS FORMED 1,200 TO 1,400 M.Y. AGO

Granitic gneisses, found through much of southeastern New Mexico, were grouped into the Chaves granitic terrane by Muehlberger and others (1967). It now seems desirable to extend this unit into the Texas Panhandle on the basis of scattered unpublished age determinations (by Mobil Research and Development Corp.) and petrographic similarities of rocks encountered. These rocks have yielded ages in the 1,400 m.y. range, the oldest ages known in Texas. Some of the ages measured reflect periods of metamorphism, but others are probably close to the time of original intrusion. Differentiation of rock units within the area is not justified on the basis of the available data.

The Sierra Grande terrane of northeastern New Mexico and the Texas Panhandle (Muehlberger and others, 1967) is the oldest of the large areas underlain by anorogenic granite. These rocks are distinguished from older units by the absence of metamorphic features and by their more silicic chemical composition.

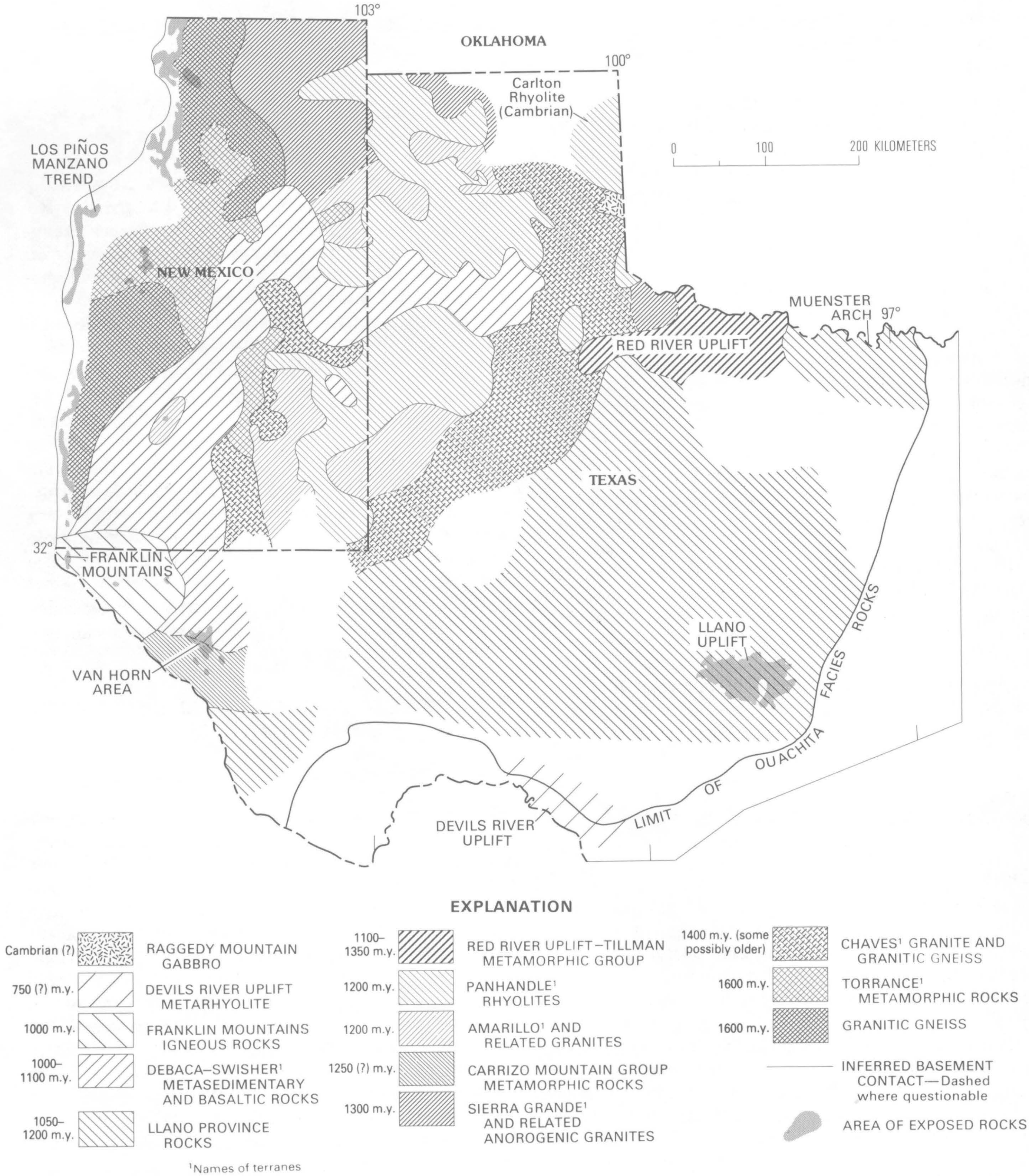

FIGURE 4.—Sketch geologic map of basement rocks in Texas and eastern New Mexico. Unpatterned areas have no control. Well control essentially that of Bayley and Muehlberger (1968).

Rb-Sr data from several published and unpublished determinations of whole rocks, feldspars, and micas form an isochron indicating an age of about 1,300 m.y. Apparent ages on some rhyolites that are petrographically and geographically inseparable from the younger Panhandle volcanic terrane indicate that volcanism also occurred during this period.

The metamorphic rocks called the Red River mobile belt by Flawn (1956) and the Tillman Metasedimentary Group by Ham and others (1964) remain an unresolved problem. Rocks grouped under these names have yielded metamorphic ages from 1,380 m.y. to about 1,000 m.y. (Wasserburg and others, 1962; and R. E. Denison, unpub. data, 1981). The rocks around the Muenster arch are now believed to be related in time of metamorphism to those in the Llano province. Rocks to the west, along the Red River uplift, are older, but their relationship to surrounding rocks is not known.

