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METALLOGENIC EVOLUTION OF THE SOUTHERN APPALACHIAN OROGENIC BELT AND MISSISSIPPI VALLEY

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INTRODUCTION

The southern Appalachian region has long been an important contributor to the mineral economy of the United States (US). The region contains many valuable ore producing areas, although both fuels and industrial materials outrank the metallic ores in both tonnage and value. The southern Applachians contains important zinc and pyrite deposits and is also an important source of iron, copper, lead and titanium. Historically the region was important as the site of early mining of gold, iron, manganese, titanium, and other ores. In the midcontinent region the most important types of mineralization are the Mississippi Valley type deposits of lead, zinc, barite, and fluorite. Of lesser importance are the Missouri iron deposits in Precambrian volcanic rocks.

Plate tectonic theory has greatly improved our understanding of geologic processes, including the formation of mineral deposits. Plate tectonic models have been constructed for both presently active and for more ancient orogens, and metallogenic interpretations have been made in terms of plate tectonics for these regions.

It is the purpose of this dissertation to examine the tectonic setting and evolution of mineralized environments in the southern Appalachians and the central US, starting with the Late Precambrian, and continuing through to the end of the Paleozoic when orogenic activity ceased. The emphasis will be on metallic mineral deposits, but brief coverage is given to non-metallic deposits. Figure 1 is an outline map of the US showing the major physiographic provinces and the study area boundaries. Figure 2 shows many of the geographic and geologic features that will be referred to in the text.

Location and Geographic Setting

The Appalachian Mountains, taken in the broadest sense, are that chain of mountains that follow the eastern coast of North America. The Appalachian orogenic belt extends 3600 km from Newfoundland to Alabama, extending under the continental shelf to the northeast and under the deposits of the Coastal Plain on southwest.

Figure 1. Outline map of the United States showing physiographic provinces and study area boundaries. From Hunt(1974).

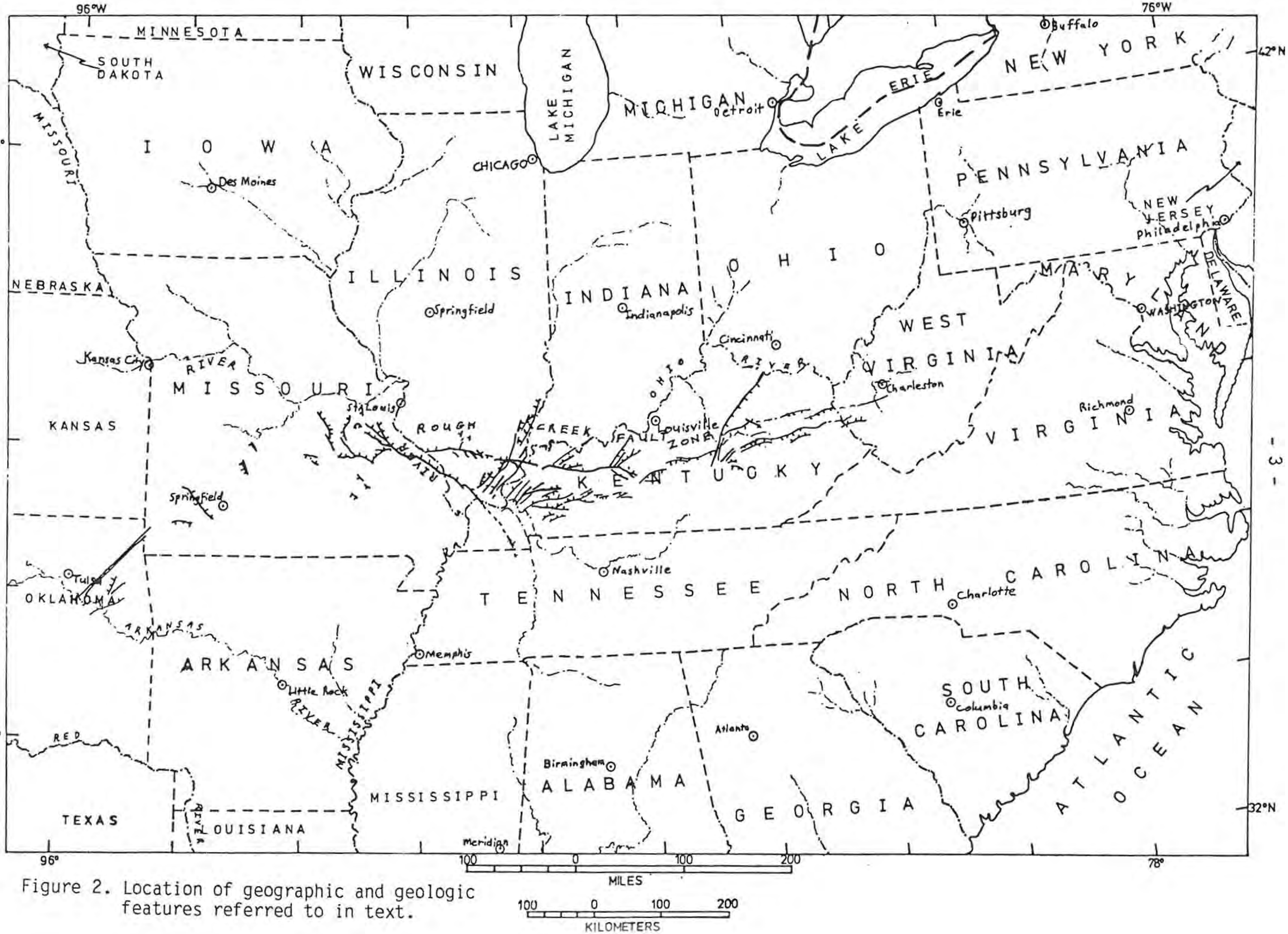


Figure 2. Location of geographic and geologic features referred to in text.

Topographically the term "Appalachian Mountains" applies more strictly to the high ridges of the southern Applachians that extend from from Pennsylvania southward to Georgia and Alabama. The New England Upland and Canadian Maritime Provinces are also geologically part of the Appalachians, although this more northerly portion is largely separated from the southern Appalachians by a depressed section near New York City, partly covered by younger deposits and partly by the sea. The northern portions of the Appalachians are known under various local names, although the Canadians use the term Appalachians for ridges northeast of New England in southeastern Quebec and in the Maritime province.

West of the Appalachians Mountains lie the Interior Lowlands which form a vast plain between the Rocky Mountains and the Applachians. The rocks exposed in the region are generally flat lying or only gently folded rocks of Paleozoic age overlying Precambrian basement. Most of the area stands only a few hundred meters above sea level. Eastward towards the Appalachians and in the Ozarks of Missouri the surface rises in the intricately dissected plateaus. The Ouachita Mountains in Oklahoma and Arkansas are an extension of the Appalachian structural belt, and forms the only folded mountains within the midcontinent region.

Physiography

The United States has been subdivided into a number of physiographic provinces which indirectly reflect the present and past tectonic environment. Figure 3 is a representation of the landforms within the physiographic provinces and is at the same scale as Figure 1. Provinces of relevance to this dissertation are the Appalachian Provinces (Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateau) and the Interior Lowlands (Central Lowland, Interior Low Plateau, Ozark Plateau, and Ouachita province). The complex geologic history of these provinces will be analyzed in a later section.

Appalachian Provinces

King (1977) has divided the Appalachian belt into two parts which he has termed the "sedimentary Appalachians" characterizing the Valley and Ridge province, and the "crystalline Appalachians" characterizing the Piedmont. Between these two provinces is the Blue Ridge Province

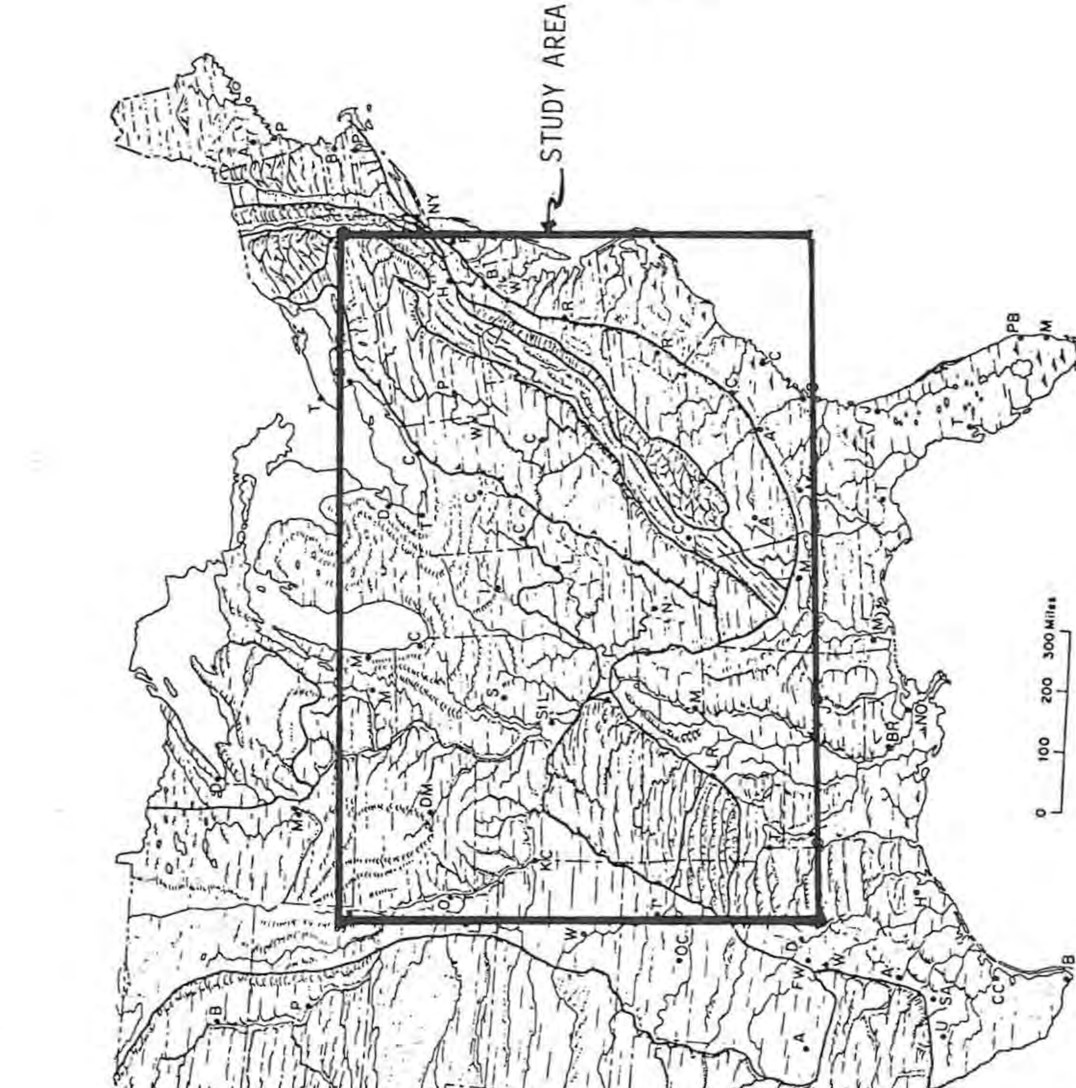


Figure 3. Representation of landforms within the various physiographic provinces. From Hunt (1974).

which shares something of the character of each of the two areas. Figure 4 is a generalized cross section showing the structural framework of the Appalachian region.

Piedmont Province - Fisher (1970) eloquently describes the Piedmont province, as seen on a map, as having "the shape of a wild duck swimming gracefully northward. From its beak in central New Jersey to its tail in Alabama, it stretches 1350 km. At its neck in northern Virginia, it is only 16 km across but at its belly in the Carolinas it widens to nearly 240 km." In the east the Piedmont is overlapped by the younger sediments of the Coastal Plain. Along the western margins in Virginia the Piedmont rocks apparently merge with those of the Blue Ridge, but in the Carolinas, Georgia, and Alabama, they are bounded on the west by the Brevard Fault zone (Fig. 5)(Hatcher, 1972).

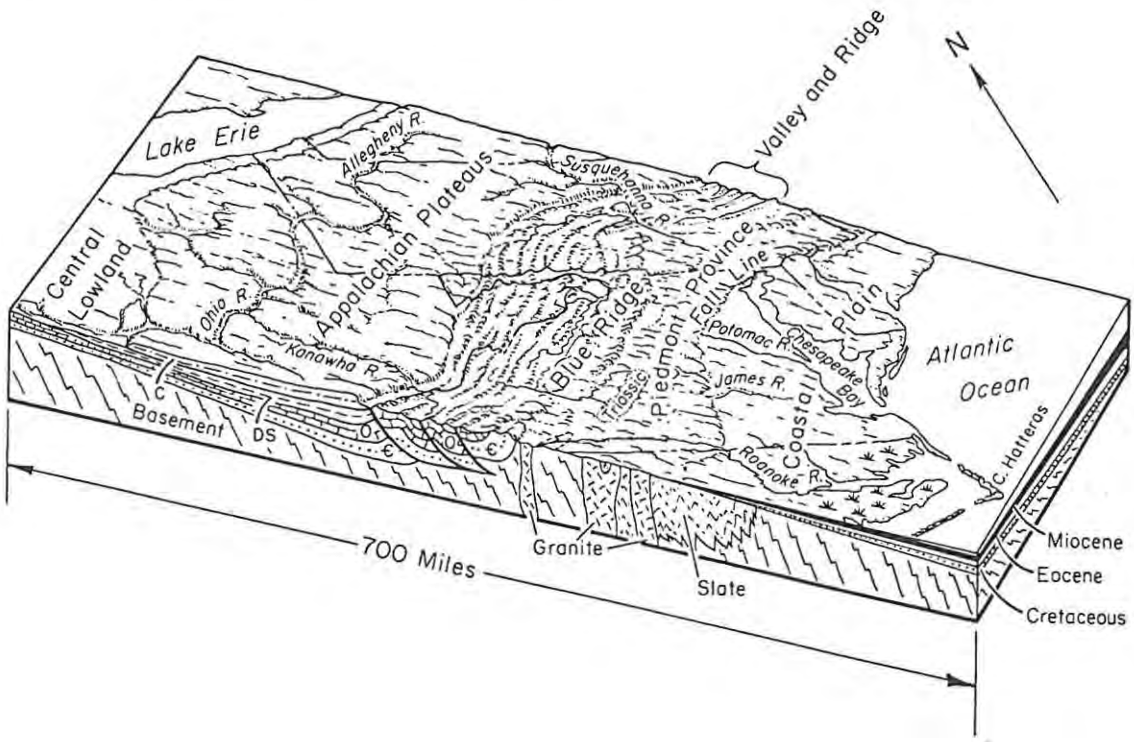


Figure 4 Structural framework of the Appalachian Plateaus, Valley and Ridge, Blue Ridge, and Piedmont Provinces. C, Cambrian; O, Ordovician; DS, Devonian, Silurian; C, Carboniferous (Mississippian, Pennsylvanian, and Permian). From Hunt (1974).

Fisher (1970) continues, "The older Precambrian basement rocks appear first in the northern tip of the beak, in a series of anticlinoria, and recumbent folds. Southward, they reappear in a series of elongate domes

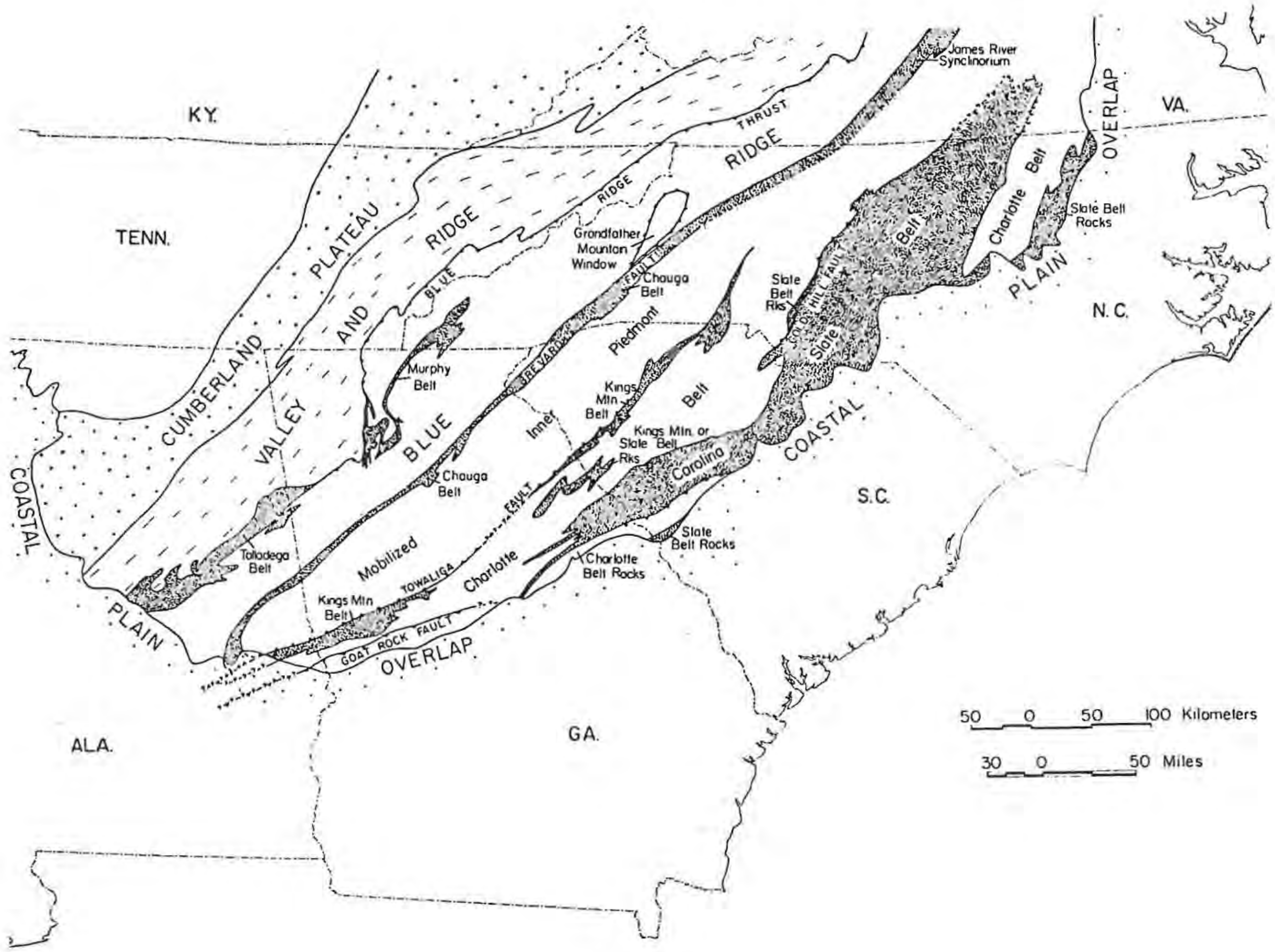


Figure 5 Map of the southern Appalachians showing the relative positions of the respective belts. The heavily stippled areas represent belts in the Blue Ridge and Piedmont composed predominantly of late and post-Precambrian sedimentary and volcanic rocks. From Hatcher (1972).

along the throat in Maryland, and northeastern Virginia and also in a nearly continuous strip along the spine of the Blue Ridge, from the head in Maryland to nearly the tail in northeast Georgia." Radiometric dating has clearly established that these rocks are a southward extension of the Grenville Province (Tilton et al., 1960). Mantling these basement rocks is a thick pile of variably metamorphosed sedimentary rocks, eugeosynclinal for the most part, but including some miogeosynclinal and transitional rocks near the Blue Ridge.

The rocks of the Piedmont are a metamorphic complex of felsic and mafic paragneisses, migmatites, schists, slates, and orthogneisses, containing embedded granitic plutons and a few mafic plutons of various Paleozoic ages. These rocks slope gradually southeastward from the southeastern foot of the Blue Ridge to the Fall Line where they pass under the Cretaceous and Tertiary deposits of the Coastal Plain. The area has been deeply eroded and saprolite conceals most of the unweathered bedrock, especially in the most southerly portions of the area where the accumulation of soil and saprolite is as much as 40 m thick (Davies, 1968). Elevations are generally higher towards the north.

In the Carolinas the province is divisible into four belts (Overstreet and Bell, 1965), which are, from east to west (Fig. 5):

(1) the Carolina slate belt, containing chiefly volcanic and sedimentary rocks of low metamorphic grade, cut by mafic and felsic intrusives; few rocks in the belt are true slates.

(2) the Charlotte belt, a conspicous zone of predominantly intrusive rocks of moderate metamorphic grade between two belts of lower grade rocks. The belt is also notable for the swarms of mafic dikes, which appear as feeders for volcanic flows in the middle and upper sequences in the Piedmont (Overstreet, 1970).

(3) the Kings Mountain belt, of metasedimentary and metavolcanic rocks of low to moderate grade, consisting of sericite schist, hornblende schist, and sparse quartzite and marble. A well defined unconformity separating an upper sequence of rock from a middle sequence can be correlated with an unconformity having the same stratigraphic position in the slate belt.

(4) the Inner Piedmont belt of high grade metasedimentary and metavolcanic rocks, with minor felsic and mafic intrusives. The boundary between the Inner Piedmont and the Kings Mountain belt appears to represent a change in metamorphic grade instead of the juxtaposition of rocks of different ages.

The Talledaga slate belt lies between the Brevard fault zone and the Valley and Ridge in Alabama. It may be the southwesternmost extension of the Blue Ridge (Tull and Stow, 1982), but is referred to as the Northern Alabama Piedmont by Tull (1978). The slate belt is composed dominantly of metapelites and metasandstones, but it contains a distinctive metavolcanic complex at the top, the Hillabee greenstone, which contains numerous occurrences of massive sulfides throughout its entire 170 km strike length.

Metamorphic grade throughout the Piedmont decreases northeastward along strike to the extent that metamorphic rocks do not extend beyond southwestern Maine. In Canada metamorphism is generally low or non-existent (King, 1977). The low grade belt along the Connecticut Valley and the low grade rocks of northeastern Maine and southeastern Canada provide students of Appalachian geology with abundant stratigraphic data that assist in unravelling the more metamorphosed crystalline rocks farther south. Enough fossils have been found in these low grade regions to demonstrate that the crystalline rocks include a sequence of Cambrian, Ordovician, Silurian, and Devonian age rocks. These were orginally argillites, sandstones, tuffs, and lavas that were largely contemporaneous with the Paleozoic rocks of the sedimentary Appalachians but formed in quite a different environment.

<u>Blue Ridge Province</u> - The Blue Ridge is a rugged mountainous province more than 1100 km long, ranging in width from less than 8 km in Maryland and Pennsylvania to about 80 km in Tennessee and North Carolina. It is one of the largest outcrop areas of Precambrian rocks in North America outside the Precambrian shield. Its western boundary is separated from the miogeosynclinal rocks of the Valley and Ridge by a major west-directed thrust fault. The southeastern margin of the Blue Ridge belt in Pennsylvania, Maryland, and northern Virginia is separated from the eugeosynclinal rocks of the Piedmont by a series of downfaulted basins filled with unmetamorphosed Triassic sedimentary rocks. In central and southwestern Virginia, the southeastern boundary is separated from the Piedmont by the James River synclinorium, which contains low- and medium-grade metamorphic rocks of Paleozoic age. In the Carolinas and Georgia the southeastern boundary is generally considered to be the Brevard fault zone. Establishing the correlation between the miogeosynclinal rocks to the northwest and the eugeosynclinal rocks to the southeast has become one of the most vexing problems in Appalachian geology (Reed, 1970).