ROCKS FORMED 1,000 TO 1,200 M.Y. AGO

A sequence of rhyolites and comagmatic granites was extruded and emplaced over much of the Texas Panhandle and far eastern New Mexico about 1,180±20 m.y. ago. The age of this extensive rhyolite field, the Panhandle volcanic terrane, is known from Rb-Sr whole-rock isochron studies. It covers more than 52,000 km^2 despite considerable diminution by erosion and partial covering by younger rocks. Many of the rhyolites preserve delicate ignimbritic features. The associated granites, grouped into the Amarillo granite terrane, are typical hypersolvus epizonal intrusives; micrographic textures are common. The rocks are leucocratic and are composed almost entirely of quartz and perthite.

A wide variety of Precambrian metamorphic and igneous rocks is exposed in the Llano uplift of central Texas. These rocks and their subsurface equivalents are here called the Llano province. This suite of rocks can be traced in the subsurface with some degree of confidence nearly 300 km north of the uplift. The boundary to the west is difficult to define because of sparse control and other complications. To the south and east the Precambrian is buried beneath thick Paleozoic rocks of the Ouachita foldbelt. The geology of the Precambrian rocks in the Llano uplift has been summarized by Clabaugh and McGehee (1962) and Garrison and others (1978). The geochronology of certain of the rock units has been studied by Zartman (1964, 1965), Delong and Long (1976), and Garrison and others (1979).

Three major rock units constitute the Llano province. The oldest of two metamorphic units is the Valley Spring Gneiss. It is overlain by the Packsaddle Schist, which has a measured thickness of 7,330 m and is composed of hornblende, graphite, biotite, muscovite, and actinolite schists; marble and various leptites also make up a substantial part of the Packsaddle section. These two units form the country rock for the third unit, which is composed of a variety of granitic intrusions.