There is a signficiant change in gravity on passing from the Blue Ridge into the sedimentary Appalachians. The southeastern part of the sedimentary Appalachians shows a prominent gravity minimum throughout its length (up to 100 milligals in places) which changes abruptly in the Blue Ridge and southeastward into positive gravity anomalies (King, 1977).

The gradient generally follows the northwestern edge of the Blue Ridge, but drops back behind it where the Blue Ridge rocks are known to be thrust over the sedimentary rocks of the Valley and Ridge. King (1977) attributes part of the positive anomalies to the presence of mafic intrusives, but he states that to a large extent they reflect differences in the nature and thickness of the crust -- an approach to a thinner, more oceanic crust, rather than a thicker continental crust. Bryant and Reed (1961) suggest that the change in position of the gravity low indicates as much as 130 km of gross northwestward displacement over the low.

During the course of a COCORP (Consortium for Continental Reflection Profiling) survey across the Brevard zone in northeastern Georgia, Cook et al. (1979) found that the major reflection feature of this area is a relatively horizontal, layered sequence of rocks. They have interpreted these as sedimentary rocks, underlying near-surface crystalline rocks between 6 and 15 km thick. These data indicate that relatively undeformed and unmetamorphosed strata of the Valley and Ridge extend beneath the Brevard zone and that overthrusting may have been as great as 260 km horizontally and perhaps considerably more.

The Blue Ridge rises 300-500 m above the adjacent Piedmont province. The mountains tend to become progressively higher towards the southeast, reaching 2037 m at Mt. Mitchell, South Carolina, the highest summit in the eastern US. Lower Cambrian quartzites, arkoses, and conglomerates which form the base of the Paleozoic geosynclinal sequence, and various stratified upper Proterozoic rocks are exposed here. The latter consist mainly of basaltic lavas in Virginia, but further southwest these Upper Proterozoic rocks consist of a great thickness of graywackes and other clastics (King, 1977). Late Precambrian and Early Cambrian rocks lie on a basement of earlier Precambrian granites and gneisses, which have been forced up as a welt in the midst of Appalachian structure (Fig. 6). Plutonic rocks comprise a wide variety of Precambrian and Paleozoic granites, layered and non-layered granite gneisses, and migmatitic rocks that crop out chiefly along the northwestern edge of the Blue Ridge in western North Carolina and southwestern Virginia (Bryant and Reed, 1970).

Folding is mainly by shear, or penetrative deformation, so that rocks have been deformed by laminar flow. Nearly all the present metamorphic

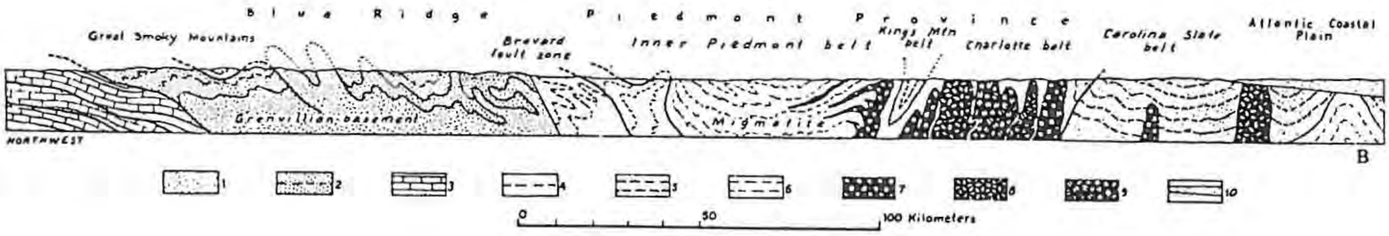


Figure 6 Section across the crystalline Appalachians in Tennessee and North Carolina. Explanation of symbols: 1-Precambrian basement rocks, Middle Proterozoic to northwest, Upper Proterozoic to southeast. 2-Altered sedimentary rocks of Upper Proterozoic age (Ocoee Series). 3-Paleozoic quartzite, limestone, and shale, formed in miogeosynclinal area. 4-Metamorphic complex, mainly of Upper Proterozoic age (schist, gneiss, migmatite, and amphibolite). 5-Older eugeosynclinal rocks (Upper Proterozoic and Cambrian). 6-Younger eugeosynclinal rocks (Silurian and Devonian). 7-Older Paleozoic granite rocks (mainly Ordovician). 8-Younger Paleozoic granitic rocks (Devonian and younger). 9-Paleozoic mafic intrusives. 10-Cretaceous and Tertiary deposits of Atlantic Coastal Plain. From King (1977).

textures and mineral assemblages are products of regional dynamothermal metamorphism during the Paleozoic (Bryant and Reed, 1970). In general the grade of metamorphism increases southward, as is the case in the Piedmont province.

Valley and Ridge Province - West of the Blue Ridge the Valley and Ridge forms a long narrow belt of mountains and parallel valleys. The mountainous belt is 1900 km long and is 130 km wide in Pennsylvania, 100 km wide in Maryland, and 65 km wide in Tennessee. A structural tendency found in the Blue Ridge is also found in the Valley and Ridge, i.e., progressively higher uplift towards the southeast. In the north the major ridges are 400-1370 m in altitude, with as much as 760 m of relief. In the south, near Roanoke, Virginia, the altitudes are as much as 1430 m.

The Valley and Ridge province is built exclusively of rocks of Cambrian to Permian age that were laid down in the Appalachian geosyncline southeast of the continental platform. These sediments are about 10 000 m thick, strongly folded and thrust-faulted, but not metamorphosed. Lower Paleozoic rocks, up to Middle Ordovician, consist mostly of carbonate rocks (limestone and dolomite). The Upper Paleozoic rocks are dominantly sandstones and shales. The carbonate rocks are more susceptible to erosion than the sandstones and shales, and where folding and faulting have uplifted these formations and exposed them to weathering, the limestones and dolomites are worn down to low ground, whereas the adjacent sandstones and shales project at ridges. This produces the characteristic topography of the Valley and Ridge province. In the southeast the underlying limestones and dolomites are raised highest and here they occupy their widest surface extent forming a broad expanse of lowland -- the Appalachian Valley (King, 1977).

The strata of the province have been flexed into a succession of tight anticlines and synclines, each several kilometers across and overturned to the northwest. These folds resulted from compression toward the northwest, the push being stronger in the southeastern portions of the province. With increase of the northwestward compression, strata on the steeply dipping sides have been broken by southeast dipping faults. Folds dominate the structure of the Valley and Ridge in Pennsylvania, but southwestward across Virginia into Tennessee faults increase in number and magnitude until few unbroken folds remain (Fig. 7). Many of the faults are great low angle thrusts that have carried sheets of rock for kilometers northwestward over the rocks beneath. Some of the great thrusts are traceable for hundreds of kilometers along strike (King, 1977).

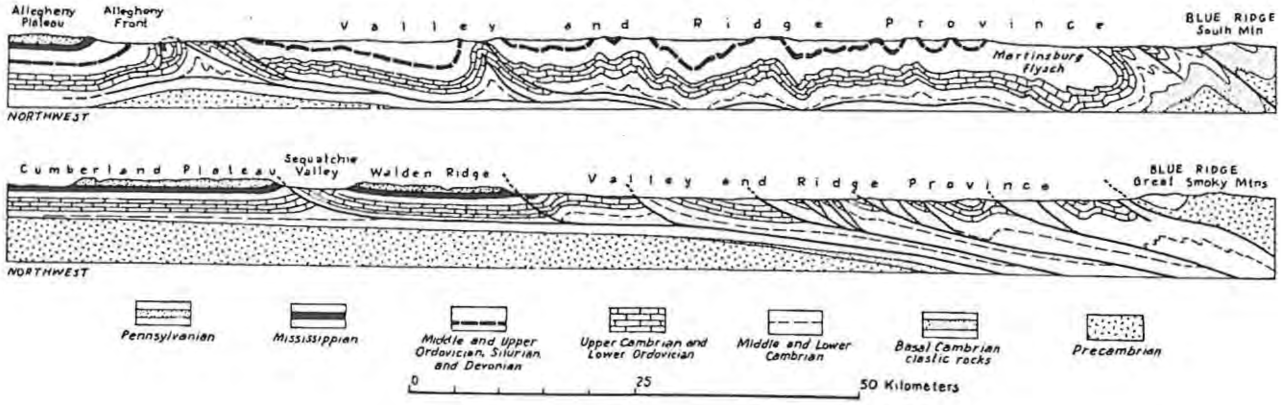


Figure 7 Generalized sections across Valley and Ridge province from Allegheny and Cumberland Plateaus on the northwest to Blue Ridge on the southeast. Above, in southern Pennsylvania in area of dominant surface folding. Below in southern Tennessee, in area of dominant faulting. From King (1977).

The term "thin-skinned" tectonics has been coined for the thrust sheets in the Valley and Ridge because the thrusts were formed by tearing loose of higher parts of the mass of sedimentary rocks from the lower parts along weak shaly layers in the succession. The thrusts do not penetrate basement rocks. This concept is illustrated by a great thrust block in the Cumberland Mountain (Fig. 8). In the structurally more complex portion of the Valley and Ridge province to the southeast, seemingly simple folds in the rocks on surface turn out, when drilled, to be the result of piling up of thrust sheets beneath (Fig. 9).

Appalachian Plateau Province - Immediately west of and in sharp contrast with the Valley and Ridge province is a high upland dissected by many streams forming the Appalachian Plateau province. The contrast in land forms is a result of the abrupt change in rock structure, from highly folded in the Valley and Ridge to nearly horizontal or very gently dipping strata in the Appalachian Plateau. The Plateau is known as the Allegheny Plateau in the north and its southward extension is the Cumberland Plateau.

The Allegheny Plateau forms a basin known as the Allegheny basin or Allegheny synclinorium (Figs. 10 and 11), which extends along the front of the Appalachians from New York to Kentucky and preserves Pennsylvanian and Early Permian continental beds and coal measures in its trough. These lie conformably above Mississippian and Devonian strata. The whole sequence has been warped into a series of anticlines and synclines by the Appalachian movements, but most of the deformation is so slight that over wide areas the strata appear to lie nearly flat (King, 1977).

Interior Lowlands Provinces

The Interior Lowlands region is dominated by gently dipping Paleozoic strata deposited upon a stable basement floor of Precambrian rocks. This large area is a part of the North American craton, the Precambrian basement differing from the Canadian Shield merely in possessing a sedimentary cover.

Interior Low Plateau Province - The Interior Low Plateau is part of a broad anticline -- the Cincinnati arch -- which forms the western flank of the Appalachian geosyncline (Figs. 11 and 12). The axis of the arch

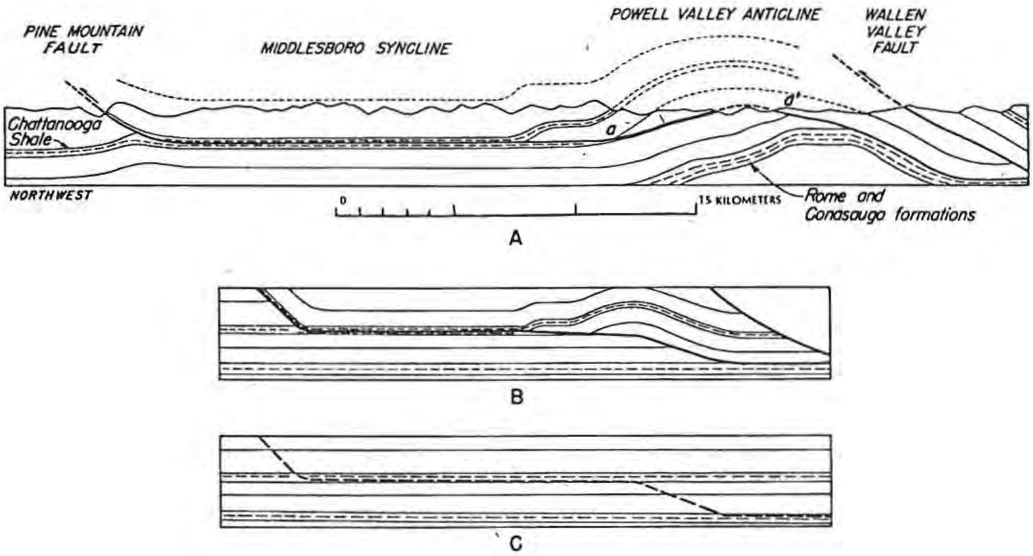


Figure 8 Sections across Cumberland Mountain thrust block, Virginia and Kentucky. (A) Present structure, with displacement on Pine Mountain fault indicated by points a-a'. (B) The same, with folding in overridden block eliminated. (C) Area before faulting, showing initial course of break that later became Pine Mountain thrust. From King (1977).

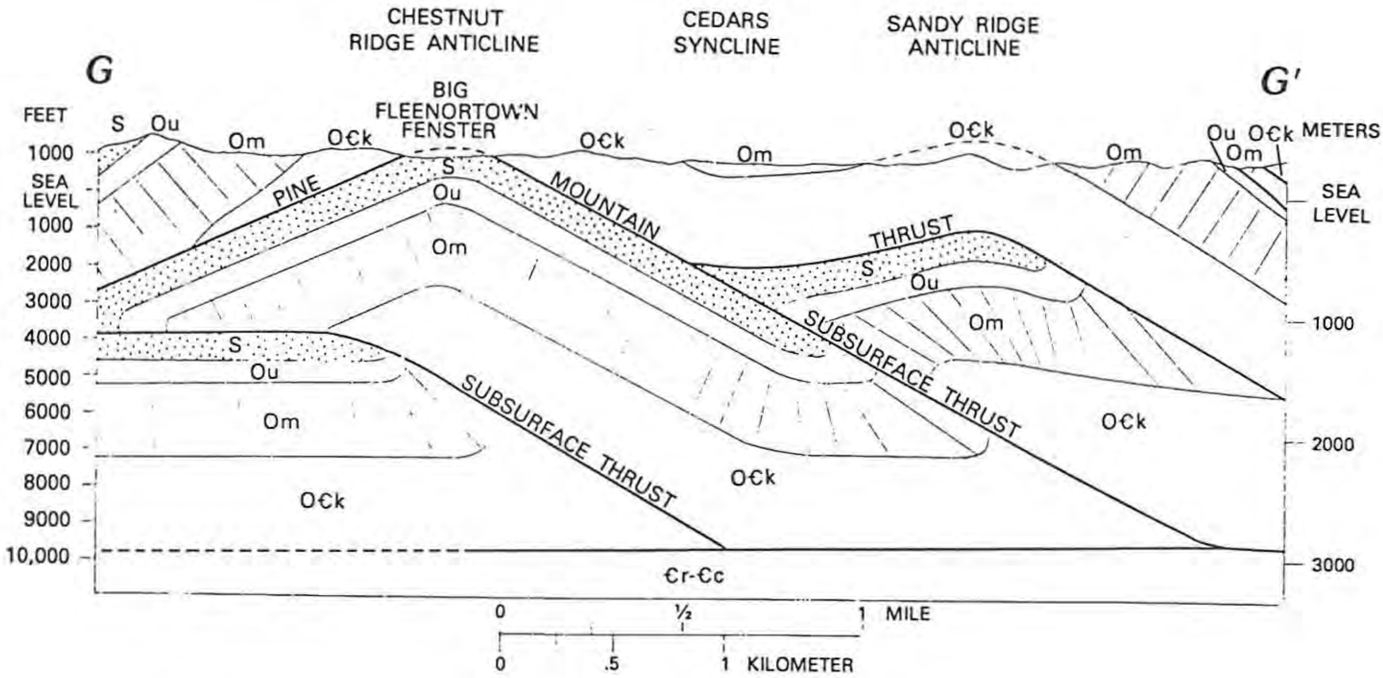
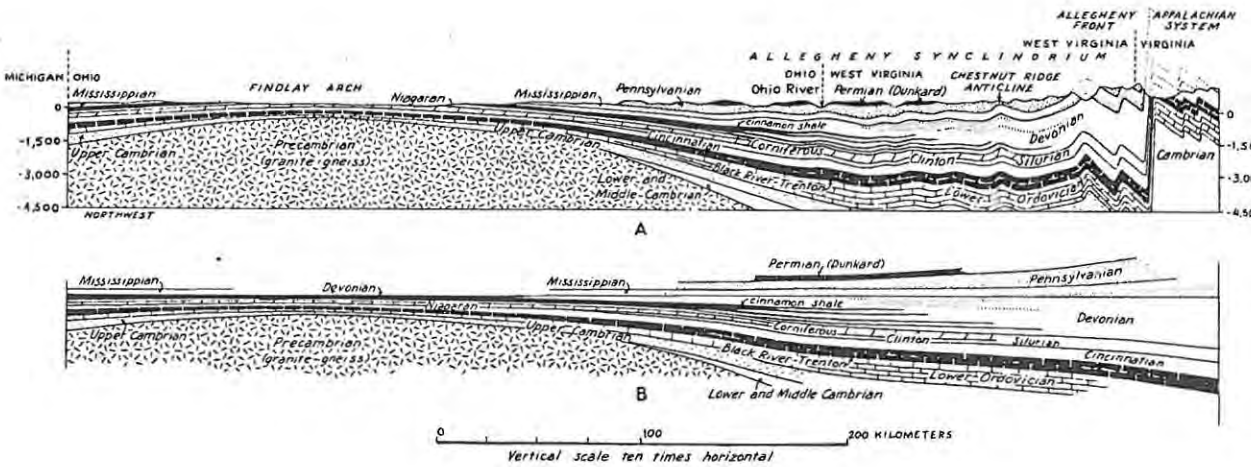


Figure 9 Subsurface duplication from the autochthonous plate that has warped the Pine Mountain thrust sheet into a series of anticlines and synclines. Massive subsurface duplication provides a favorable structural setting for hydrocarbon reservoirs. Rome Formation (Ꞓr), Conasauga Group (Ꞓc), Knox Group (OꞒk), Middle Ordovician limestone sequence (Om), Upper Ordovician rocks (Ou), Silurian rocks (S). From Harris and Milici (1977).



<u>Figure 10</u> Section across Allegheny synclinorium from Findlay arch on the northwest to Appalachian Mountain belt on the southeast, along a line extending from northwestern Ohio to eastern West Virginia. (A) Structure section. (B) Stratigraphic diagram along same line as structure section, with effects of deformation eliminated. Section B demonstrates that the apparent thinning of the formation in southeast part of section A is due to exaggeration of vertical scale and the rocks of the synclinorium were not laid down in an independent depositional basin. From King (1977).

is approximately parallel to the Appalachian highlands and extends some 970 km from northwestern Alabama to northwestern Ohio. North of the Ohio River the arched Paleozoic formations are obscure due to Pleistocene glaciations.

The province is divided into four sections (Fig. 12). Both the Lexington Plain and the Nashville Basin are on structural domes where Ordovician formations, mostly limestone, are exposed at surface. These limestones are cavernous and karst topography is well developed. Cuestas surround and dip away from both the Lexington Plain and Nashville Basin, and make up the Highland Rim. The remainder of the province is a low dissected plateau (Hunt, 1974).

<u>Central Lowland Province</u> - The Central Lowland is the largest of the physiographic provinces, covering nearly 1.7 million square kilometers in

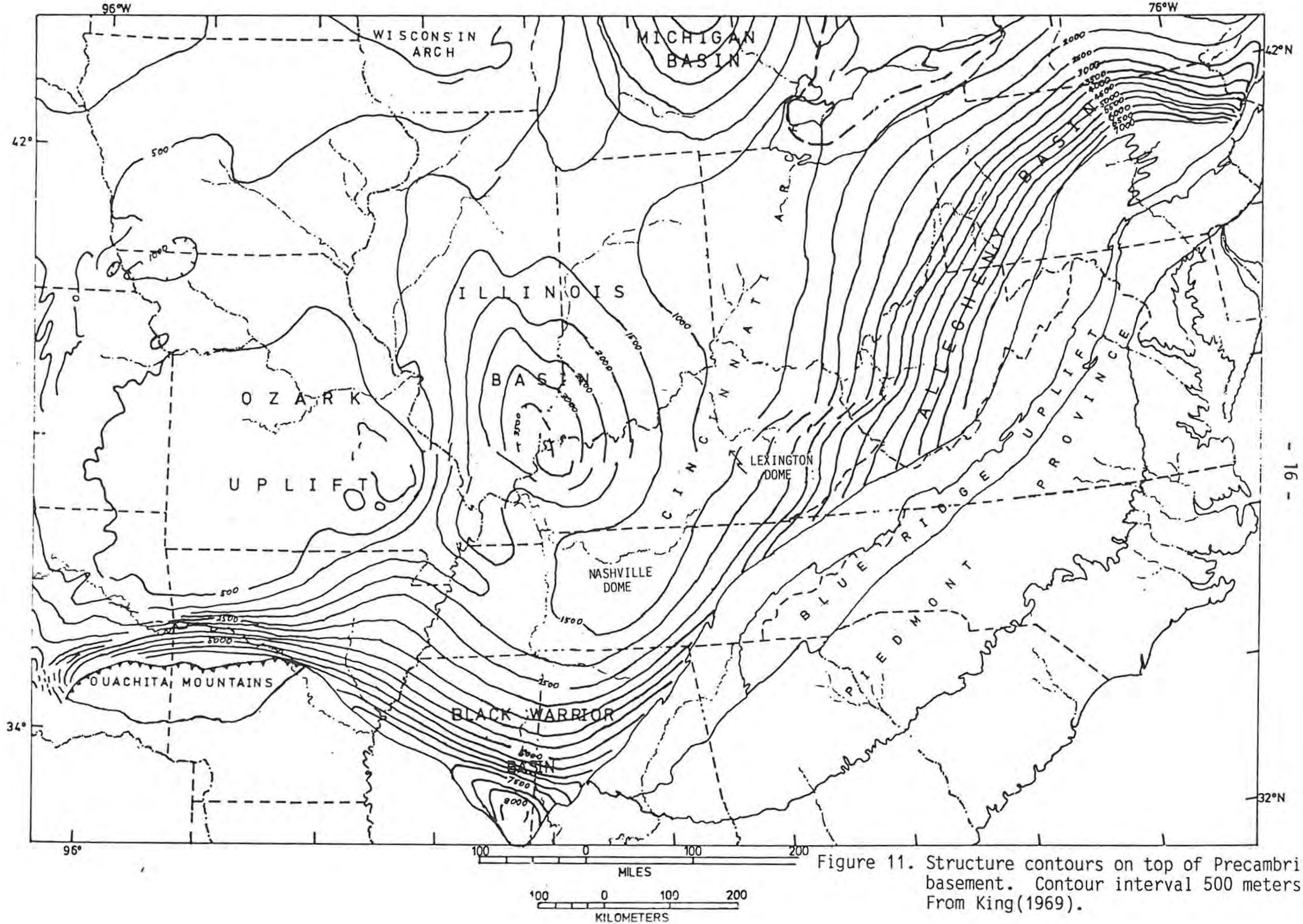


Figure 11. Structure contours on top of Precambrian basement. Contour interval 500 meters. From King (1969).