The Valley Spring Gneiss has yielded an age of about 1,160±30 m.y. (Zartman, 1965). Foliated granitic intrusive rocks (Big Branch Gneiss and Red Mountain Gneiss) that cut the Valley Spring and lower Packsaddle have yielded a Rb-Sr isochron age of 1,167±12 m.y. (Garrison and others, 1978; Garrison and others, 1979). These results suggest that the Packsaddle Schist was deposited during the relatively narrow time span between 1,190 and 1,155 m.y. ago. All these older rocks were intruded by massive plutonic granites such as the Town Mountain Granite about 1,060 m.y. ago, near the end of an episode of regional metamorphism (Zartman, 1964).

The Van Horn area of western Texas is underlain by a wide variety of metaigneous and metasedimentary rocks (King and Flawn, 1953; King, 1965). Dating of these rocks, the Carrizo Mountain Group, indicates a period of regional metamorphism about 1,000 m.y. ago with the development of pegmatites (Denison and others, 1971). The age of deposition of the Carrizo Mountain Group has not been clearly defined. The metarhyolites in the Van Horn area may not be as old as the calculated Rb-Sr age of about 1,280 m.y. (Denison and Hetherington, 1969), but they appear to be distinguishably older than the rhyolites in the Franklin Mountains, on the basis of comparative Rb-Sr and $^{207}Pb/^{206}Pb$ ages. (See also Wasserburg and others, 1962.)

The DeBaca terrane and the Swisher diabasic terrane appear to be isochronous. Muehlberger and others (1967) and Denison and Hetherington (1969) have reviewed previous information and correlations from the outcrop into the subsurface. Outcrops of these metasedimentary and basaltic rocks are found in the northern Van Horn area, the Franklin Mountains, and in small outcrop areas in southeastern New Mexico. In far western Texas the metasedimentary rocks are in part demonstrably of marine origin. Northward into the subsurface the rocks become increasingly arkosic and are probably nonmarine. Basaltic rocks associated with the metasedimentary units are more common northward.

The time of sedimentation has not been strictly determined. In the Franklin Mountains metasedimentary rocks are conformably overlain by rhyolites and intruded by granites that have ages near 1,000 m.y. It seems probable that the original sedimentary rocks were deposited just prior to the extrusion of the rhyolites, perhaps in the interval between 1,100 and 1,000 m.y. ago.

The Franklin Mountains have some exceptionally fine exposures of Precambrian igneous and metamorphic rocks (Harbour, 1972). Nearly 460 m of rhyolite flows overlies metasedimentary rocks of the DeBaca terrane and is in turn intruded by diverse granitic stocks and sills.

The ages of rhyolites and granites in the Franklin Mountains all fall into a rather narrow range around 1,000 m.y. (Denison and Hetherington, 1969). These ages indicate that this is the youngest of the Precambrian rhyolite-epizonal granite associations. These igneous rocks appear to be rather limited in areal extent. Small isolated outcrops are found about 100 km to the east and some 150 km to the north of the Franklin Mountains. This igneous activity evidently did not cover as great an area as the older rhyolite fields. Perhaps a smaller volume of magma erupted; but the rocks may also have been removed by erosion, or they may extend to the south into north-central Mexico where no information is available.

PROTEROZOIC TIME (INTERVAL OCCURRING 600–900 M.Y. AGO)

METARHYOLITE OF DEVILS RIVER UPLIFT

A few wells along the Devils River uplift southwest of the Llano uplift in Texas have penetrated metarhyolite. The few isotopic measurements available from these rocks suggest late Precambrian or Early Cambrian ages (Nicholas and Rozendal, 1975; Denison and others, 1977). The rhyolites are underlain in part by massive granitic rocks about 1,250 m.y. old that have been penetrated in only one well.

The best interpretation of the isotopic data is that the rhyolites were extruded not less than 725 m.y. ago. The extent of this unit and its significance are not known because of sparse control from drill holes; it would appear to be the youngest Precambrian igneous rock found in the area. Micas from the metarhyolites yield mid to late Paleozoic ages, indicating that they have been strongly affected by younger metamorphism.