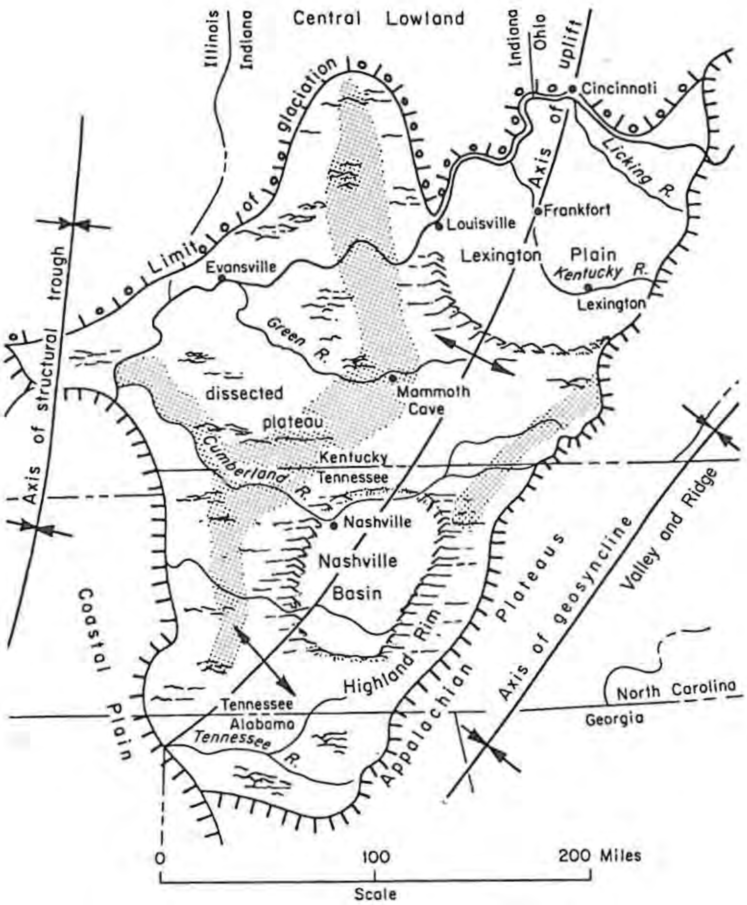


Figure 12 Interior Low Plateau Province, which lies south of the limit of glaciation and along the axis of the Cincinnati Arch. The Province is divided into four sections. North is the Lexington Plain, corresponding to the bluegrass areas of Kentucky. South is the Nashville Basin; the Plateaus around it make up the Highland Rim. The remainder of the province is low, dissected plateau. Areas of limestone sinks (karst topography) on the Highland Rim and dissected plateau are indicated by stippling. From Hunt (1974).

the United States and Canada. At the eastern edge where it joins the Appalachian Plateau, the altitude is about 300 m. Its western boundary lies at about 600 m in elevation.

The Paleozoic sedimentary cover is usually less than 1500 m thick in the uplifts and reaches a maximum thickness of about 5000 m in the Illinois and Michigan basins (Fig. 11). The rocks generally dip less than 1 degree. Most of the province was glaciated and much of the surface is covered by glacial deposits that largely conceal the underlying formations. The Rough Creek fault zone trends eastward through the southern portion of the Illinois basin, and has a length of 320 km and a maximum vertical displacement of about 900 km (Ham and Wilson, 1967). This is the largest fault shown on the Tectonic Map of North America (King, 1969) within the craton proper.

The Paleozoic tectonic record of the region is characterized by epeirogenic activity. Episodes of marine sedimentation were terminated by episodes of uplift, gentle folding and erosion resulting in overlap of younger strata upon the unconformable surface (Ham and Wilson, 1967). Fourteen unconformities can be recognized and traced widely. The magnitude of folding, geographical extent, and time elapsed between cycles varies widely.

Ouachita Province and Ozark Plateau - The Ouachita Province and Ozark Plateau resemble the Appalachian provinces and Interior Low Plateau in may respects. The Ouachita Mountains are defined by east-west trending folds of thick Paleozoic formations (Fig. 13). These formations thin northward under the Arkansas River Valley in a structural basin containing coal measures of Pennsylvanian age similar to those in the Appalachian Plateau, but more folded.

The Ouachita Mountains and Ozark Plateau regions are characterized by lower average relief than in the Appalachian Mountains, but landforms are similar. The Ozark Plateau forms a broad upwarp to the north of the Arkansas River and it exposes Early Paleozoic limestone formations, with elevations of about 600 m in the south and about 500 m in the north.

The Ouachita orogenic belt begins near the southwestern terminus of the Appalachian belt and extends 1800 km across the southern United States and probably into Mexico (Fig. 14); however, unlike the widely exposed Appalachian belt, the Ouachita belt is only exposed for 450 km of this distance -- in the Ouachita Mountains of Arkansas and Oklahoma, and in the Marathon region and several smaller areas in western Texas. The remainder is covered by Mesozoic and Cenozoic deposits of the Gulf Coastal Plain, but much is known about the covered part from drill hole data.

Development of the Ouachita orogenic belt was about as prolonged as

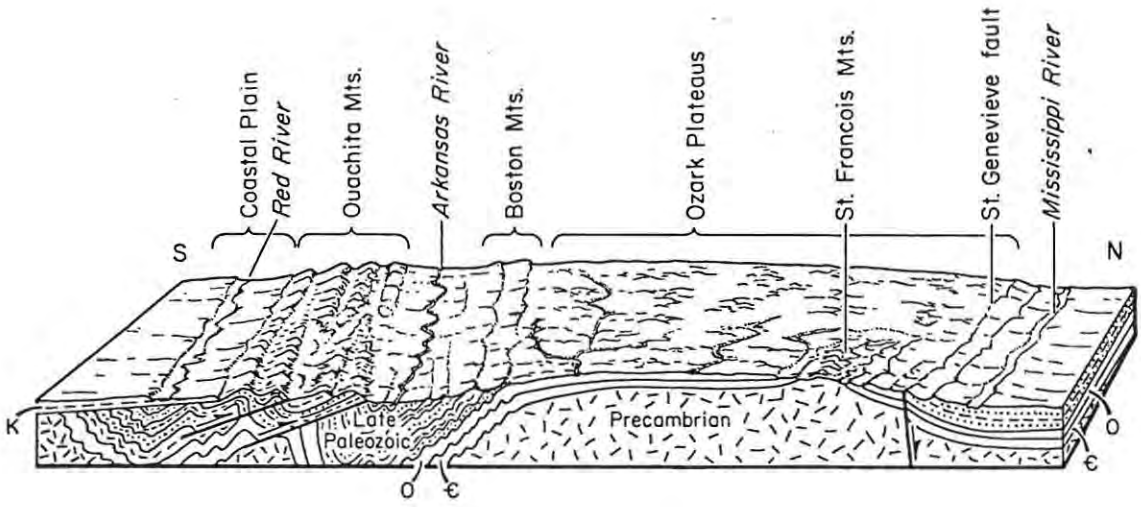


Figure 13 Diagram of the Ouachita Mountains and Ozark Plateaus. The cross section extends from the Coastal Plain in north Texas to the Mississippi River below St. Louis, a distance of about 500 kilometers. The Ouachita Mountains, composed of Paleozoic formations in folds broken by thrust faults directed toward the core of the continent, developed over a Paleozoic geosyncline where the formations are very thick, as in the Valley and Ridge province. The south flank of the geosynclinal belt is buried under Coastal Plain formations of Cretaceous age (K). Northward under the Arkansas River the Paleozoic formations thin and form a broad basin containing Pennsylvanian coal measures. The Ozark Plateaus consist of early Paleozoic formations (O, Ordovician; €, Cambrian) and, in the St. Francois Mountains, Precambrian rocks. From Hunt (1974).

that of the Appalachian orogenic belt. However, the carbonate bank remained outside the Ouachita orogenic belt, and the geosyncline received deep water, "off-the-shelf", deposits, almost eugeosynclinal in character (King, 1977). As in the Appalachians, the sediment in the geosyncline under the Ouachita Province were derived from what is now the seaward side of the geosyncline. Also, the folding and thrusting in the Ouachita province was directed towards the old Precambrian shield in the interior of the continent, as in the Valley and Ridge province.

The relation between the Ouachita and Appalachian systems is not yet clear. The southward extension of the Appalachian rocks beneath the Coastal Plain is well defined from well logs. Belts of Lower Paleozoic carbonates and Upper Paleozoic clastics like those of the Valley and Ridge province extend southward and across into the state of Mississippi near the town of Meridian, where they trend to the west-northwest. South

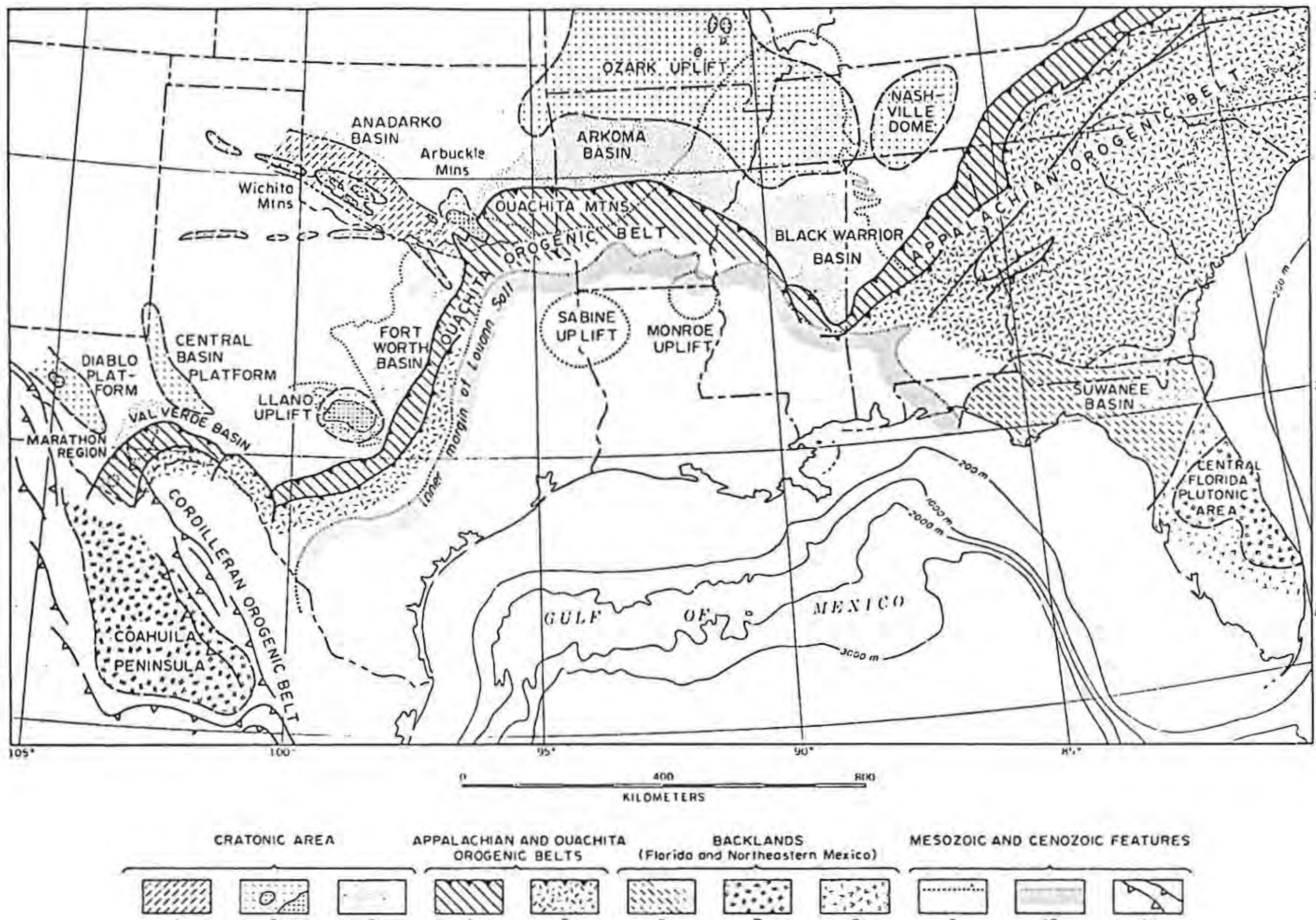


Figure 14 Map of south-central and southeastern United States, showing the Ouachita orogenic belt, the southwestern segment of the Appalachian orogenic belt, and adjoining tectonic units to the north, south and west. Explanation of patterns: Cratonic area : (1) Late Proterozoic-early Cambrian aulogcogen, in Wichita Mountains belt. (2) Positive areas, with small outcrops of Precambrian basement in darker shading. (3) Basin or foredeeps bordering the orogenic belts. Appalachian and Ouachita orogenic belts: (4) Deformed sedimentary rocks. (5) Metamorphic and plutonic rocks. Backlands in Florida and northeastern Mexico: (6) Flat-lying Paleozoic strata. (7) Plutonic rocks. (8) Volcanic rocks, part or all of Mesozoic age. Mesozoic and Cenozoic features: (9) Inner margin of Cretaceous and Tertiary Coastal Plain deposits. (10) Inner margin of Louann Salt, of early Jurassic age. (11) Frontal structures of Cordilleran orogenic belt. From King (1975).

of the carbonate and clastic strata some wells have penetrated rocks that are part of these interior belts of the Appalachians -- metamorphosed slate, quartzite, and marble. The extension of the Ouachita rocks is less well known, but a few wells in Mississippi penetrate slate, seemingly a part of the Ouachita belt that extends southeastward toward Meridian. The exact nature of the junction is uncertain, but it would seem that either the Appalachian rocks simply change facies westward into the Ouachita rocks, or the Ouachita rocks are thrust over the Appalachian rocks. Both belts formed along the margin of the original North American continent and were obviously involved in the same sort of tectonic episode. But, King (1977) states that on the southern side of the continent, instead of dealing with the interaction between two Atlantic plates, we are dealing with a complex of smaller shifting plates between the North and South American continental blocks.

TECTONIC FRAMEWORK OF THE EASTERN UNITED STATES

The breakup of Pangea and the opening of the Atlantic Ocean during the Mesozoic and Cenozoic is well documented. However, evidence concerning the history of the Precambrian and Paleozoic is not as clear, and the subject has been open to speculation. In 1966 J. Tuzo Wilson shed new light on the subject when he asked, "Did the Atlantic Ocean close and then reopen?" Since that time much suggestive evidence for such an interpretation has accumulated. Wilson's successors have improved and elaborated on the idea, and for Late Precambrian and Early Paleozoic history the question might well be rephrased "Did the Atlantic Ocean open and then reclose?"

Precambrian

In eastern North America 1000 m.y. old rocks involved in the Grenville orogeny consist of metamorphic and intrusive rocks as well as relatively unmetamorphosed sedimentary rocks (Stewart, 1976). Evidence by Irving et al. (1974) and Dewey and Burke (1973) indicates that the Grenville orogeny is due to a major collision of continents occurring in Grenville terrane about 1000 m.y. ago, forming a supercontinent which may be referred to as proto-Pangea. In the Appalachians, rocks of Grenville age are exposed as inliers in the core of a chain of anticlinoria along the western margin of the Appalachian metamorphic terrane (Blue Ridge province) from the Long Range in Newfoundland to at least as far south as Cartersville, Georgia (Fig. 15). Rankin (1976) terms the trace of the axis of these anticlinoria the Blue-Green-Long axis after three of the structural units.

Dewey and Burke (1974) have attributed the jaggedness of many continental margins to the breakup of continental masses along zones of extension that link rift valley systems formed on hot spots, and have suggested that these continental margin irregularities will influence the shape of an orogenic belt resulting from subsequent continential collision. Rankin (1976) demonstrated that the salients and recesses in the Appalachians are the failed arm (also known as an aulacogen) of triple junctions, linked by rift valleys, related to the breakup of proto-Pangea and the opening of the Iapetus Ocean (proto-Atlantic Ocean), and that the western margin of the rift valley system coincides roughly

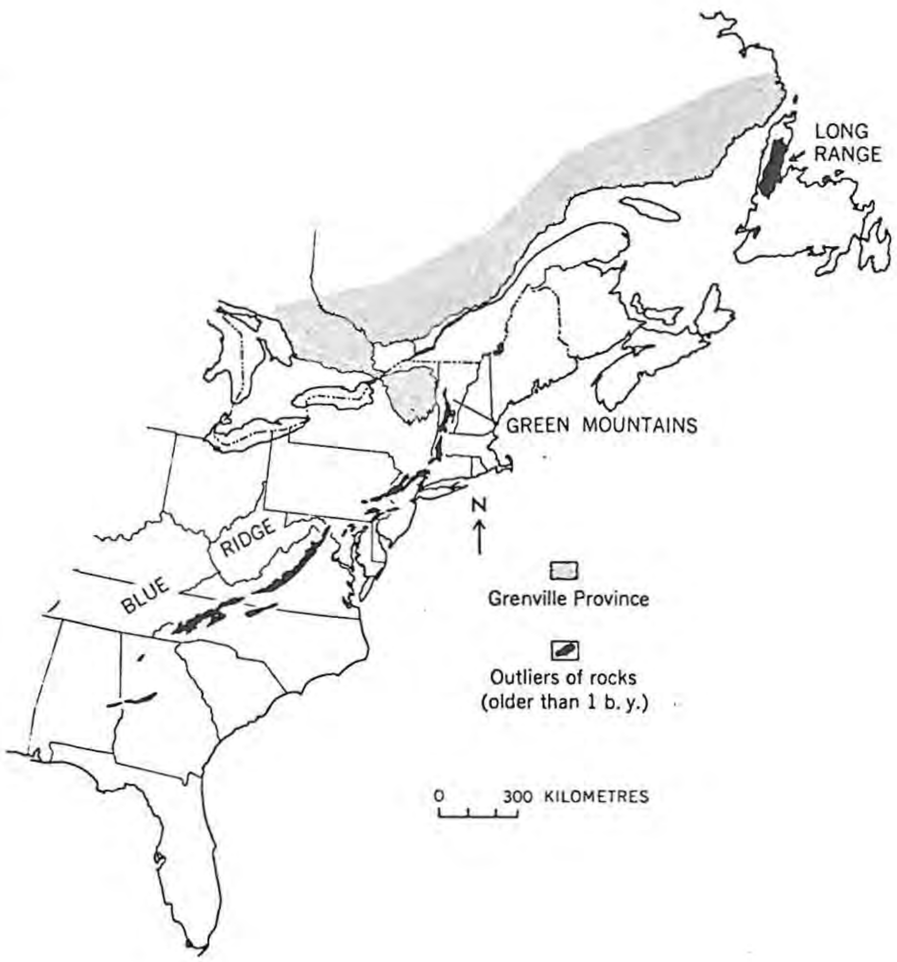


Figure 15 Distribution of rocks older than 1 b.y. in eastern North America. From Rankin (1976).

with the trace of the axis the Precambrian massifs (Blue-Green-Long axis). Several of the massifs or parts of them have been transported westward or northwestward from their original positions in Cambrian and Early Ordovician time; therefore, the position of the ancient rift system is only relative, and its shape is only a first approximation. Rankin (1976) concludes that the incipient opening of the present Atlantic (as evidenced by the Triassic basins) was essentially parallel to and nearly coincident with the incipient opening of Iapetus, demonstrating the persistence of zones of weakness through time. Certain massive sulfide deposits in the southern Appalachians, the most notable of which are probably the Ore Knob and Great Gossan Lead deposits in the Blue Ridge of North Carolina and Virginia respectively, are thought to have formed in this rifting environment. According to Stewart (1976) this rifting took place approximately 850 m.y. ago. Subsequent to rifting each of the resulting continental margins, were probably of the Atlantic type. Rankin (1976) also points out that the sharp bends from the Appalachian structural trends to the Ouachita structural trends may involve one or more triple junctions. The Reelfoot rift under the Mississippi embayment may be a somewhat older (1.3-1.1 b.y.) but similar failed arm associated with alkalic rhyolite of the St. Francois Mountans in southeast Missouri (Ervin and Mc Ginnis, 1975).

Volcanic rocks (greenstone and metarhyolite) make up the bulk of the exposed upper Precambrian rocks on the northwest limb of the Blue Ridge anticlinorium and were erupted subaerially (Mt. Rogers and Catoctin Formations). However, it has recently become apparent that thick piles of metamorphosed sedimentary rocks of Late Precambrian age are present throughout most of the length of the Appalachian chain southwest of Philadelphia (Hadley, 1970). The most notable of these are probably the sediments of the Ocoee Supergroup of the Great Smoky Mountains of Tennessee and North Carolina. The Ocoee consists of a minimum of 12 000 m of metasediments, predominantly arkoses, conglomerates, graywackes, siltstones and shales and possibly some minor intercalated metavolcanic rocks, and is host to the massive sulfide deposits of the Ducktown District in the Blue Ridge province of southeastern Tennessee. Rankin (1975) suggests deposition could have taken place in a graben or series of grabens (or aulacogens) some distance west of the opening of the Iapetus Ocean.

In a study of the Ocoee Supergroup and correlative rocks in the Blue Ridge, Hadley (1970) concluded that the known Late Precambrian sedimentary rocks were laid down in deep orogenic basins or troughs partly bordered by highlands of considerable relief. There were probably several of these basins separated by tectonically active ridges marginal to the continent. Depositional conditions within these troughs varied. Many were filled with the products of turbidity flows or other gravity powered mechanisms. Others were filled with bottom traction deposits, possibly deposited at shallow depth, while some reveal concurrent volcanism within the troughs marginal to them. The western limit of these troughs lies in the vicinity of the Blue Ridge anticlinorium, which marks the hinge line or western limit of early crustal downwarping that initiated the complex geosynclinal and orogenic development of the Paleozoic Era.

In latest Precambrian time a subduction zone and island arc system formed adjacent to what is now Virginia and the Carolinas (Hatcher, 1978b). The Precambrian massive sulfide deposits in the Carolina slate belt and those of the Virginia volcanic-plutonic belt are intepreted as having formed in this ancient island arc environment (Pavlides et al., 1982; Pavlides, 1981; Whitney et al., 1978). Worthington and Kiff (1970) also attribute certain gold deposits to these volcanics. The post-magmatic hydrothermal tungsten quartz veins of the Hamme tungsten district are also thought to be genetically related to this environment (Casadevalle and Rye, 1980). Sundelius (1970) reports that volcanic activity in the slate belt occurred until at least the Middle Cambrian and possibly until the Ordovician.