THE VAN HORN SANDSTONE

This sedimentary rock unit may be late Precambrian or earliest Paleozoic in age. It is geographically restricted to an area north of Van Horn in far western Texas. McGowan and Groat (1971) have shown that the unit was deposited as an alluvial fan upon strongly folded, faulted, and dissected Precambrian rocks that were metamorphosed about 1,000 m.y. ago. The Van Horn Sandstone is overlain by the Bliss Sandstone, which is of Ordovician age in this area. Thus the Van Horn must have been deposited between about 1,000 and 480 m.y. ago. The available data do not permit extension of this unit into the subsurface.

PHANEROZOIC TIME (PALEOZOIC ERA, CAMBRIAN PERIOD)

Areas underlain by the subsurface extension of the Wichita province igneous rocks (see discussion of Area III) are found in adjacent parts of the Texas Panhandle. Muehlberger and others (1966) reported a rhyolite yielding an apparent Cambrian age in the central Texas Panhandle, well away from the principal exposures and subsurface extent in southern Oklahoma.

AREA V—EASTERN MIDCONTINENT

Area V (fig. 5) is underlain by two widespread basement rock terranes. In the eastern part of the area is the subsurface extension of the Grenville province of Canada. To the west of the Grenville province is a terrane that consists predominantly of granite, rhyolite, trachyte, basalt, and related rocks of middle and late Proterozoic age.

PROTEROZOIC TIME (INTERVAL OCCURRING 900–1,600 M.Y. AGO)

GRANITE-RHYOLITE TERRANE

Southern Wisconsin, Illinois, Indiana, and the western parts of Ohio, Kentucky, and Tennessee are underlain by a vast terrane of essentially unmetamorphosed rhyolitic and trachytic volcanic rocks and epizonal granitic rocks. These rocks represent an apparent continuation of the anorogenic terrane to the north in central Wisconsin. Van Schmus (1978) found that the Precambrian basement in central Wisconsin consists in part of 1,780–1,800-m.y.-old rhyolitic ignimbrites, granophyric granites, and porphyritic granites intruded by 1,500-m.y.-old rapakivi-type granites.

The anorogenic terrane is extensively developed in the eastern and south-central midcontinent. It apparently extends from central Wisconsin southwestward to northern New Mexico and Arizona (Bass, 1960; Zietz and others, 1966; Muehlberger and others, 1967; Bickford and Mose, 1975; and others).

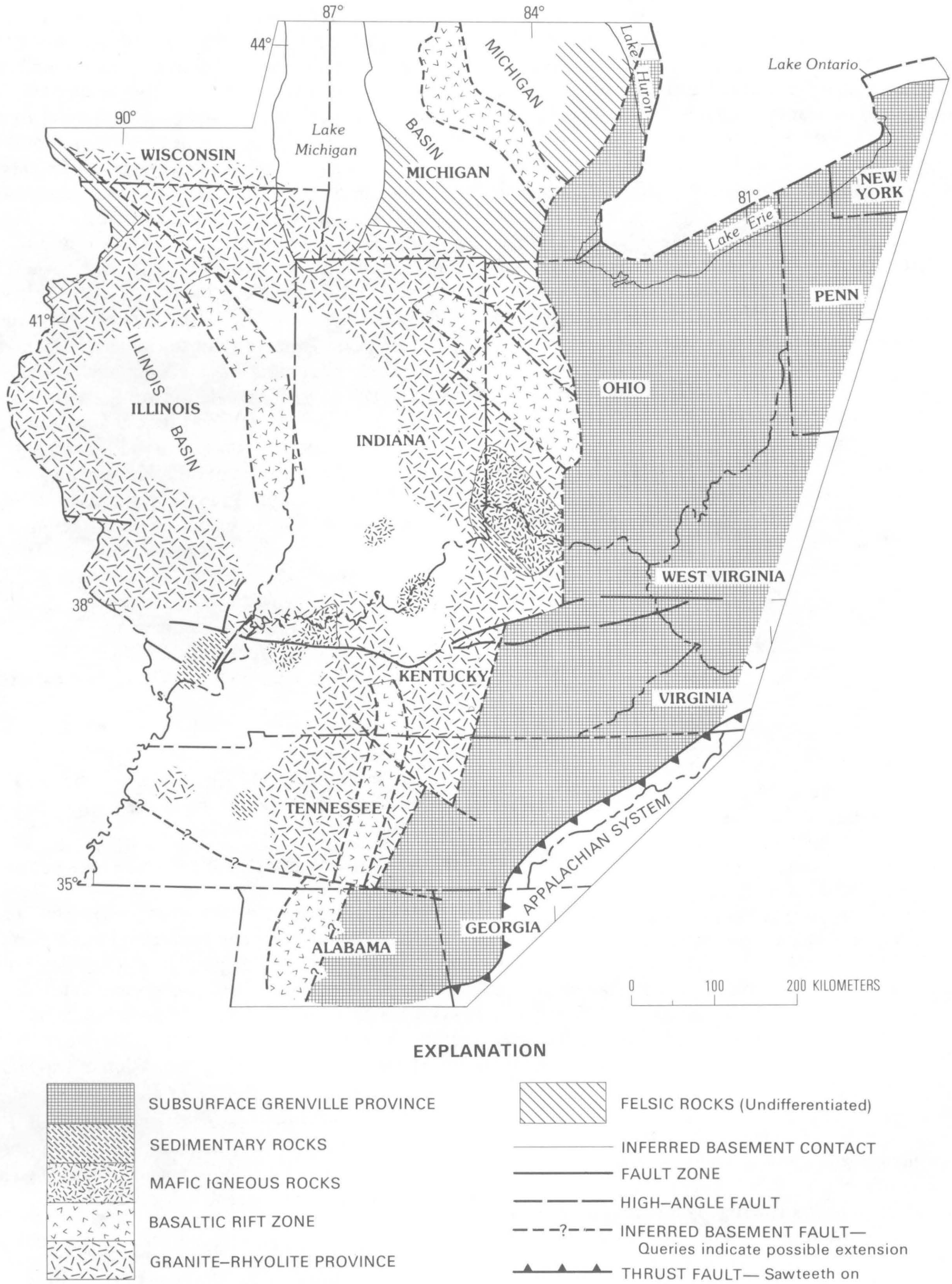

FIGURE 5. Sketch geologic map of basement rocks in the Central Interior region east of the Mississippi River. Unpatterned areas have no control.

The granite-rhyolite terrane of the eastern midcontinent is characterized by an overall homogeneity and relatively subdued magnetic anomaly pattern, suggesting that the area forms a distinct crustal unit of essentially undeformed volcanic rocks and mainly epizonal granitic rocks. The western boundary of the terrane is drawn near the Iowa-Illinois State line along a distinct change in magnetic anomaly pattern (Zietz and others, 1966).

The apparent age and petrographic character of the granite-rhyolite terrane were described by Lidiak and others (1966). Granitic igneous activity appears to have occurred between 1,200 and 1,500 m.y. ago. Most of the available age determinations, however, are Rb-Sr and K-Ar dates on micas, and thus they may be minimum ages that have been reduced by later igneous or metamorphic activity. An unpublished Rb-Sr measurement on a micrographic granite from Fulton County. northern Indiana, yielded an apparent age of 1,480±40 m.y. This age corresponds to the age of the Wolf River batholith of central Wisconsin (Van Schmus and others, 1975) and suggests that granitic igneous activity was widespread at this time. The age of the volcanism is also uncertain. Apparent ages from rhyolite and trachyte are between 1,250 and 1,350 m.y. (Lidiak and others, 1966). However, the volcanism may be older: it may date from 1,500 m.y. to possibly 1,760±10 m.y. ago.