Many workers agree (Cook et al., 1980; Cook et al., 1979; Hatcher, 1978a) that west of the island arc (towards proto-North America) there was at least one other fragment of continental material, but oceanic crust (small oceans, marginal seas, or back arc basins) probably separated it from the continent and from the slate belt island arc. This fragment (referred to as the Piedmont microcontinent by Cook et al., 1979), then, is that portion of land known as the Inner Piedmont. Figure 16 is a model proposed by Cook et al. (1980) for the Precambrian tectonic history of the southern Appalachians.

The Precambrian history of the continental interior is difficult to interpret due to the thick sequence of overlying Phanerozoic sedimentary rocks, but according to Hinze et al. (1980), the Precambrian rocks of the continental interior are characterized by linear orogenic belts prior to about 1600 m.y. ago. In late Precambrian time continental stabilization occurred. Shelf-type sedimentation, anorogenic igneous activity, continental rifting and epeirogenic deformation was effected by orogenic activity which continued along the eastern and southern continental margin.

Most of the displacement of the Rough Creek fault zone (Fig. 2) and its extensions (also known as the 38th parallel lineament) is thought to have occurred in late Precambrian time. This is an east-trending zone of nearly continuous faults and intrusions that follows the 38th parallel of latitude from northeastern Virginia to south-central Missouri, a distance of some 1300 km. This zone delineates a wrench fault zone in the

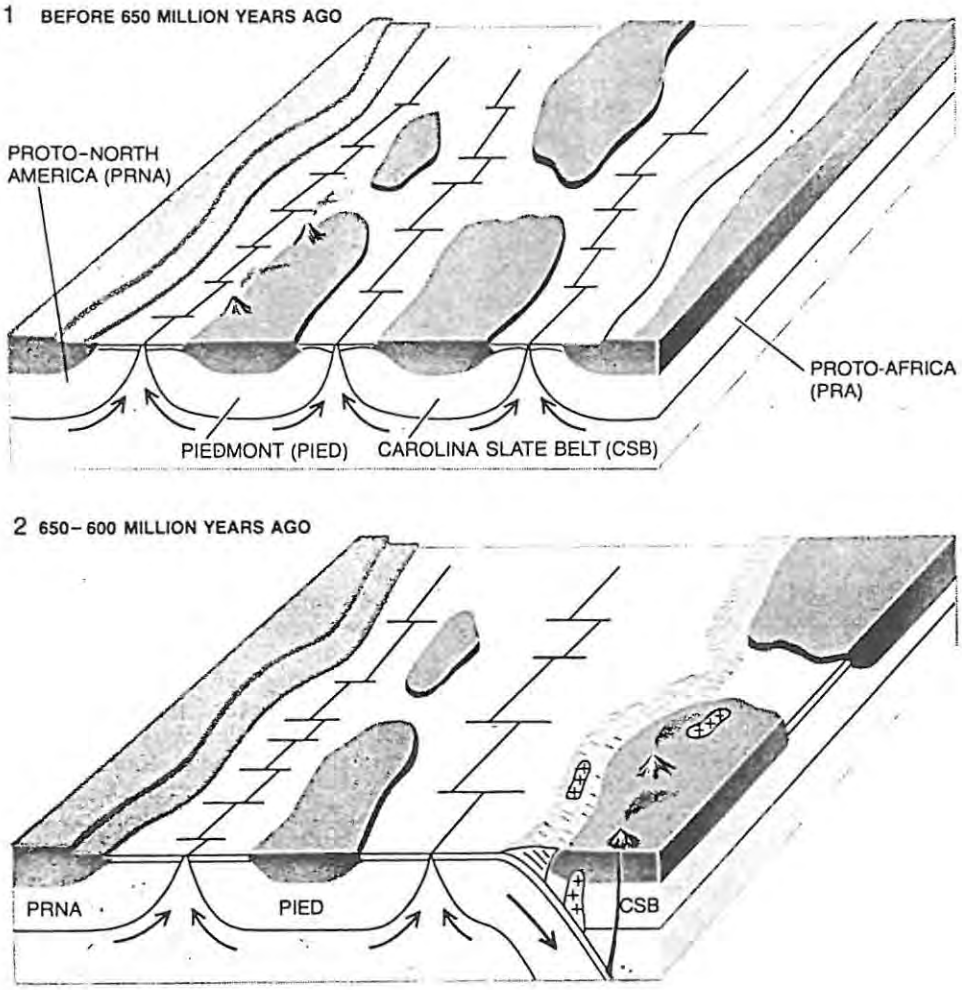


Figure 16 Precambrian tectonic history of the Southern Appalachian Mountains. (1) Some 650 million years ago in the Precambrian a megacontinental mass split into two continental plates (proto-North America and proto-Africa) and several smaller fragements including the Piedmont and the Carolina slate belt. (2) Subduction gave rise to volcanism in the Carolina slate belt, probably about 625 million years ago. The volcanic activity lasted until about 500 million years ago. From Cook et al. (1980).

basement. Alkalic and gabbroic intrusions, including ultramafic and mantle derived kimberlites, were intruded at intervals along the fault zone from Cambrian through at least Eocene time. Several major lead-zinc-(fluorspar) mining districts (Timberville, Virginia zinc district; Central Kentucky district; Illinois-Kentucky fluorspar district; Southeast Missouri district; and Central Missouri district) and numerous noncommercial mineralized zones occur at intervals along this fault zone (Fig. 17).

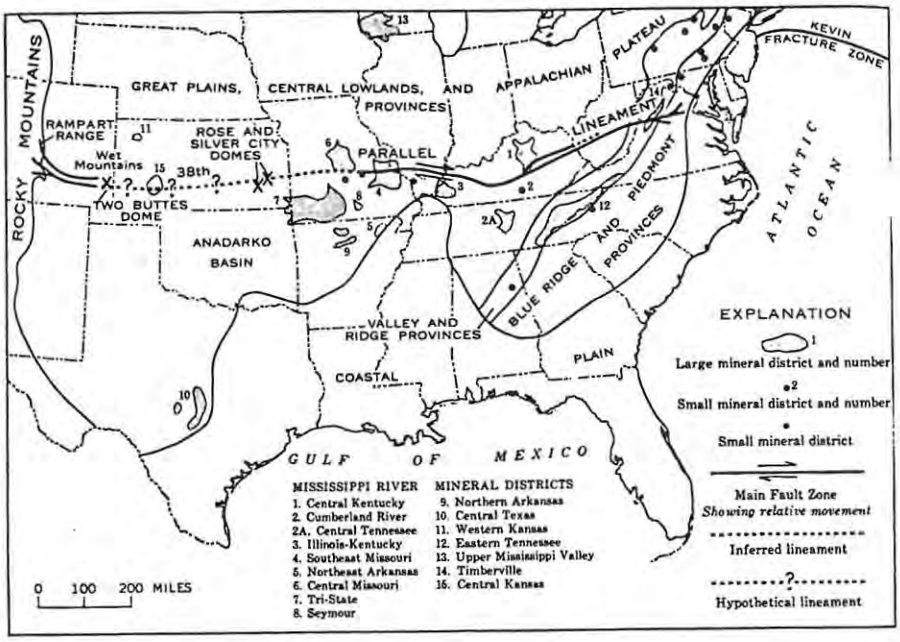


Figure 17 Location of the 38th parallel lineament showing relationship to major mining districts. From Heyl (1972).

A striking feature of the midcontinent region is a great terrane of rhyolite and epizonal granite about 500 km wide that stretches a distance of some 2000 km from northern Ohio across Indiana, Illinois, Missouri, southern Kansas, and Oklahoma at least into the Texas panhandle (Fig.18). These rocks were formed in the interval 1200-1500 m.y. ago. The abundant granites and silicic volcanics encountered in many drillholes and exposed in a few areas of the continental interior are part of a belt of igneous activity in which the rocks all become progressively younger southward (Goldrich et al., 1966), as shown in Figure 19.

The St. Francois Mountains expose some 900 square kilometers of this terrane in southeast Missouri (Fig. 18). This hilly region is the structural apex of the Ozark uplift (Fig. 11). Several major deposits of rather unique magnetite-hematite-apatite and magnetite-copper sulfide ores occur in the Precambrian rhyolites and related epizonal intrusive rocks of southeast Missouri. Work by Muehlberger et al. (1966) indicates that the iron was derived from the same magmatic source. This Precambrian high also had a major influence on the localization of several major lead-zinc-copper deposits which occur in overlying Upper

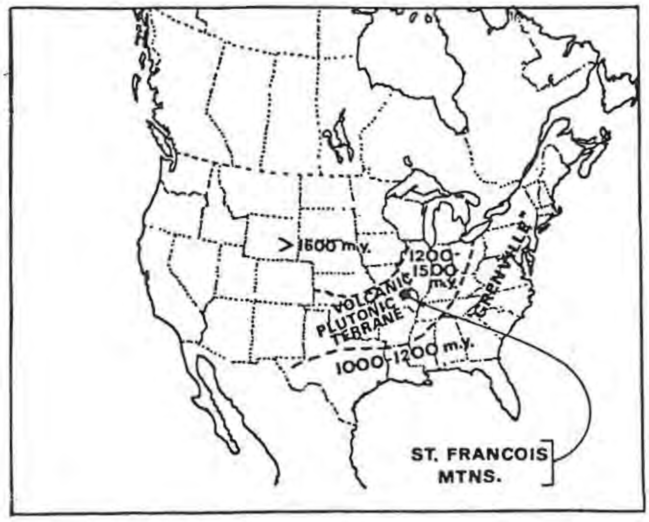


Figure 18 Sketch map showing location of St. Francois Mountains within volcanic-plutonic terrane. From Bickford et al. (1981).

Cambrian carbonate strata.

Basement rocks of the eastern midcontinent fall within the 800 m.y. to 1000 m.y. age range (Lidiak et al., 1966), representative of the Grenville orogeny. Basement rocks in the western midcontinent fall within the 1100-1500 m.y. range. According to Snyder (1968) the boundary between the groups of rocks of the two different ages appears to be a fault extending from northeast Arkansas to the St. Lawrence Valley.

Paleozoic

The study of Paleozoic tectonism in the eastern United States is, in essence, a study of Appalachian orogenic episodes and of epeirogenic episodes in the midcontinent region. Three well documented orogenic episodes occurred in the Appalachian region during the Paleozoic. The Taconic Orogeny initiated during the early, contracting stages of the then relatively narrow Iapetus Ocean in Middle Ordovician time. Continued contractions led, in the Devonian, to the Acadian orogeny, and again in the Pennsylavanian to the Alleghany orogeny (a less preferable term in use for this late Paleozoic orogeny is Appalachian orogeny).

Figure 20 illustrates that the major orogenies in North America

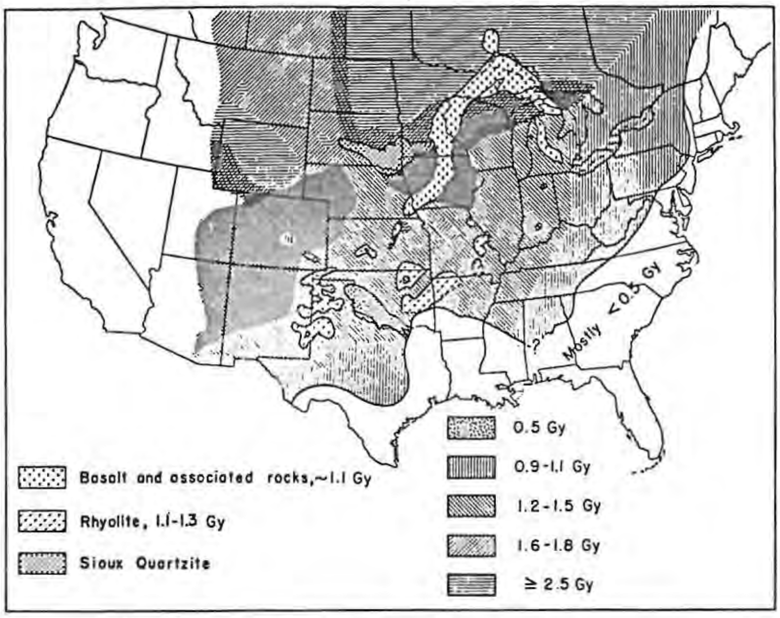


Figure 19 Interpretation of ages of basement rocks of the midcontinent region. Overprint patterns show some areas in which two events have been recognized. Some larger areas of Precambrian cover rocks include the Sioux quartzite, Keweenawan basalt and associated rocks, and 1100-1300 m.y. rhyolites. The 500 m.y. (Cambrian) igneous complex of Oklahoma and Texas is also shown. (Gy = gigayear = 1 billion years.) From Goldrich et al., (1966).

began, reached climactic stages and went through waning stages during the time epicontinental seas were transgressing to their maximum extent and then regressing to form great onlap-offlap sequences. Commonly, these sequences each extend over a large part of the central interior and into the geosynclines on each side, and are bounded below and above by regional unconformities. Johnson (1971) points out, "Apparently, orogenic compression of the marginal geosynclinal sedimentary prisms, epeirogenic warping of the continental interiors, and eustatic sea-level fluctuations are differing manifestations occurring in response to the same driving mechanism." Johnson (1971) coined the term "Antler Effect" for this correspondence of orogenic events with onlap upon the craton, the term being taken from the Antler orogeny of western North America.

The sedimentary sequences within the continental interior are host to lead-zinc-fluorite-barite deposits of the Mississippi Valley type throughout the entire Paleozoic section. The commercial deposits occur

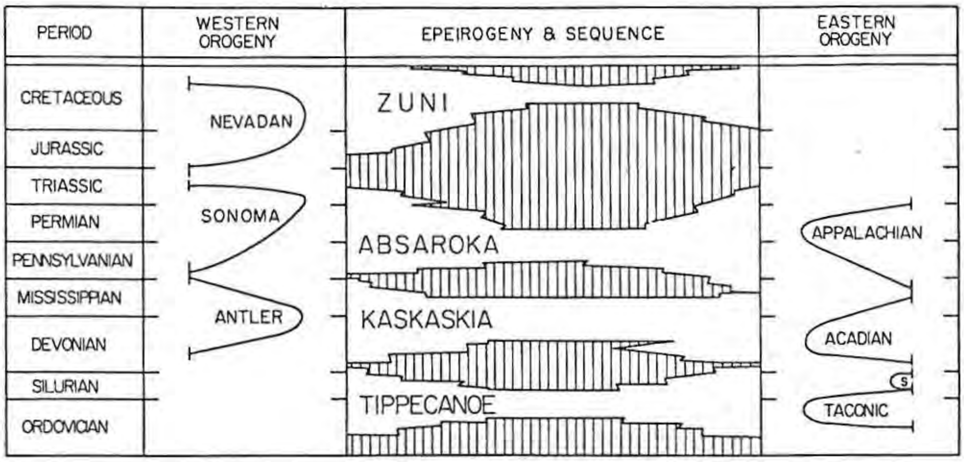


Figure 20 Table of orogenies on opposite sides of North America and of the sequences of sedimentary rocks that developed on the continental interior. The named sequences are modified from Sloss (1963, Fig. 6). Vertical lines indicate hiatus. S = salinic disturbance. From Johnson (1971).

largely in limestones and dolomites, but many are also in shales and sandstones. The deposits are clustered on the flanks of gently flexed or folded major domes or anticlines; deposits are rare in basins (Heyl, 1969).

Cambrian through Early Ordovician

The Appalachian miogeosyncline is an elongate, downwarped segment of the earth's crust in which a great thickness of sediment accumulated throughout the Paleozoic era. From these rocks the Appalachian Plateau and Valley and Ridge provinces were formed. The area is bordered on the east and southeast by the crystalline rocks of the Piedmont. To the west the basin is flanked by two broad upwarps -- the Findlay and Cincinnati arches. These arches separate the more mobile Appalachian basin from the stable intracratonic basins to the west. The mass of sedimentary rock was uplifted and deformed to some extent during deposition, but largely after the bulk of the sedimentary sequence had been deposited.

Throughout most of the Paleozoic the miogeosyncline was a region of quiet sedimentation and slow subsidence with little other crustal activity and no volcanism. Subsidence and deposition commenced in the eastern portion of the basin in Late Precambrian time and continued intermittently throughout most of the basin until late Paleozoic. Sedimentologic and stratigraphic studies indicate that most of the sediments were deposited in shallow waters, indicating that the rate of deposition closely balanced the rate of subsidence of the sea floor (Colton, 1970). The sediments represent a variety of depositional environments, all of which are elements of a broad coastal plain flanking a marine embayment.

Initial Paleozoic deposits in the Appalachian miogeosyncline are Lower Cambrian marine clastics comprised of conglomerates, arkoses, and shales. In much of the basin the top of the sequence is marked by a blanket of cleanly washed quartzites laid down in the shallow waters of a northwest-transgressing Cambrian sea (Colton, 1970). Figure 21 illustrates that this is a wedge shaped mass, thickest along the eastern margin of the basin where the rocks are predominantly Early Cambrian in age, and thinnest along the western and northern margins where the rocks are predominantly Late Cambrian age. The greatest accumulations of Lower Cambrian strata occur in southwestern Virginia where the thickness is approximately 3050 m.

The regional thickness gradient is noticeably altered along the dislocation marked at the surface by the Kentucky River fault system (an extension of the Rough Creek fault zone; see Fig. 2) as shown in Figure 21. Core from deep wells in eastern Kentucky delineate a thin sandstone sequence north of the fault zone and a thick sequence of shale, sandstone, and interbedded carbonate rock south of the fault zone. The data are not unequivocal, but the thickness pattern suggests the possibility of right lateral strike slip displacement along the fault zone as suggested by Summerson (1962, referenced in Colton, 1970) from a study of the configuration of the basement surface.

The Lower Cambrian clastic sequence is conformably overlain by a great sequence of carbonate rocks composed largely of dolomite and limestone. The carbonate sequence ranges in thickness from about 180 m in northern New York to somewhat more than 3000 m in southeastern Tennessee. The axis of greatest thickness runs approximately parallel to the eastern edge of the Appalachian basin (Fig. 22), extending from eastern New York to northern Alabama (Colton, 1970). These rocks embrace the remainder of the Lower Cambrian and extend through the Lower

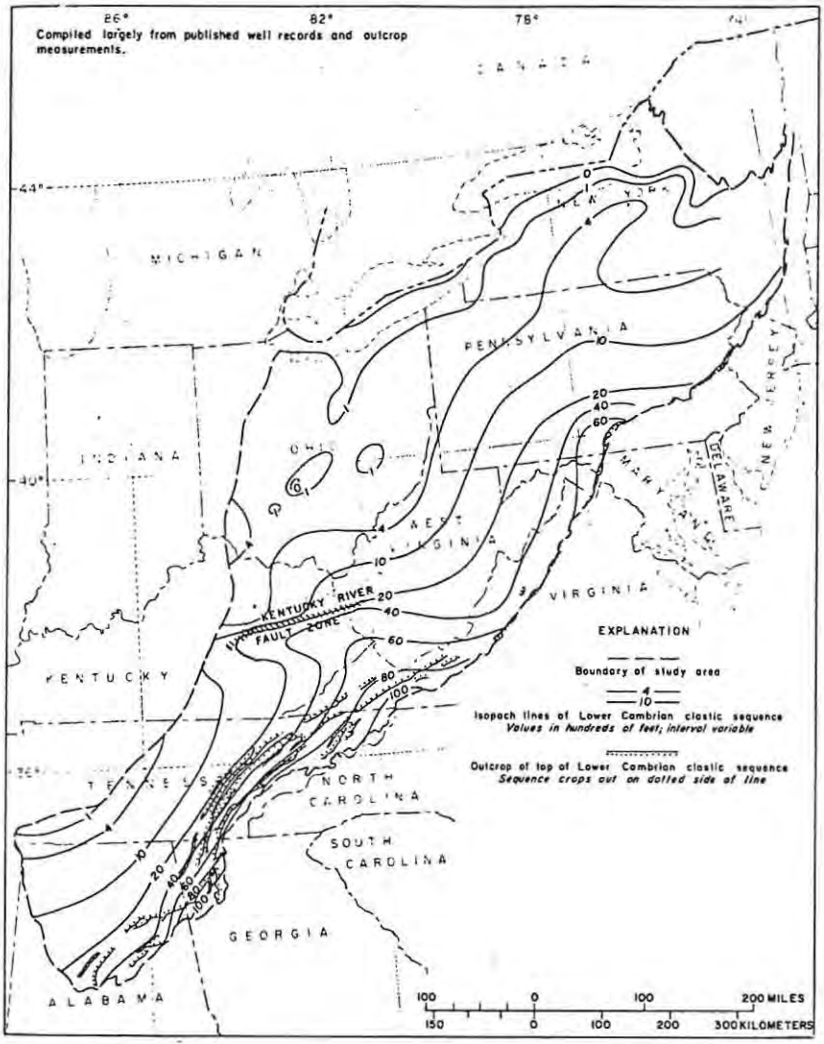


Figure 21 Isopach map of Lower Cambrian clastic sequence. Modified from Colton (1970).

Ordovician, and in places includes the Middle Ordovician as well. The base of the Middle Ordovician is marked by an unconformity over much of the eastern United States and karst topography was widespread over much of the carbonate lowland (Harris and Milici, 1977). This gentle epeirogenic uplift is called the Blountain disturbance (Kay, 1942). The regional paleoaquifer system that developed in the underlying carbonate rocks at this time is the major contributing factor in regional dolomitization and localization of solution-thinning and karst-related breccia zones which are responsible for the concentration of metals in the Appalachian type zinc-lead deposits of the Valley and Ridge province (Harris, 1971). Although these features are much more extensive in

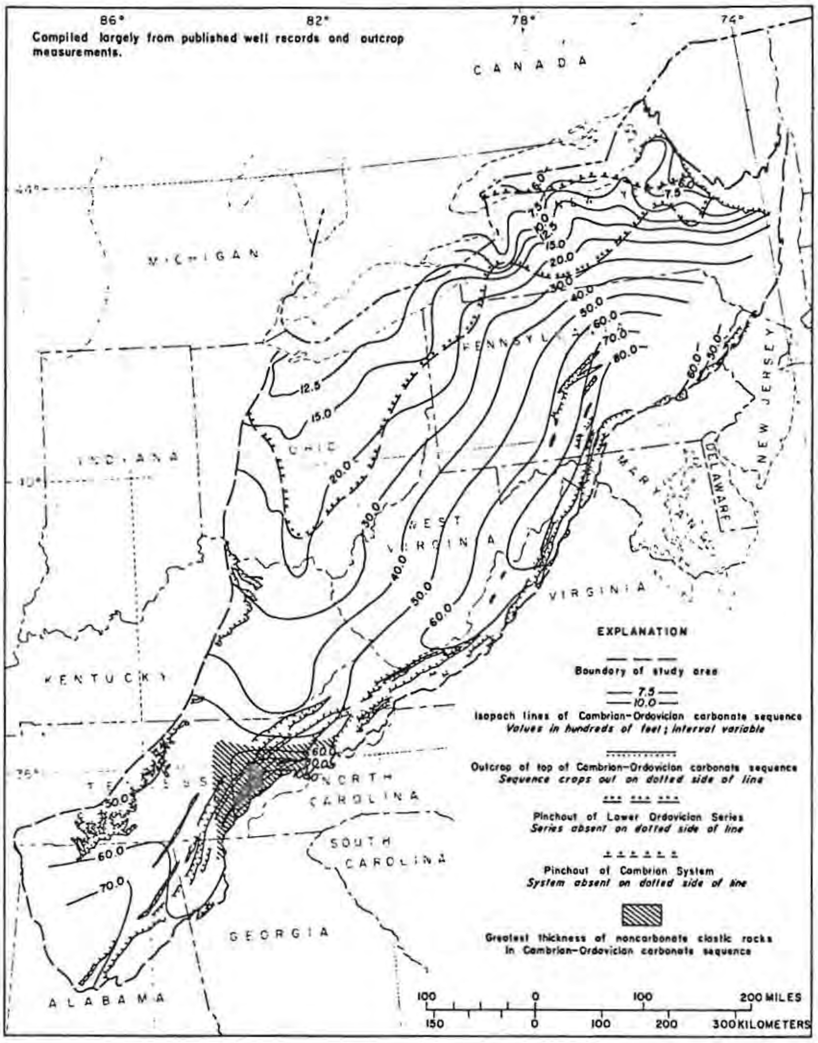


Figure 22 Isopach map of Cambrian-Ordovician carbonate sequence. From Colton (1970).

distribution than ore, they appear to have been a necessary feature of the system which brought the mineralizing solutions into the depositional sites.