SEDIMENTARY ROCKS

Unmetamorphosed to slightly metamorphosed sedimentary rocks of pre-Late Cambrian age occur in widely spaced wells in the eastern midcontinent. At least some of the rocks are of middle Proterozoic age. For example, the Baraboo Quartzite and related rocks of south-central Wisconsin (Dott and Dalziel, 1972) were deposited later than 1,760 m.y. ago. The Baraboo Quartzite and the previously described Sioux Quartzite of South Dakota are probably correlative and represent widespread sedimentation. Similarly, the quartzites and slates in the subsurface of southern Wisconsin (Thwaites, 1931) may have been deposited during this period of time.

BASALTIC RIFT ZONES

A series of north- to northwest-trending basement rift zones occurs in the granite-rhyolite terrane (fig. 5). The rifts, which are probably underlain by mafic igneous rocks, are delineated mainly by linear gravity and magnetic anomalies and by sparse basement well control. None of these rocks have been dated, but they are tentatively assigned a middle Keweenawan age (1,000–1,200 m.y.) because of their general similarities to rocks of the Central North American rift system.

The best documented of these inferred rifts occurs in the Michigan Basin. Hinze and others (1975) made a detailed study of the linear gravity and magnetic anomalies and concluded that they represent a middle Keweenawan rift zone. A recent deep test drilled near the center of the basin encountered mafic igneous rocks beneath a thick section of red clastic sedimentary rocks (Bradley and Hinze, 1976; Van Der Voo and Watts, 1976), thus supporting the rift zone interpretation.

The linear gravity high in eastern Indiana and western Ohio is also regarded as indicating a rift zone. Three of the six wells to basement along this structure bottomed in basalt; the other three bottomed in felsic igneous rocks. Immediately to the south of the rift, two micrographic granites have Rb-Sr ages on feldspars of about 1,125 m.y. The relation of these felsic rocks to the basalts is not established, but the ages suggest that felsic igneous activity also occurred during the development of the rift zones in middle Keweenawan time.

Northwest-trending gravity and magnetic highs outline an inferred belt of basalt or gabbroic igneous rocks in eastern Illinois. Rudman and others (1972) recognized an area of magnetic and gravity highs immediately to the south in southwestern Indiana and concluded that the area is underlain by basalt. No basement well control presently exists for this proposed structure in Illinois or for its possible extension into Indiana.

The inferred north-trending rift zone in Kentucky, Tennessee, and Alabama also coincides with gravity and magnetic highs. The geophysical anomalies suggest the presence of a thick sequence of mafic igneous rocks.

RIFT-RELATED SEDIMENTARY ROCKS

Unmetamorphosed sedimentary rocks that are apparently associated with the basaltic rift zones have been encountered in the Michigan Basin (Bradley and Hinze, 1976), western Ohio, and northern Kentucky. These rocks occur beneath Upper Cambrian strata and are of probable late Proterozoic age. They are inferred to have been deposited during formation of the rift zone.

Other sedimentary rocks of pre-Late Cambrian age are also present in western Tennessee and Kentucky and in southern Illinois near the center of the Illinois Basin. They are apparently not associated with basalts and may be as old as latest Proterozoic.

SUBSURFACE GRENVILLE PROVINCE

The Grenville province of Canada extends into the subsurface of the United States near the west end of Lake Erie along a series of prominent south-trending gravity and magnetic highs. These anomalies appear to cut and thus postdate the northwest-trending anomalies associated with the rift zone in the Michigan Basin (Hinze and others, 1975). The south-trending anomalies continue into Ohio and form a sharp gradient, separating a series of positive magnetic and gravity highs on the east from broader, less intense anomalies on the west (Zietz and others, 1966).

Petrographic study and age determinations (Lidiak and others, 1966) show that this sharp gradient coincides with the boundary between a granite-metamorphic complex on the east and an older, less deformed terrane on the west. East of the boundary in eastern Ohio and West Virginia, the basement rocks consist mainly of mica and hornblende schist and gneiss, two-feldspar granite, and less commonly marble and calc-silicate rock. Most of the metamorphic rocks are of amphibolite grade.