During Cambrian and Early Ordovician time sediment contributions within the miogeosyncline were mainly from the north and west. The sandy and shaly layers were derived from distant parts of the continental interior and laid down during a prolonged time of crustal quiescence when no nearby lands were being strongly eroded (King, 1977; Colton, 1970).

Ore deposits associated with miogeosynclinal rocks of lower Paleozoic, besides the Appalachian type lead-zinc deposits of Early Cambrian to Early Ordovician, age include residual manganese and bedded iron ores of Early Cambrian age, and bauxite which occurs in sinkholes or other depressions in carbonate rocks of Cambrian to Ordovician age.

Southeast of the Appalachian miogeosyncline, away from the continent, is the Appalachian eugeosynclinal area from which the rocks of the crystalline Appalachians were formed. The tectonic and metamorphic evolution of the Piedmont was very complex and only the broad outlines have been worked out. As indicated earlier, the crystalline rocks in the southern Appalachians are extensively metamorphosed and intruded by plutonic rocks, and most of the Paleozoic systems are missing. However, from reconstructions of Early Paleozoic history made primarily by analogy with the northern Appalachians where metamorphic grade is lower it seems that the area was characterized by much crustal mobility during the Paleozoic, with the accumulation of a typical eugeosynclinal assemblage of Cambrian to Devonian slates, graywackes, cherts, and volcanics (King, 1977). The lithologies and structures indicate that it was the site of an active continental margin bordered by a subduction zone and at least a small ocean basin, particularly in earlier Paleozoic time. Volcanism is thought to have continued in the Carolina slate belt island arc system until the beginning of the Ordovician. The slate belt rocks are invaded by widely spaced granitic plutons with ages of 520 to 595 m.y., which are probably congenerically related to the volcanic activity. The Piedmont rocks are quite different from the Paleozoic eugeosynclinal sequence and closely resemble the Avalonian rocks of Newfoundland, which are thought to be some sort of independent fragment in the midst of an orginally very wide Appalachian orogen.

The southern margin of North America is characterized by a longer period of stability than the Appalachian margin and apparently behaved as a passive continental margin through early and medial Paleozoic time (Thomas, 1972). Early and Middle Paleozoic rocks exposed in the Ouachita uplift consist mostly of dark shales, sandstones, beds of chert and novaculite, and some cherty limestones. The exposed strata range from Late Cambrian or Early Ordovician to Early Mississippian age and are not more than 1800 m thick (Ham and Wilson, 1967). The early phase of black shale-chert sedimentation is closed by the deposition of the Arkansas Novaculite, the uppermost beds of which are Early Mississippian age. The novaculite is quarried and used as a whetstone for sharpening cutting instruments. It is a very hard and dense, even textured, cryptocrystalline, siliceous sedimentary rock considered to be a result of primary deposition of silica under geosynclinal conditions (Gary et al., 1974).

Widespread sedimentation occurred in the midcontinent region during Early and Middle Paleozoic time and the development of numerous basins and arches was initiated (Fig. 23). The basal beds of the Sauk sequence

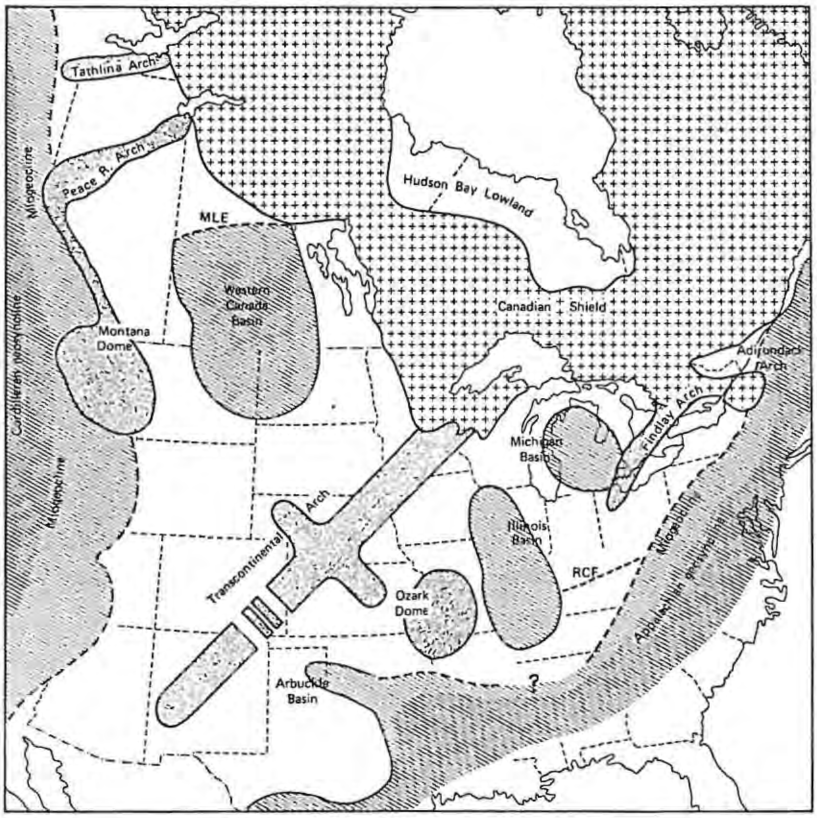


Figure 23 Arches and basins active in the early Paleozoic Era in the North American craton. MLE = Meadow Lake Escarpment. RCF = Rough Creek Fault Zones. From Stearn et al., (1979).

range in age from late Precambrian in the basins marginal to the craton to Late Cambrian over much of the cratonic interior, to Early Ordovician at the margin of the Canadian Shield and on certain positive elements (Sloss, 1963). The first Cambrian deposits are conglomerates and arkoses, grading upward into feldspathic and generally glauconitic sandstones. These are succeeded upward by limestones and dolomites which continue to the top of the Cambrian (Howell et al., 1944). The carbonates are interbedded with sandstones in marginal areas near remaining exposures of basement rocks. Carbonate deposition continues with only minor interruptions until the Lower Ordovician (Ham and Wilson, 1967). The cratonic interior areas are characterized by dolomitized carbonates above the basal sandstone, with a marked increase in the number and thickness of regressive sandstone tongues as the margin of the Canadian Shield is approached. Sauk strata have been deeply affected by pre-Tippecanoe erosion in many of the cratonic Middle Paleozoic positive areas.

Greater areas of most of the craton appear to have remained above sea level at the climax of Sauk submergence than is the case for later submergent episodes. Also, according to Sloss and Speed (1974), the degree to which the tectonic pattern of the cratonic interior is differentiated into subsiding basins and less subsident shelves, domes, and arches is distinctly less than that typical of younger submergent episodes. Instead, differential subsidence was confined primarily to basins on the cratonic margins and to embayments off the margins. Sloss and Speed (1974) conclude, "... there is a real difference between the tectonism expressed during Sauk deposition and that of the younger tectonic episodes but we believe the difference to be one of degree rather than kind."

Middle Ordovician through Silurian (Taconic Orogeny)

Evidence for Middle and Late Ordovician orogenic movements is present in many places in the northwestern portion of the Appalachian chain, and also locally in the southeastern part. In the miogeosynclinal area, a sequence of predominantly noncalcareous clastic deposits overlies the Cambrian-Ordovician carbonate sequences throughout most of the basin (Fig. 24). In portions of the basin deposition began in the Early Ordovician, but the bulk of the sequence is Late Ordovician in age. The clastics consist largely of shale, siltstone and sandstone, and smaller amounts of limestone and quartz pebble conglomerate (Colton, 1970). The boundary between the Upper Ordovician clastic sequences and the underlying Cambrian-Ordovician carbonate sequence is conformable, while the boundary with the overlying Silurian clastic sequence is disconformable in the northeastern and southwestern parts of the basin. The absence of younger Upper Ordovician rocks and the sharp angular

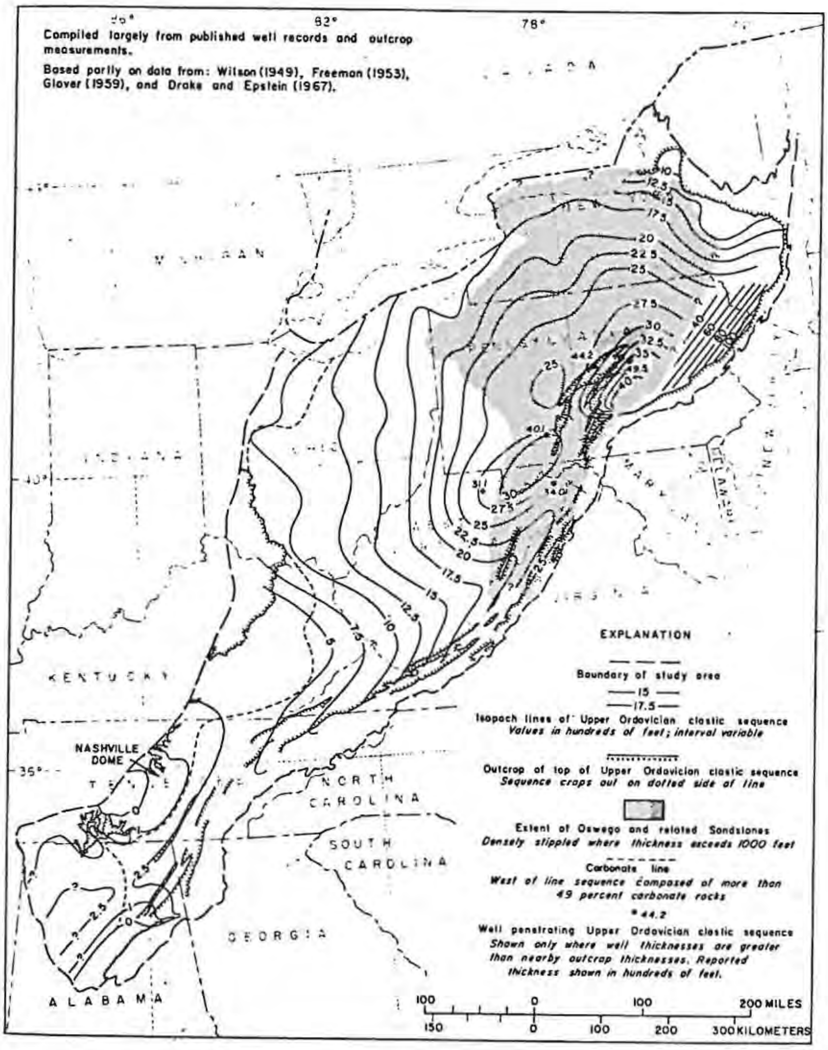


Figure 24 Isopach map of Upper Ordovician clastic sequence. From Colton (1970).

unconformity at the contact with the overlying sequence are evidence of diastrophic activity during this time (Colton, 1970). The major source for clastic rocks accumulating in the developing Appalachian sedimentary basin during Middle Ordovician to Pennsylvanian time was from lands that had recently been uplifted to the east or southeast. In the northern Appalachians two principal disturbances are well documented which account for the uplift responsible for the clastic sequences -- the Taconic orogeny toward the end of the Ordovician, and the Acadian orogeny in the Middle Devonian. Clastic sequences in the southern Appalachians undoubtedly originated in the same manner. A foredeep formed within the former Cambrian to Lower Ordovocian shelf west of the uplifted area in the Piedmont during Middle Ordovician time (Harris and Milici, 1977). The foredeep was bordered on the west by a shallow-water Middle

Ordovician carbonate shelf.

In the northern Appalachians the first clastics are Middle and Upper Ordovician deposits consisting of up to 3000 m of flysch deposited in rapidly subsiding linear troughs. Lying on or in the flysch are allochthonous slices of Cambrian and Ordovician shaly and sandy rocks which have been moved from their areas of accumulation to the east. According to King (1977), these allochthonous masses moved as great gravity slides onto the sea floor where the flysch was accumulating. The best known of these allochthonous masses are those of the Taconic Range of eastern New York State. Similar allochthonous masses of the same facies of Cambrian and Ordovician rocks rest on flysch at the top of the miogeosynclinal sequence along the west coast of Newfoundland. The uppermost allochthons here, however, are great tabular masses of obducted oceanic crust, thus furnishing conclusive proof of the existence of oceanic crust beneath the eugeosynclinal rocks not far to the east of the miogeosyncline.

The Lower Paleozoic clastic deposits of the southern Appalachians are, for the most part, younger than those of the northern Appalachians, and do not have the flysch-like qualities of those in the northern Appalachians; instead, they are broad sheets of detritus spread over the miogeosyncline and northwestward over the foreland, thinning and tapering in this direction. These are illustrated in the columnar section of Figure 25. King (1977) terms these deposits "clastic wedges".

In Tennessee the clastic segment begins in the Middle Ordovician as in the northern Appalachians, but here and elsewhere they are succeeded by younger Paleozoic clastic deposits. These are chiefly marine at the base, but pass upward into continental beds that begin, in some areas, in the Devonian or Mississippian, and in other areas in Pennsylvanian time. These Middle Paleozoic clastics include persistent units of sandstone that are the chief ridge-makers of the Valley and Ridge province (King, 1977).

In Alabama the Middle Ordovician through Devonian clastics are insignificant (Fig. 25); the thick accumulations began in the Mississippian and continued through the Pennsylvanian. In Tennessee the thick clastic deposits are Middle and Upper Ordovician, the Mississippian

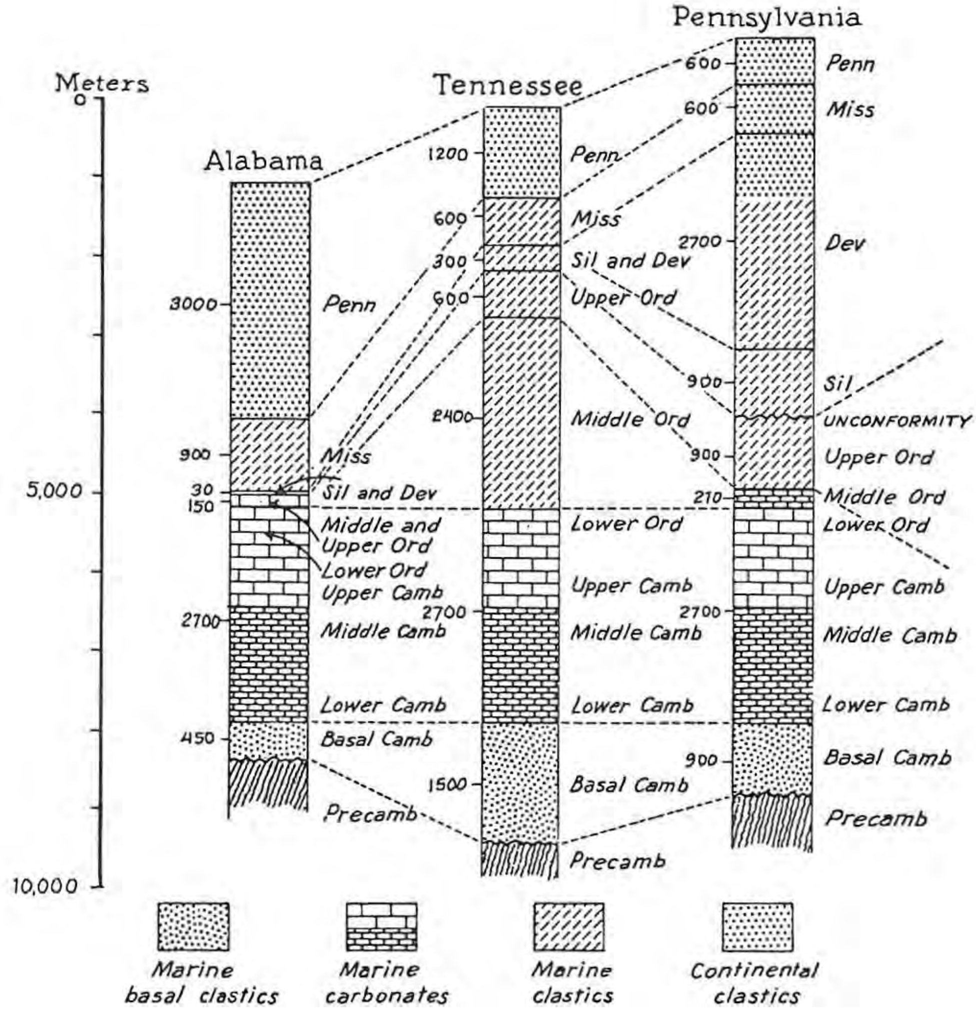


Figure 25 Generalized columnar sections of the Paleozoic rocks from southwest to northeast in the Valley and Ridge province in Alabama, Tennessee, and Pennsylvania to show the sequence and character of the deposits along the strike of the Appalachian miogeosyncline. From King (1977).

and Pennsylvanian are thinner, and the Silurian and Devonian are inconsequential. In Pennsylvania the thickest accumulation of clastics occurred during the Silurian and Devonian, and the Pennsylvanian and Mississippian continental beds that cover the Allegheny Plateau to the west are thin by comparison. Some of the most productive oil and gas sands in the Appalachian basin occur in the Silurian clastic sequence.

Figure 25 illustrates that the clastic sequences thin from north to south along strike. Figure 26 is a section across strike in southern New York State, from the Catskill Mountains to Erie Pennsylvania, showing that the clastic wedges also thin from east to west. As illustrated in the figure, the Devonian is only 800 m thick near the western portion of

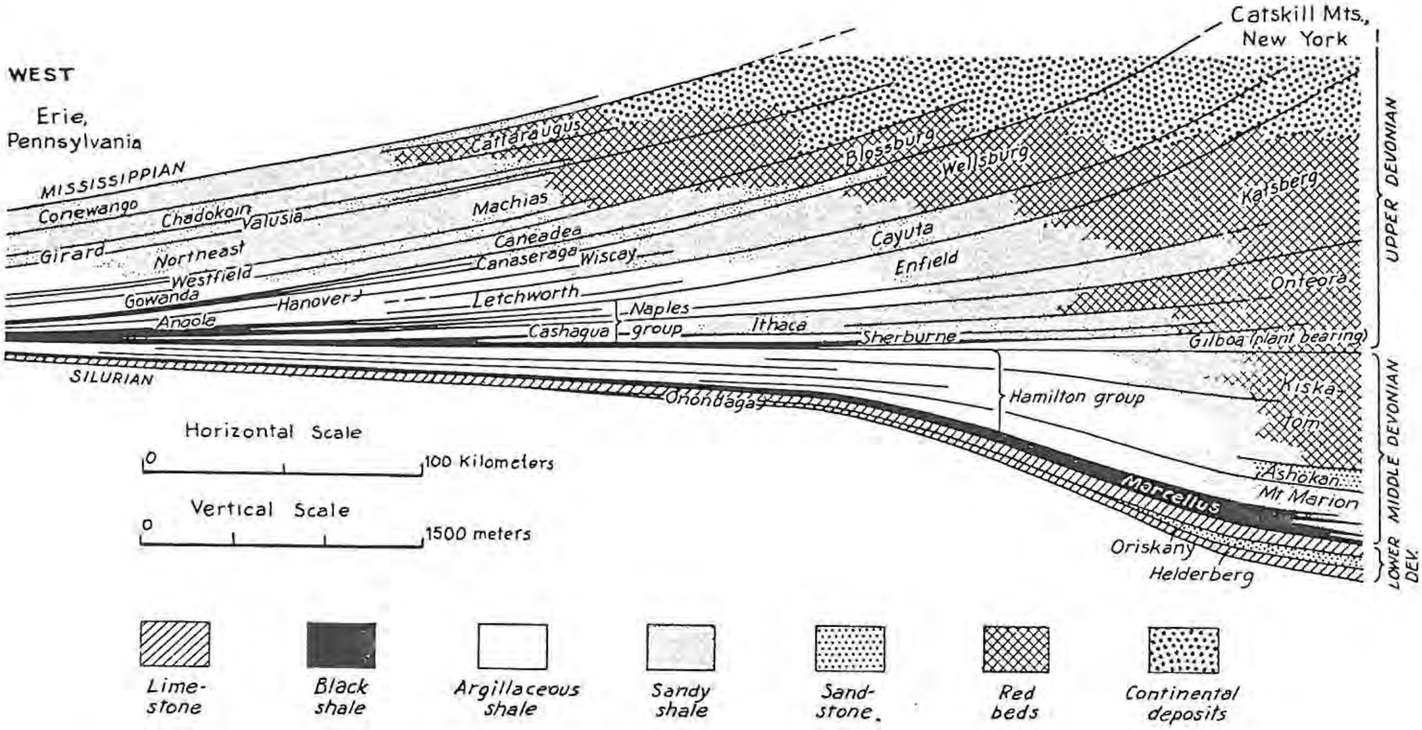


Figure 26 Stratigraphic diagram from west to east in New York State showing the clastic wedge structure of the Devonian rocks and details of their lithology and thickness. Based on the work of G.H. Chadwick and G.A. Cooper. From King (1977).

the state, whereas to the east the thickness exceeds 3000 m. Most of the thickening occurred in the Upper Devonian, somewhat less occurred in the Middle Devonian, and very little occurred in the Lower Devonian.

King (1977) likens the whole mass of clastic wedge deposits in the Appalachians to a "set of fish scales rooted on the southeast, each wedge thinning not only northwestward across strike, but northeastward and southwestward along it. Each wedge (or 'fish scale') lies at a different level, and each younger one overlaps the older one adjoining it" (Fig. 27).

Some of the most important sedimentary ore deposits of the southern Appalachian region are the so-called "Clinton" hematite ores of Early and Middle Silurian age. These occur in many localities, primarily within the Valley and Ridge province, from New York to Alabama. The Clinton Ores are generally considered to be of sedimentary origin, and contain up to about 37% iron as hematite.