Age determinations on micas from gneiss, schist, and granite in parts of Michigan, Ohio, Pennsylvania, and West Virginia are in the range 800–1,000 m.y. These ages are in good agreement with mica ages determined from the Grenville province in Canada. Most of the mica ages do not date the main period of orogeny, but instead reflect later tectonic or thermal disturbance and probably deep burial and subsequent uplift. The last main period of metamorphism occurred about 1,100 m.y. ago. (Compare Lidiak and others, 1966.) More recent studies by Krogh and Davis (1969) indicate that regional metamorphism and formation of paragneiss in the northwest Grenville area occurred between 1,500 and 1,900 m.y. ago. Other periods of Grenville regional metamorphism occurred about 1,300 and 1,100 m.y. ago.

The Grenville Front extends southward into Kentucky and Tennessee (Lidiak and Zietz, 1976). The predominant rock types east of the front are granite gneiss, two-feldspar granite, medium-grade metamorphic rock, and anorthosite. Trachyte, rhyolite, basalt, and weakly metamorphosed sedimentary rocks are the characteristic rocks west of the front. Locally felsic volcanic rocks also occur immediately east of the front. The Grenville Front is tentatively shown extending into Alabama on figure 5.

The only available isotopic age determinations on the subsurface rocks of the Grenville province are the previously mentioned K-Ar and Rb-Sr ages on micas. Consequently, the period or periods of sedimentation, anorthosite intrusion, and granitic plutonism that are shown on the chronometric chart have been inferred. They are based mainly on regional correlations and extrapolations from outcrops.

METALLOGENIC SIGNIFICANCE OF THE PRECAMBRIAN BASEMENT

Better understanding of the Precambrian geology of the Central Interior region is a key to understanding the evolution and distribution of its resource systems. The shallow volcanic-plutonic complexes are potentially the most important tectonic and metallogenic units of the region. The St. Francois terrane of southeastern Missouri constitutes an iron metallogenic province and has in fact been the source of iron production for more than 150 years. Kiruna-type iron (apatite) and iron-copper deposits, some of them rare-earth enriched, are associated with the silicic volcanic rocks of the terrane. Marginal manganese mineralization has occurred in the volcanic rocks; hypo-xenothermal veins of W–Pb–Ag–Sn occur in at least one of the plutonic bodies; and late-stage two-mica granites of the terrane are among the most uraniferous granites of North America (Malan, 1972).

The metallogenesis of the volcanic-plutonic complexes, as suggested by observations in the St. Francois terrane, is intimately related to the complex magmatic-tectonic processes that produced this extensive anorogenic suite of rocks. Two lines of metallogenic evolution are indicated and have the potential for enrichments in ore deposits: (1) the ferrous metals, related to alkaline intermediate magmatism, and (2) W, Ag, Sn, Pb, U, Th, and F in the late granites (Kisvarsanyi, 1976).

The metallogenesis of the older metamorphic basement is not known because of lack of outcrops and no proven ore bodies. By analogies with Canadian Shield provinces, however, it may contain complex and varied mineral deposits. The resource potential in the basement complex of Missouri has recently been evaluated on the basis of drill-hole data (Kisvarsanyi and Kisvarsanyi, 1977). Among the most interesting possibilities are the layered mafic intrusions, which have a potential for Fe-Ni-Cu-Co and Pt- Cr-Ti mineralization. The Central North American rift system is a favorable site for rift-related metallogeny.

Another important metallogenic aspect of the Precambrian basement is its tectono-morphologic control on the emplacement and localization of ore bodies in the overlying sedimentary rocks. Major mineral districts in Missouri, Oklahoma, Kansas, and Illinois are located over Precambrian topographic and structural highs and ancient fracture zones (Snyder, 1970; Kisvarsanyi, 1977). Although the metals may have been derived from multiple sources, at least some of the metals may have been recycled from a Precambrian source and redistributed into flanking sedimentary basins.

As near-surface resources are depleted, the vast resource potential inherent in the buried basement rocks becomes of increasingly greater interest, particularly where depth to basement is not prohibitive to mining.

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