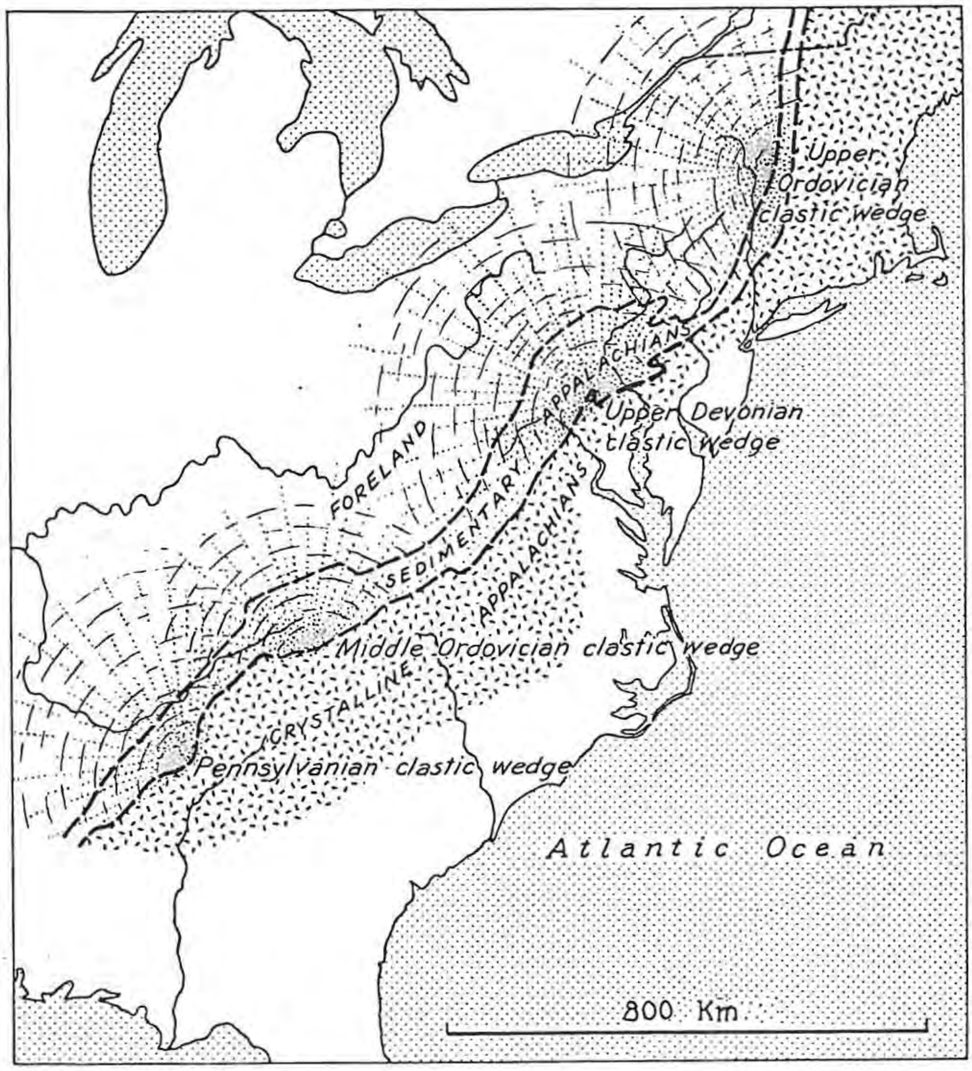


Figure 27 Sketch map of eastern United States showing extent of the principal clastic wedge deposits of different ages in the sedimentary Appalachians (miogeosynclinal area) and the foreland of the Appalachian system. From King (1977).

Radiometric ages in the Piedmont of the southern Appalachians are difficult to interpret, but isotopic dating, though equivocal, and various other lines of reasoning (Rogers, 1967), indicate that the larger part of the metamorphism, and some of the older plutonism, occurred early in the Middle Ordovician to late in the Upper Ordovician. Evidence from the South Carolina Piedmont indicates that metamorphism took place during the Ordovician (Overstreet, 1970). The island arc that may have existed was probably destroyed at this time. Radiometric dates on zircon and feldspar from post-orogenic pegmatites show that major deformation had ended by Late Ordovician or Early Silurian time (Wetherill et al., 1966). These dates agree well with stratigraphic evidence in the Appalachian miogeosyncline for the timing of the Taconic Orogeny and with more reliable age dates in the northern Appalachians for the timing of these events. The Baltimore-State Line peridotite-gabbro complex, which lies within the Piedmont of Maryland, Pennsylvania, and Deleware, was emplaced in this time interval and contains historically productive deposits of chromite and asbestos (Pearre and Heyl, 1960).

Radiometric age determinations on the polymetamorphosed rocks of the Blue Ridge are also frought with uncertainties. But, with the uncertainties in mind, Hadley (1964) found a close correlation between Paleozoic K/Ar and Rb/Ar ages in the crystalline rocks of the Blue Ridge and Piedmont and the thickness of clastic deposits in the Appalachian basin.

According to Bryant and Reed (1970) the earliest frequency peak of mineral age determinations in the Blue Ridge is in the Early Silurian at about 430 m.y. Just prior to the thermal event that these dates record, a thick wedge of clastic rocks was deposited unconformably on the Cambrian and Ordovician carbonate sequence in the Valley and Ridge of Tennessee and adjacent Georgia and Virginia. This detritus indicates uplift of the Blue Ridge to the southeast. It has been suggested (Bryant and Reed, 1970) that perhaps uplift and erosion of the Blue Ridge crystalline rocks during the Middle Ordovician resulted in the cooling which is recorded by the radiometric age dates in the Silurian.

According to Hatcher (1972) the Early Paleozoic deformation of the southern Blue Ridge resulted in isoclinal recumbent folding in northeast Georgia and adjacent North and South Carolina, and more open folds in the eastern Blue Ridge of western Georgia. The Murphy syncline and the anticlinal core of the Blue Ridge, which extends from Virginia to Georgia were also formed at this time.

Sedimentation within the continental interior during the Middle and Late Ordovician was greatly influenced by the uplift of the Appalachian eugeosyncline during the Taconic orogeny. Arch and basin development continued during this time, with more numerous basins and intervening positive areas (Sloss and Nobles, 1972). The axes of the arches and centers of the basins shifted through time, but the arches were rarely above sea level. Figure 28 illustrates the Sauk sequence, the base of the Tippecanoe sequence, and the gross relationships of the interregional unconformity between the two sequences.

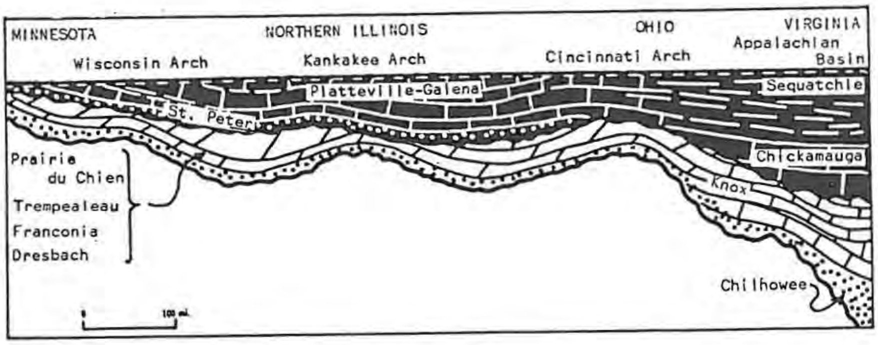


Figure 28 Diagrammatic cross section of the Sauk sequence (white) and the lower part of the Tippecanoe sequence (black). From Sloss (1963).

Clark and Stearn (1960) described the sea that represented the maximum onlap of the Tippecanoe sequence as, "The greatest epeiric sea of all time." The first onlap of the Tippecanoe sequence and the initial pulse of the Taconic orogeny occurred in the Middle Devonian (Figure 20.) West of the Cincinnati arch - Nashville dome axis the base of the Tippecanoe is marked by the very persistent, pure, well-sorted St. Peter sandstone which is up to 100 m thick and covers an area of more than 1.8 million square kilometers in the north central states (King, 1977). East of the Cincinnati arch - Nashville dome axis and in the Appalachian basin Middle Ordovician carbonates rest on the sub-Tippecanoe surface without significant development of a basal clastic zone (Sloss, 1963). A later orogenic pulse occurred in Late Ordovician time. At this time the Taconic Highlands were emerging and shedding a clastic wedge westward (Johnson, 1971). This is the time of the greatest extent of the vast Ordovician sea and the Tippecanoe sequence (Fig. 29). Limestones and dolomites dominate over much of the cratonic area characterized by numerous algal-coral-reef trends at the margins of interior basins, indicating clear, shallow seas. After the termination of the Taconic orogeny in Early Silurian time, the marine seas in which the Tippecanoe was deposited were regressing from the craton (Fig. 20). Maximum regression did not occur, however until earliest Devonian time.

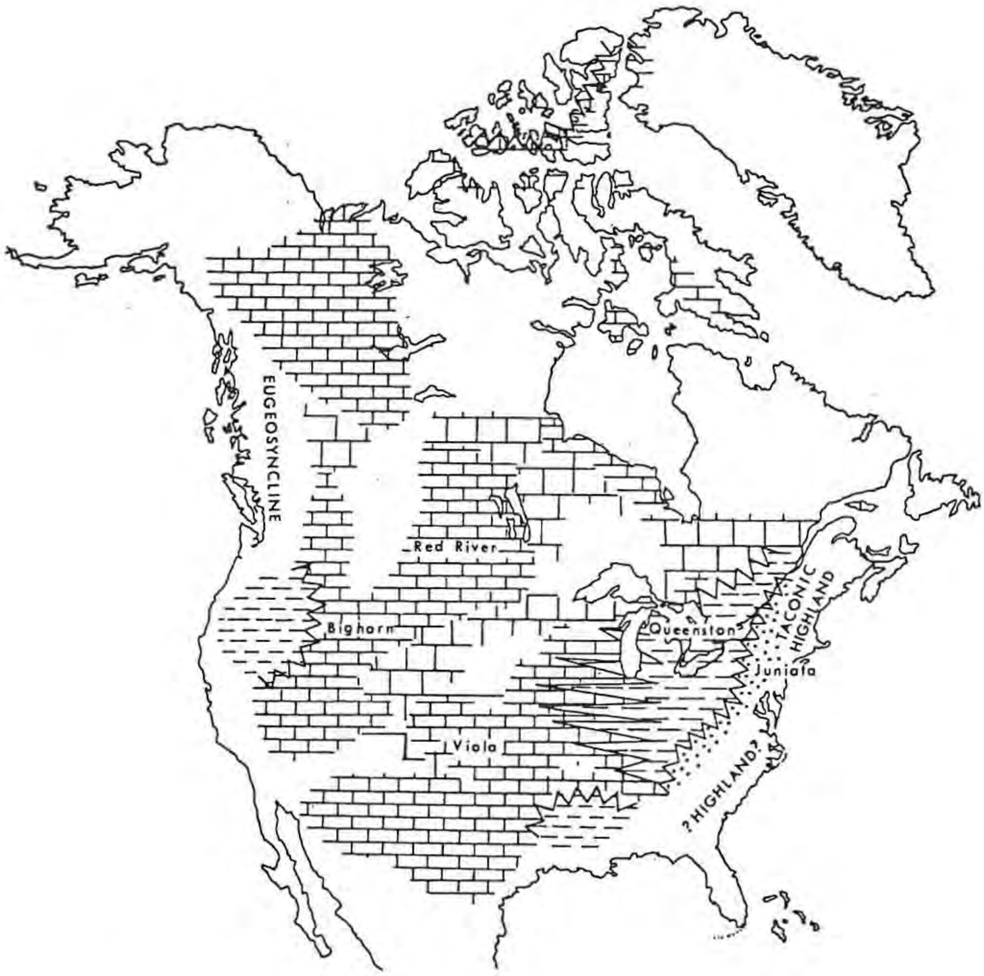


Figure 29 Distribution of upper Ordovician rocks in North America. This is the greatest extent of Tippecanoe Sequence. Clastic wedge and delta sediments of the Juniata and Queenston record a major phase of the Taconic orogeny. Fine and coarse block symbols indicate known and probable areas, respectively, of marine carbonates; horizontal lines indicate marine shale and siltstone; dots indicate nonmarine clastics. From Johnson (1971).

According to Ham and Wilson (1967), exposures in the Ouachita Mountains display no compelling evidence for widespread or significant unconformities throughout the Early and Middle Paleozoic. The Ordovician sediments are black graptolite bearing shale and chert that accumulated in a starved basin of considerable depth (Thomas, 1972). There are no indications of a significant tectonic sediment source; the deposition of the sediments was independent of, and generally undisturbed by, tectonic pulses on the craton. King (1975) cites evidence indicating that during

Ordovician time, at least, the cratonic border of the Ouachita belt was probably a steep shelf break, which was a source of exotic bouldery debris in the geosynclinal deposits. Minor clastic wedges in Ordovician and Silurian strata were formed from sediments derived from uplifts seaward in the geosyncline, but these are not comparable in thickness to Late Paleozoic trough-filling sediments. Most of the depositional and tectonic activity in the building of the Ouachita system belongs to what King identifies as the late geosynclinal phase; the orogenic phase does not get well underway until Middle Mississippian.

Devonian (Acadian Orogeny)

Evidence for the Devonian Acadian orogeny is almost universal in the northern Appalachians but is less conclusive father southward. Figure 30 is an isopach map of the Devonian clastic sequence in the Appalachian miogeosyncline. In the Devonian, as in the Ordovician, a great clastic wedge (Catskill delta) pushed westward and northward out of New England and the Maritime region. Relatively coarse grained sedimentary rocks, including some red beds deposited in a subaerial environment, predominate in the northeastern portion of the basin where the sequence attains a thickness of over 3050 m. Medium-grained gray rocks deposited in a marine environment predominate where the sequence is of intermediate thickness, and fine-grained black shale and calcareous gray shales predominate in the southwest portion of the basin where the sequence is thinnest (Colton, 1970).

The sediments generally become younger westward and southward (Rodgers, 1967). Coarse sediments pushed down the Appalachian trough as far east as Tennessee and continental redbeds reached west-central Virgina, but their distribution suggests that they came entirely from the northeast and that the southernmost sediment-carrying river debouched in Pennsylvania. In contrast with the Ordovician there was no local source of sediments in the Carolinas. The accumulation of black muds over large areas in the late Middle Devonian, forming the Chattanooga and related shales, must have been in response to the initiation of a long continued orogenic event. These clastic deposits probably record uplifts related to the Acadian orogenic movements, though not necessarily contemporaneous. The clastics that record the Acadian orogeny extended into the Mississippian, but mainly in a waning phase.

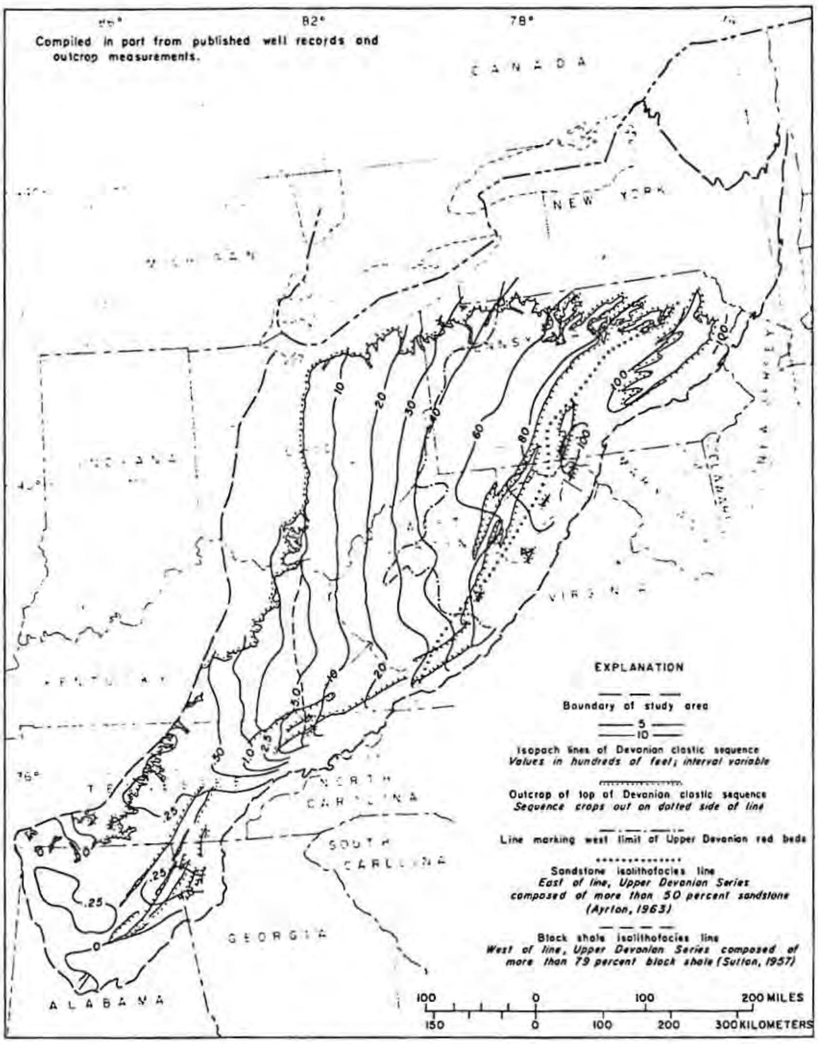


Figure 30 Isopach map of Devonian clastic sequence. From Colton (1970).

In the northern Appalachians, radiometric ages dating the Acadian orogeny in the 360 to 400 m.y. range are widespread. Some of these granitic bodies are clearly overlapped by Upper Devonian or Mississippian strata (Faul et al., 1963). Age dating in Maine and vicinity strongly suggests that two pulses of plutonism and metamorphism occurred during the Devonian, perhaps centered in different belts. Spooner and Fairburn (1970) regard the earlier of the two episodes as the least pervasive.

Age dating in the southern Appalachians gives comparable numbers, but the broad regional spread of ages suggests that most of the post-Ordovician numbers record only uplift and cooling, not plutonism and orogeny (Rodgers, 1967). According to Bryant and Reed (1970) there is a clustering of radiometric age dates from the crystalline rocks of the southern Appalachians ranging between 380 and 320 m.y., with a frequency peak at about 350 m.y. Uplift and erosion of the Blue Ridge and Piedmont during this period are indicated by a wedge of Upper Devonian and Lower Mississippian rocks in the miogeosyncline which rests on a regional unconformity that bevels beds ranging in age from Early Devonian in northeastern Tennessee to as old as Early Ordovicain in Georgia and Alabama.

The dearth of radiometric mineral ages younger than 350 m.y. in the southern Blue Ridge indicates that the climax of regional metamorphism occurred prior to Early Mississippian. But, as Bryant and Reed (1970) point out, it is not clear whether there were two main episodes of metamorphism, one prior to cooling in Early Silurian time (Taconic orogeny) and a second prior to cooling in Early Mississippian time (Acadian orogeny), or whether metamorphism continued intermittantly over a long interval, punctuated by two periods of uplift, erosion, and cooling.

Tull and Stow (1982) have recently proposed that volcanism was initiated during Early and Middle Devonian time along the continental margin of what is now Alabama and Georgia. This volcanism gave rise to the tholeiitic basaltic pyroclastic lavas and associated massive sulfide deposits of the Hillabee greenstone, which occurs at the stratigraphic and structural top of the Talladega slate belt nappe (Fig. 5). The Hillabee greenstone appears to be the distal continentward portion of a volcanic arc system which developed during the middle Paleozoic in the southernmost Appalachians. Strata-bound massive sulfide deposits are common very near the base of the volcanic sequence. The deposits appear to be of the distal zinc-copper-pyrite type.

During the time interval between the withdrawl of the Tippecanoe Sea and the transgression of the Kaskaskia Sea the rising arches of the craton were eroded and the tilted edges of the sedimentary layers were truncated on the margins of the basins (Fig. 31).

The first Kaskaskia beds to be deposited were of late Early Ordovician age. These basal beds are clean quartz sandstone, similar to the basal Sauk and Tippecanoe sandstones, except not as widespread; in

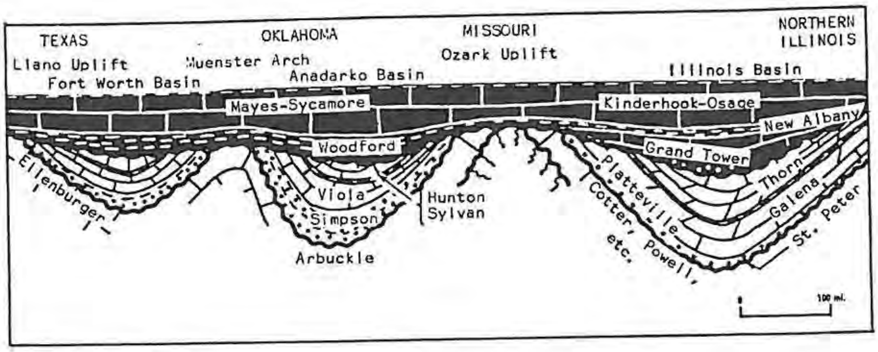


Figure 31 Diagrammatic cross section of the Sauk and Tippecanoe sequences (white) and the basal part of the Kaskaskia sequence (black). Sequence boundaries are indicated by heavy wavy lines. From Sloss (1963).

other areas the basal beds are limestone. Where these beds rest on older carbonate rocks the unconformity is difficult or impossible to recognise in any single exposure or well. The largest of the sandstone bodies at the base of the Kaskaskia sequence are the Oriskany sandstone of New York and Pennsylvania, and the Ridgley sandstone further south. These basal sandstone units are an important source of glass sand and reservoir of many gas fields (Stearn et al., 1979).

Limestones and dolomites are the dominant constitutents of the Kaskaskia sequence in the midcontinent region, suggesting the re-establishment of clear, shallow seas. Thick shale and chert sequences are found in marginal basins to the south and west, and coral reefs and evaporites occur in the Michigan basin. All sediments, except those in the adjoining Appalachian basin are clean and well sorted, and lack unstable minerals (Sloss and Nobles, 1972).

Initial Kaskaskia strata (late Early and Middle Devonian) are limited to basins and flanks of basins, while Late Devonian and Early Mississippian strata are more widespread over basins and intervening shelf areas. The climax of transgression appears to have been in early Middle Mississippian time when the maximum overlap of the Transcontinental arch and other positive features seems to have occurred (Sloss, 1963). Late Mississippian strata are limited by pre-Absaroka erosion to marginal basins and larger interior basins. These are predominantly sandstones (in part non-marine) which indicate withdrawal of widespread seas toward the close of deposition of the sequence. The distribution and character of these sandstones suggest a source in the interior of the craton, including the Canadian Shield (Sloss and Nobles, 1972), and from locally active uplifts within extracratonic orogens such as the northern Appalachian trend (Potter and Pryor, 1961).

Sloss (1963) stresses the continuity of transgression from late Early Devonian through Middle Mississippian time, but he states that the Kaskaskia sequence appears to represent a double tectonic and depositional cycle with Devonian and Mississipian phases. It seems that the subsiding tendencies of a number of cratonic basins (e.g. the Williston and Michigan basins) reached an early climax in the Middle Devonian, as is evidenced by common thick evaporites. In later Devonian time there was lesser differentiation between basins and shelves, followed by widespread tectonic stability which culminated near the Devonian-Mississippian boundary, as indicated by the widespread but thin dark shales of the Chattanooga Shale and its equivalents. Sloss (1963) notes that the cratonic stabilization which closed the Devonian phase of the Kaskaskia deposition was not accompanied by general regression and erosion. Instead, transgression continued, accompanied in Middle Mississippian time by renewed subsidence in the basins and a return to the deposition of thick evaporite successions.

Mississippian through Permian (Alleghanian Orogeny)

As mentioned in an earlier section, the sedimentary rocks of the Valley and Ridge province in the southern Appalachians seem to be entirely conformable and to have been deformed together. The youngest rocks involved in Late Paleozoic (Alleghanian) deformation are Late Pennsylvanian in the anthracite coal fields of eastern Pennsylvania, and presumably lower Permian in the bituminous coal fields of western Pennsylvania, western Maryland, and northern West Virginia. From southern West Virginia southwestward, no rocks younger than Middle Pennsylvanian are preserved. The next younger rocks preserved anywhere in the Appalachians are the Upper Triassic rocks of the Newark group found in a series of fault troughs within the crystalline Appalachians from the Nova Scotia southward to the Carolinas (Rodgers, 1967).

A clastic wedge recording the initial pulse of the Alleghanian orogeny makes its appearance in early Late Mississippian time, first in central Alabama, at the southern end of the presently visible Appalachians. According to Rodgers (1967), these clastics indicate a southern source which persisted at least into the Pennsylvanian. Because these strata are similar to a contemporaneous clastic wedge in the Ouachita Mountains, they probably reflect the beginning of the uplift and orogenic movement that swept from south to north during the Carboniferous (Ham and Wilson, 1967). Rodgers (1967) states, "By late Mississippian time, ... (late Chester or earliest Namurian), clastics were appearing all along the chain (for example, Pennington and Mauch Chunck formations), probably from a southeastern or eastern source, and by the beginning of the Pennsylvanian (Pottsville formation, mid-Namurian), clastic deposition was general and moderately coarse over the whole Appalachian region and far west onto the platform of the continent. With some fluctuations it continued as long as the record indicates, producing the typical Coal Measures of the Appalachian and central interior coal fields."

Structures in the southeastern part of the sedimentary Appalachians probably began to form earlier than those in the northwestern part. In the northern portion of the southern Appalachians, in the Valley and Ridge and Appalachian Plateau provinces, much of the movement must have been post-Carboniferous or post-Lower Permian, but in the southern Appalachians the climax need only have been later than mid-Pennsylvanian, and the stratigraphic history suggests that movement began well before the end of the Mississippian. Be that as it may, many of the superposed structures evident in the Valley and Ridge province did not develop during any single deformational event, but during a considerable span of time. For example, thrust sheets that have been emplaced, then folded, then off-set by transverse faults may have required as long as a geological period or two to develop (King, 1977).

Fullagar and Butler (1979) have found at least twenty 325-265 m.y. old granitic plutons in the central and eastern Piedmont of the southern Appalachians that give the first good evidence for Alleghanian deformation and metamorphism in the southern Appalachian Piedmont. All the late Paleozoic plutons are normal calc-alkaline granites. Strontium isotope ratios suggest that the granitic magmas were derived from the lower crust. Granitic plutons of these ages are uncommon in the northern

Appalachians and in the northern portion of the southern Appalachians.

Major displacement of the Blue Ridge thrust sheet has been shown to have occurred in the Late Paleozoic. In a study in the Great Smoky Mountains, Carpenter (1970) has concluded that the relationships of metamorphic isograds at the Grandfather Mountain Window, and other windows in the western Blue Ridge, indicate that the major period of movement occurred after mid-Paleozoic metamorphism, probably during the Alleghanian orogeny near the end of the Paleozoic. A minimum horizontal displacement of 70 km has been postulated for the Blue Ridge (Hatcher, 1978b).

There is an obvious correspondence in time between the Alleghanean orogeny and the Absaroka Sequence (Fig. 20); onlap - offlap cycles of the Absaroka sequence begins in latest Mississippian to earliest Pennsylvanian time and extends, according to Johnson (1971), into the Early Triassic. As Figure 32 suggests, the unconformity at the base of the Absaroka sequence involves the most complex paleogeographic patterns of any of the interregional unconformities in the North American cratonic succession.

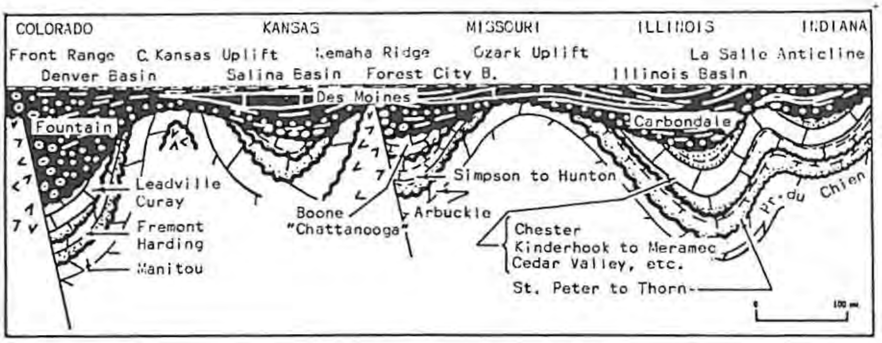


Figure 32 Diagrammatic cross section showing relationships of lower part of Absaroka Sequence (black) to older units (white). Sequence boundaries are shown by heavy wavy lines. From Sloss (1963).

The Absaroka sequence is a sedimentary regime much different from the platform regimes of the early and middle Paleozoic, which were dominated by carbonates and evaporites. This sequence marks the first time carbonate deposition ceased to dominate the platform east of Texas; this is also the first time that sediment thicknesses in the western

Appalachians were not significantly greater than on the platform. According to Sloss and Nobles (1972), this complete change in distribution pattern and nature of dominant rock types indicates a radical shift in the behavior of the craton as compared to earlier sequences. Sloss (1963) attributes this change to two major factors. One is the disappearance of the Transcontinental arch as a controlling element in distribution, thickness, and facies of preserved sediment. Secondly, abrupt uplift and erosion of many positive elements within the midcontinent, and rejuvenation within the Canadian Shield, provided large volumes of clastic detritus to areas which have previously been the sites of relatively pure carbonate deposition. In addition, sands and shales derived from extracratonic sources in the Ouachita and Appalachian trends are evident among the Pennsylvanian sedimentary rocks.

In latest Mississippian time, clastics had replaced limestones throughout the Valley and Ridge province and into the Appalachian Plateau. In Pennsylvanian time clastics had spread westward across the continent as far as Kansas above a widespread erosion surface, the whole area becoming a vast plain where "coal swamps and river flood plains alternated rhythmically with shallow seas" (Rodgers, 1970). Such cyclical repetitions have produced important coal bearing cyclothems. In Illinois fifty coal seams have been found in the Pennsylvanian system, and in Pennsylvania, more than one hundred. Many of the coal seams are less than a meter thick and are, therefore, uneconomical; however, many are remarkably persistent and some of the coal beds may be traced for hundreds of kilometers (Stearn et al., 1979).

In the Ouachita Mountains the Arkansas Novaculite is overlain by the thickest sequence of Middle Mississippian-Early Pennsylvanian turbidites known in North America. The total maximum formational thickness over the region is nearly 13 000 m, consisting of proximal and distal turbidite sandstones, black shales, and minor interbedded wildflysch and volcanic ash. These formations were deposited in a rapidly subsiding trough as is plainly shown by their abrupt northwestward and northward thinning across the Arkoma basin and onto the south flank of the Ozark Uplift. The flysch succeeds the novaculite conformably, although possibly with a small haitus, and marks a drastic change in the sedimentary and tectonic regime of the geosyncline -- from slow siliceous sedimentation in a leptogeosyncline to tectonic mobility and deep subsidence of troughs in an orogenic belt where clastic debris accumulated rapidly (King, 1975).

Infilling of the trough was accompanied by 3 phases of pre-orogenic uplift that contributed a virtually constant flood of clastics to the trough. The first is represented by deposition of conglomerates above the Arkansas Novaculite and below the Stanley Shale (Table I). These

System		Series	Stratagraphic Unit
Permian	Lower	Wolfcampian	Absent
Pennsylvanian	Upper	Virgilian Missourian Desmoinesian	Hartshorne Sandstone and higher formations in Arkoma Basin
	Middle	Atokan	Atoka Formation
	Lower	Morrowan	Johns Valley Shale,* Wapanucka Limestone, and related units
			Jackfork Sandstone (or Group)
Mississippian	Upper	Chesterian Meramecian	Stanley Shale (or Group)
	Lower	Osageian	Hiatus?
		Kinderhookian	Arkansas Novaculite
Devonian	Upper	Conewangoan	

* Occurrence of exotic bouldery debris.

Table I Carboniferous strata in Ouachita Mountains. Modified from King (1975).

conglomerates are restricted to the eastern portion of the Ouachita province, but nevertheless record the beginning of geosynclinal sedimentation. The second and most powerful episode is recorded by boulder-beds or wildflysch, which interrupt the usual deposition of the finer grained, evenly bedded flysch in the Johns Valley Shale. The wildflysch consists mostly of limestone clasts of all sizes (some are up to 100 m across), which lie helter-skelter in a muddy matrix (King, 1975). The boulders and slabs are mostly Cambrian to Devonian in age, and may have been derived from scarps of growth faults at the continental margin. Ham and Wilson (1967) conclude that 2400 to 3000 m of uplift and erosion were required to expose the oldest rocks that occur as boulders in the shale. Finally, the occurrence of coarse chert conglomerates in the Atoka Formation indicates intrabasinal uplift near the close of the geosynclinal stage, in advance of the principal orogenic stage.

The major structural features of the Ouachita Mountains were formed during the orogenic stage. Deformation occurred in several pulses, beginning in Middle Pennsylvanian and continuing through Late Pennsylvanian. The most powerful pulse occurred during Desmoinesian time, elevating the source area to provide abundant chert clasts for Upper Desmoinesian conglomerates in the Ardmore basin (Ham and Wilson, 1967). King (1975) suggests that most of the complex structures of the belt formed during the mid-Pennsylvanian pulsations. Uplift was accompanied by folding and thrusting; total northwestward thrusting toward the craton is thought to be on the order of 80 km (Ham and Wilson, 1967). A culminating pulse of Late Virgilian age is thought to have been chiefly an episode of late orogenic thrusting.

PLATE TECTONIC MODELS

The concept of plate tectonics provides a unifying model for the generation of mountain belts. Models have been proposed by several authors for the tectonic evolution of the southern Appalachians; however these models are essentially variations on a theme and differ in regard to things such as timing of events and direction of subduction. The model proposed by Hatcher (1972), which consists of 4 phases and involves the collision of African continent with the North American continent, will be briefly presented to give the reader a feel for the events that lead to the formation of the Appalachians. A hypothesis by Sloss and Speed (1974), which considers the relationship between the tectonic history of the craton and the more vigorous history of deformation and orogeny at the continental margin, will also be given brief coverage.

According to Hatcher's (1972) model, Phase 1 of the post-Grenville geological history of southeastern North America probably involved erosion of the previously formed Grenville Mountains and deposition of the erosional products in several interconnected basins along the continental margin (Fig. 33). Further seaward (east) there was sea-floor volcanic activity and probably the incipient development of an island-arc-trench-subduction zone system as is evidenced by mafic volcanic rocks in the Late Precambrian units in the Blue Ridge and Piedmont. As the westward clastic source diminished, the character of these sediments changed from poorly sorted graywackes, siltstones, shales, and conglomerates of the Ocoee series, to cleaner and better sorted sediments of the Chilhowee group.

The westward clastic source ceased briefly during the Early Cambrian. The Shady dolomite was deposited during this interval. Shortly thereafter, however, the clastic sources reappeared and supplied fine clastics throughout most of the remainder of the Cambrian. Dissappearance of this source is marked by deposition of the Upper Cambrian-Lower Ordovican Knox group of the Valley and Ridge. Phase 1 is terminated by the development of the pre-Middle Ordovician erosion surface and the paleokarst topography on top of the Knox.

Phase 2 of Hatcher's (1972) model involves the appearance of clastics of eastern provenance in the Valley and Ridge during the Ordovician. The

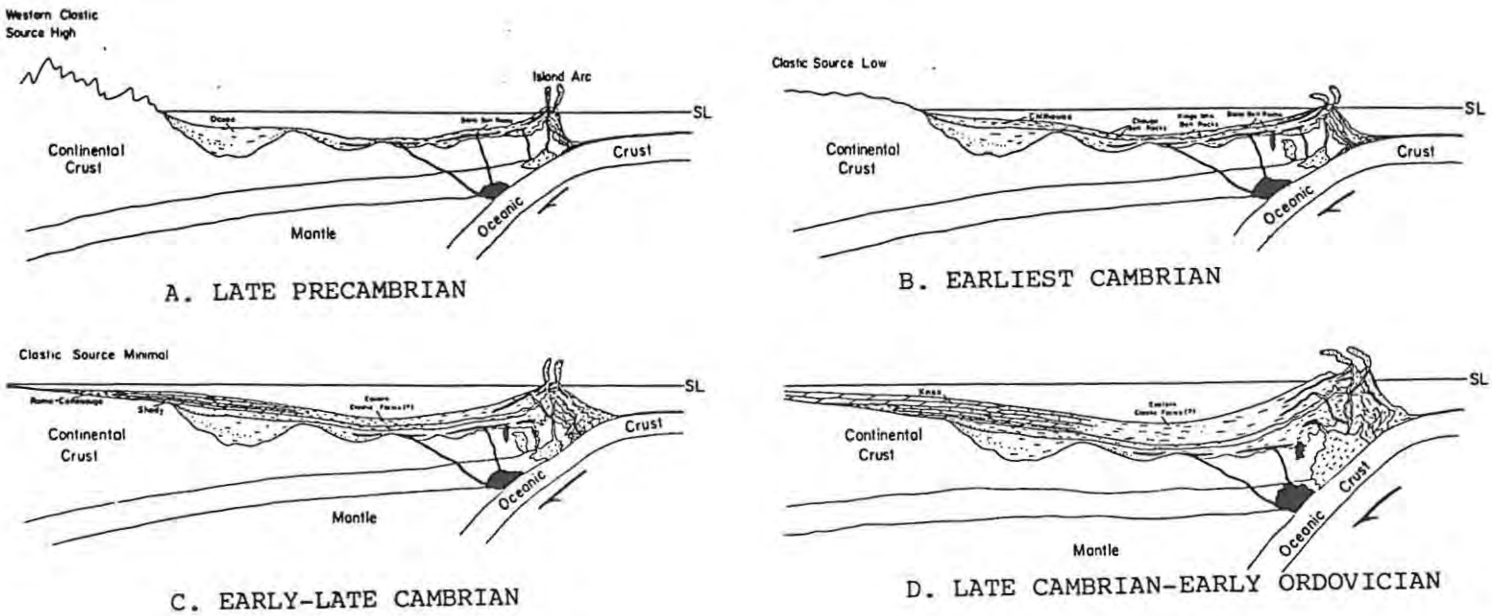
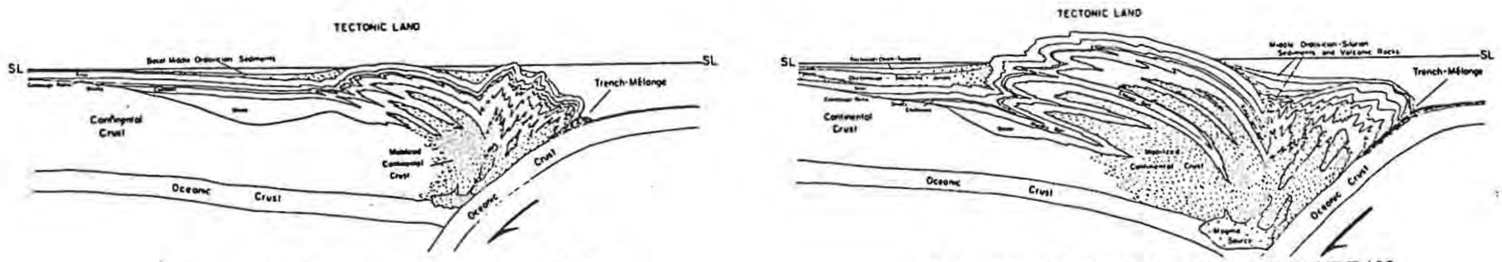


Figure 33 Phase 1, Late Precambrian through Early Ordovician continental margin sedimentation and volcanic activity. An initially high source (Grenville Mountains) provided coarse sediments from the west. This source gradually diminished and supplied successively finer sediments until it became nonexistent during the Late Cambrian and Early Ordovician when carbonate sedimentation became dominant in the western part of the southern Appalachians. The island arc-trench system came into existence during the Late Precambrian and began to contribute sediments and volcanic material to the eastern part of the depositional area. During the Early Ordovician, the large tectonic land that was to serve as the provenance area for sediments began to emerge. Pre-metamorphic intrusive bodies of both felsic (patterned) and mafic (dark) compositions were emplaced. From Hatcher (1972).

Middle Ordovician was the time of regional metamorphism in the east, and mobilization and isoclinal folding in the Blue Ridge and Piedmont occurred at this time (Fig. 34). Discordant plutons ranging from felsic to mafic compositions were also emplaced at this time. A decline in regional metamorphism and compressional stresses and a surge of intrusive activity mark the close of Phase 2.

Phase 3 is characterized by large-scale compression, low grade metamorphism, and possibly some intrusive activity carried over from Phase 2. The Brevard fault zone and other major faults are features that developed during this phase. Hatcher (1972) proposes that these structures were generated during the initial stages of collision of



A. EARLY-MIDDLE ORDOVICIAN

B. MIDDLE ORDOVICIAN-SILURIAN

Figure 34 Phase 2, Late Precambrian through Middle Devonian westward underflow of oceanic crust resulting in deformation and mobilization of continental crust and the adjacent rocks, metamorphism, and syntectonic intrusive activity. The uplift of a tectonic land over the zone of maximum mobilization and thermal activity provided a provenance area for syntectonic sediments. From Hatcher (1972).

southeastern North America with Africa (Fig. 35). Movement closing the two continents was probably not continuous but sporadic. The culmination of the collision and deformational maximum produced the great continentward - directed overthrusts of the Blue Ridge and the folds and faults of the Valley and Ridge. This compressional event is thought to be the final collision of southeastern North America with Africa and the closing of the Iapetus Ocean. At this point in geologic time, the proto-continents of North America, Europe, and Africa were sutured.

Phase 4 involves tension replacing compression in the stress field of the lithosphere. From the initiation of decoupling until the present time, the continents have moved to assume their present positions.

Sloss and Speed (1974) have proposed a hypothesis to account for the relationship between orogenic episodes on the continental margin and coincident submergence in the cratonic interior, as is illustrated in Figure 20. According to their hypothesis (Sloss and Speed, 1974), "Cratonic emergence ... is caused by retention of melt in continental asthenospheres. Retention would deprive oceanic convection systems of the discharge produced by the subcontinental heat flux and, according to ... [the] assumption that the spreading rate is proportional to discharge, there would be a minimum rate during emergent episodes. Conversely, the intitiation of cratonic submergence is thought to result

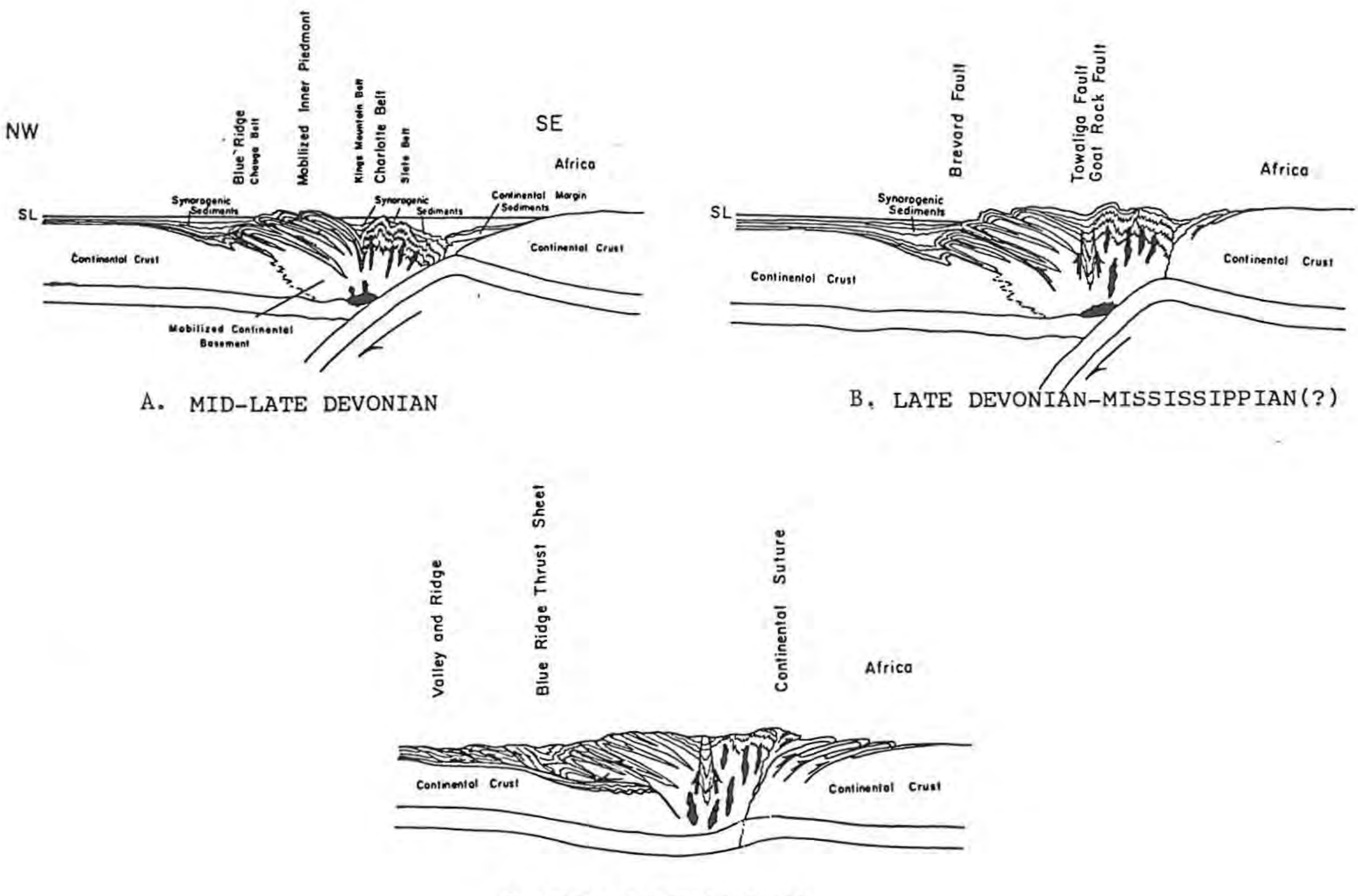


Figure 35 Phase 3, Late Devonian to Permian deformation and related events. A. End of Phase 2 or beginning of Phase 3. Initial contact between continents, intrusive activity and sedimentation continue to occur. B. Underflow of oceanic crust continues and produces collision of the two continents. Notable readjustments in southeastern North America include the formation and initial movement of the Brevard zone, Towaliga (Gold Hill), the Goat Rock faults. Intrusive activity and sedimentation continue. C. Maximum effects of collision result in stresses being transmitted laterally through the Piedmont rocks and relieved by folding and thrusting to the west. Blue Ridge and Valley and Ridge faults and folds are formed and there is renewed movement on the major faults in the Piedmont. Africa and North America become sutured, and the subduction zone along the continental margin ceases to operate. From Hatcher (1972).

from the expulsion of subcontinental melt, chiefly into suboceanic convection systems, thus increasing the volume extruded at midoceanic ridges and raising the rate of sea-floor spreading. The maximum in the outflux of subcontinental melt would be at the incidence of deflation, the time of maximum asthenospheric permeability, and maximum spreading rates would be achieved early in a submergent episode." Thus, the history of continental margins can be interpreted to indicate variations in spreading rates during cratonic submergence, and orogenic episodes would be a consequence of increased spreading at mid-ocean ridges during cratonic submergence.

METALLOGENY

Mineral deposits of widely differing types, and the geological settings in which they occur, are products of particular broad tectonic environments. These environments controlled the nature and composition of igneous rocks associated with deposits, the morphology of their depositional sites, the nature and composition of associated sedimentary rocks, and also governed the compositions of the metallic ores themselves.

Most types of ore deposits in the eastern US are restricted to certain time intervals, reflecting the limited periods of existence of favorable tectonic regimes. The later half of the Paleozoic is notably lacking in ore deposits and a literature search revealed no major deposits occurring in rocks of Pennsylvanian and Permian age.

Precambrian Magmatic Deposits of the Continental Interior

The Precambrian volcanic rocks of the St. Francois Mountains of southeast Missouri contain several major and about 30 minor magnetite deposits, and one major magnetite-chalcopyrite deposit, in an area approximately 110 km long and 60 km wide. Many of the deposits are overlain by up to 500 m of Lower Paleozoic sediments and were discovered by exploration drilling of large magnetic anomalies revealed by airborne surveys (Snyder, 1968). Others crop out on surface and have been known and mined intermittently for many years. Figure 36 and Table II illustrate the location of the district and Figure 37 shows the location of major deposits within the district.

The volcanics appear to be centrally located in a zone of rhyolite and epizonal granite that underwent intense igneous activity in the interval 1200-1500 m.y. ago (Fig. 18). Van Schmus and Bickford (1981) relate this belt of rhyolite volcanism and associated granitic magmatism to plate tectonic processes that operated in Precambrian time. The position of the granite-rhyolite terrane as a more or less arcuate belt lying across the southeastern and south central parts of the continent, and the presence of older rocks to the north and west and younger ones to the south and east suggests that the terrane formed on or near the margin of an older continental mass. Van Schmus and Bickford (1981) propose a speculative model involving a convergent plate boundary on the eastern

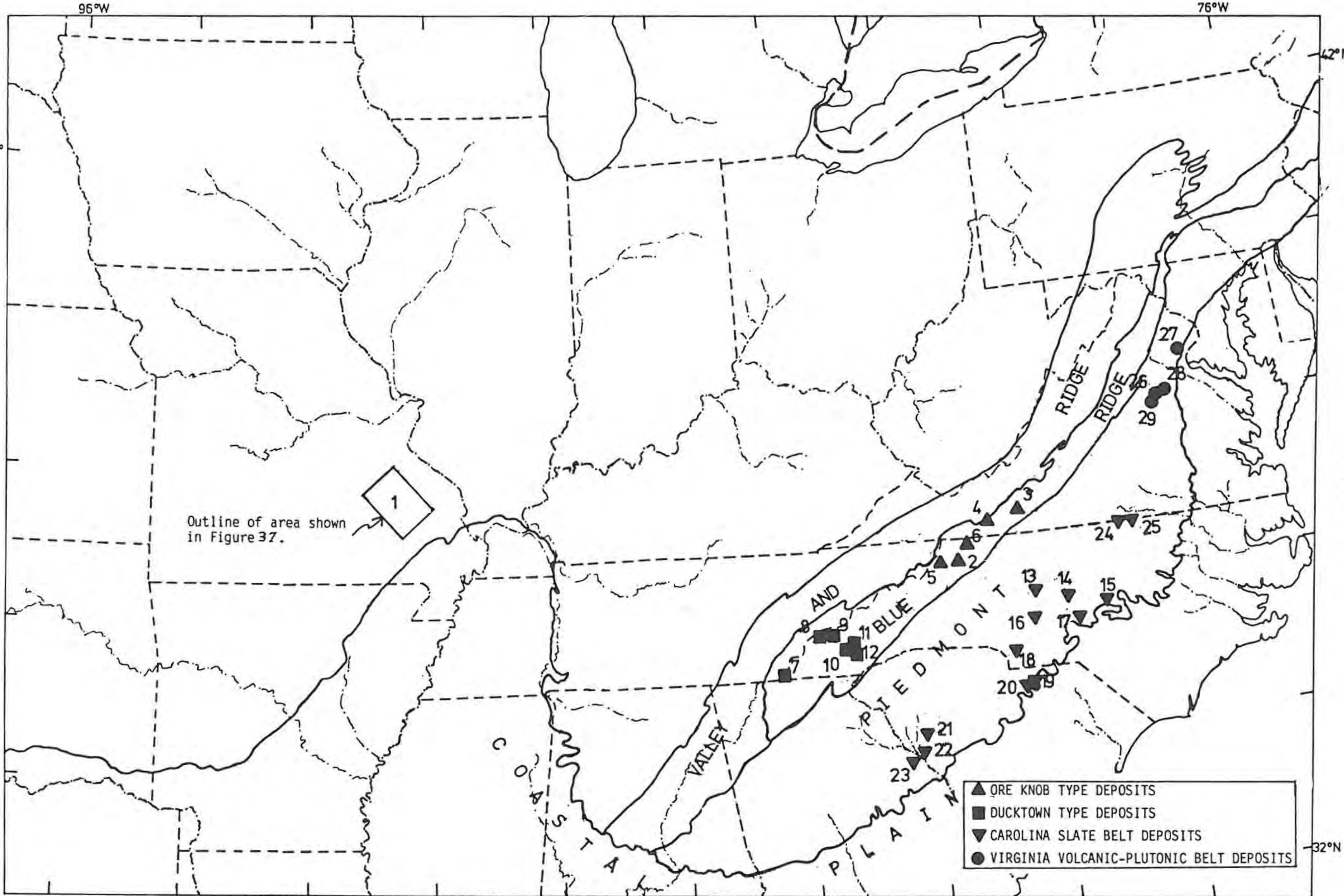


Figure 36. Precambrian-Lower Cambrian ore deposits of the Mississippi Valley and southern Appalachians. Compiled from various sources.

TABLE II

PRECAMBRIAN - CAMBRIAN ORE DEPOSITS

Deposit or district name	Host Rocks	Mineralogy*
	SOUTHEAST MISSOURI	
1. St. Francois	rhyolite flows	mg, he
	ORE KNOB TYPE	
2. Ore Knob	Ashe fm.	po, py, cy
3. Toncrae	Lynchburg fm.	po, mg, cp, py
4. Great Gossan Lead	Ashe fm.	po, sl, gn
5. Elk Knob	Ashe fm.	po, py, cp
6. Peachbottom	Ashe fm.	cp, py, bn, sl, bar
	DUCKTOWN TYPE	
7. Ducktown	Great Smoky gp.	po, py, cp, sl, mg
8. Fontana	Great Smoky gp.	po, cp, sl, (py, gn, mg)
9. Hazel Creek	Great Smoky gp.	po, cp, sl
10. Savannah	Greak Smoky gp.	py, po, sl, cp
11. Wayhatta	Greak Smoky gp.	py, po, sl, cp, gn
12. Cullowhee	Great Smoky gp.	po, cp, py, sl, mg
	CAROLINA SLATE BELT	
13. Cid/Silver Hill	Albemarle gp.	sl, gn, py, cp
14. Asheboro	Uwharrie fm.	py, cp, sl
15. Clegg	Efland fm.	py, cp
16. Gold Hill	Albemarle gp.	py, cp, gn, sl
17 Iola	Uwharrie fm and Albemarle gp.	py, cp
18. Howie	Uwharrie fm.	py, po, cp, gn
19. Brewer	volc. breccia and tuffs	py, en, bis, topaz
20. Haile	metafelsite	py
21. Dorn	sericite schist	gn, sl, cp
22. McCormic	Little River series	py, gn, sl, cp
23. Lincolnton	Little River series	py, gn, sl, cp
24. Virgilina	Virgilina greenstones	bn, cc
25. Hamme	Vance County pluton	wolframite
	VIRGINIA PLUTONIC-VOLCANIC BELT	
26. Allah Cooper/Cofer	Chopawamsic fm.	sl, gn, cp, py, po
27. Cabin Branch/Austin Run	Chopawamsic fm.	py
28. Valzinco	Chopawamsic fm.	sl, gn, cp, py, po
29. Mineral	Chopawamsic fm.	py, sl, cp, gn, po

*Mineralogy

bar = barite	bis = bismuthinite	bn = bornite	cp = chalcopyrite
cc = chalcocite	en = enstatite	gn = galena	he = hematite
mg = magnetite	po = pyrrhotite	py = pyrite	sl = sphalerite

References : Feiss and Hauck (1980); Foose et al.,(1980); Pavlides et al. (1982).

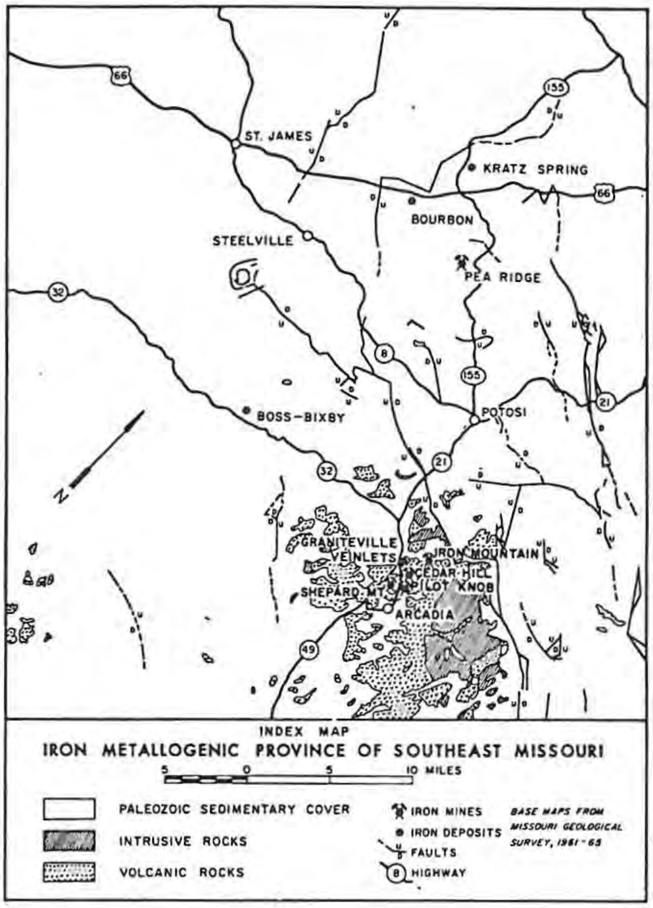


Figure 37 Iron metallogenic province of southeast Missouri. From Kisvaranyi and Proctor (1967).

and southern edges of the continent, beginning about 1500 m.y. ago with a northwestward-dipping subduction zone, which could account for the arcuate pattern of the volcanic and shallow granitic intrusives. However, there are almost no rocks of mafic or intermediate composition and compressional deformation and metamorphism are absent. Therefore, if these rocks were deformed by a continent-marginal process it was clearly one that was different from modern convergent plate boundaries.

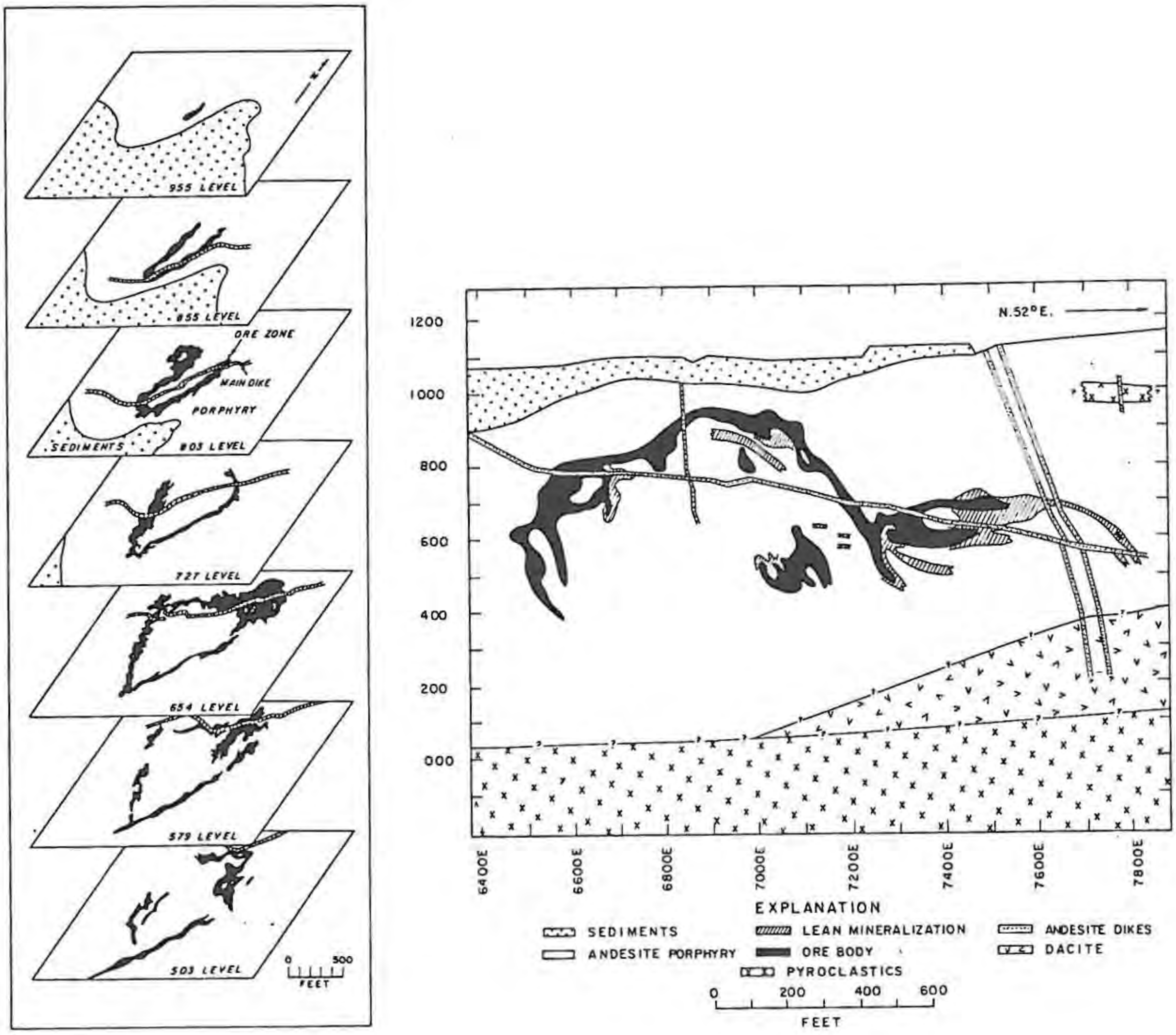
The Precambrian igneous complex consists of two series of felsite separated by a tuff bed, which have undergone two stages of granitic intrusion. Numerous Precambrian dikes of intermediate and low silica composition cut the individual iron ore deposits and the host rocks throughout the iron province (Snyder, 1968; Kisvarsanya and Proctor, 1967).

Host rocks for the iron ore deposits are mainly rhyolite flows, and to a lesser extent andesites, quartz-latites, dacites, pyroclastics, and some sub-volcanic masses. One small deposit (Greasy Mine) occurs in granite. The Boss-Bixby iron-copper deposit occurs in a syenitic intrusive stock and in overlying altered rhyolite. The host rocks are generally unaltered, however, except for local intensive garnetization, epidotization, silicification, and amphibole skarn formation (Kisvarsanyi and Proctor, 1967).

Ore emplacement is locally controlled by the lithology and structure of the host rocks. Volcanic flows, igneous contacts, tuffaceous beds, and volcanic agglomerates acted as loci of deposition. The bulk of the iron deposits were emplaced as massive fillings in fractures. Emplacement of some of the orebodies may have been controlled by contemporaneous faults, such as at Shepard Mountain and possibly Pea Ridge. The controls on emplacement of some of the orebodies is somewhat more speculative. For example, both orebodies at the Iron Mountain mine are characterized by unusual curvilinear forms (Figure 38) that have called forth a variety of explanations from geologists who have studied the mine (Murphy and Ohle, 1968).

Most of the orebodies are steeply inclined and may be discordant to the host rock structures, in which case they contain blocks of brecciated host rock cemented by iron oxide, or they may be conformable with the host rock and show replacement textures. Replacement is absent or minor in the disconformable orebodies. Magnetite is the main ore mineral. Hematite predominates only in the zone of weathering and martite occurs locally. At Boss-Bixby the iron oxide mineral is mainly magnetite, but significant amounts of chalcopyrite and bornite are also present. Minor constituents of all deposits are fluorite, and sulfides. Pyrite is the most common sulfide mineral in the magnetite deposits, and galena may also occur. Gangue minerals include garnet, apatite, numerous silicates, and lesser barite and carbonates. The orebodies average from 30 to 50% iron and may contain up to 200 million tons of ore (Kisvarsanyi and Proctor, 1967).

Trace element studies by Kisvarsanyi and Proctor (1967) indicate that the Pea Ridge, Iron Mountain, and Burbon deposits are similar to magnetite "injection" deposits elsewhere in the world. Snyder (1968) suggests that differentation of the iron from the magma took place during



A B

Figure 38 Main orebody at the Iron Mountain Mine, Iron Mountain, Missouri. (A) Plan sections at various levels. (B) Cross section. From Murphy and Ohle (1968).

extrusion of the volcanics. Magmatic pressures induced block faulting and permitted escape of the iron rich fluids that filled fracture zones and cemented rhyolite breccia fragments. Murphy and Ohle (1968) conclude that brecciation and mineralization were probably very close in time, if not actually simultaneous. When the open spaces had filled the mineralizing fluids followed flow structures giving rise to conformable replacement-type bodies. This interpretation is comparable to the interpretations made by other geologists in studies of somewhat similar deposits, such as Kiruna and Grangesberg in Sweden (Emery, 1968). Iron in the small hematite deposit hosted in granite was probably derived from the same source, but was emplaced in the granite host at a later time than the orebodies in felsite host rocks. The work by Kisvarsanyi and Proctor (1967) indicates that the Boss-Bixby iron-copper deposit is a high temperature disseminated replacement deposit, suggesting a different time of origin for this deposit as well.

Deposits Associated with Precambrian Rifting Environments

The Blue Ridge and Piedmont provinces of the southern Appalachians contain a series of syngenetic massive sulfide deposits, which are or have been mined for copper, sulfur, and iron, with gold, silver, and zinc as byproducts. These polymetallic massive sulfide deposits are all volcanogenic, but occur in a variety of Upper Precambrian and Paleozoic volcanic and sedimentary rocks and originated in distinctly different environments.

Several Late-Precambrian aulacogens developed on the eastern margin of North America during Late Precambrian-Cambrian rifting (Rankin, 1976). The Mt. Rogers salient is one of these and is located at the Virginia-North Carolina-Tennessee common border. The location of the Ore Knob, Great Gossan Lead, Toncrae, Elk Knob, and Peachbottom massive sulfide bodies (Fig. 36 and Table II) is thought to be related to this rifting environment (Feiss and Hauck, 1980). These deposits, which will be referred to as the Ore Knob type, are characterized by pyrite-pyrrhotite-chalcopyrite assemblages with generally lesser amounts of sphalerite and rare galena. They are hosted in the Ashe formation and its correlatives, which are younger Precambrian sequences dominated by mafic volcanics on the southeast limb of the Blue Ridge anticlinorium. The environment is characterized by polyphase deformation.

The Ore Knob mine is one of the best known of these deposits and was intermittently worked from the Civil War days until 1961. An estimated 32 000 tons of copper were produced, as well as 9400 ounces of gold and 145 000 ounces of silver. The orebody is veinlike to lenticular and occurs as massive lenses of pyrrhotite, chalcopyrite, and less commonly of pyrite-chalcopyrite. The massive sulfide lenses are complexly interlayered with sulfide-rich quartz masses and with coarse seams of biotite with sulfides. The gently plunging ore horizion is roughly conformable with the regional foliation in the host amphibolite schists of the Ashe formation (Kinkel, 1967). The Ashe formation has been dated at 800-850 m.y., making these the oldest massive sulfide deposits in the southern Appalachians (Feiss and Hauck, 1980).

The size of these deposits is difficult to estimate due to inadequate production records. Gair and Slack (1980) estimate that the Great Gossan Lead district contained some 20 million tons of ore averaging 0.6-0.8% Cu, 0.5-1.6% Zn, and up to 0.3% Pb. The Ore Knob mine is estimated to have contained about 1.5 million tons averaging 2.2% Cu. The other Ore Knob type deposits listed in Table II are relatively small and probably contained no more than 0.5 million tons of ore (Feiss and Hauck, 1980).

Deposits of the Ducktown District, Tennessee and surrounding area form a second major class of massive sulfide deposits in the southern Appalachians (Fig. 36 and Table II). These deposits are thought to have formed in a marginal graben that was not the site of active rifting. Rifting was to the southeast (in the vicinity of the Ore Knob deposits) and there was sufficient extension to produce this deep, marginal, marine trough. All of the deposits occur on the northwest flank of the Blue Ridge anticlinorium in an Upper Precambrian clastic sedimentary sequence of terrestial origin. The Ducktown type orebodies are hosted in the Great Smoky group of the Ocoee series. These are metamorphosed conglomerates, sandstones, and pelites.

The deposits at Ducktown are the largest massive sulfide deposits in the southern Appalachians, and according to Kinkel (1968) they are among the largest of this kind in the world. These deposits have been known, explored, and mined for 120 years. Eight massive sulfide orebodies occur in highly folded and metamorphosed graywackes, graywacke conglomerates, mica schists, chlorite-garnet schist, and staurolite schists. Several authors contend that these host rocks are exclusively metasedimentary (e.g., Emmons and Laney, 1926; Kinkel, 1967; Magee, 1968), but in many places the orebodies are bounded by thin layers of chlorite rich schist, or by fine grained quartzite which could have been a chert of volcanic origin (Gair and Slack, 1980). However, volcanic rocks have not been described elsewhere in the Ocoee series and, according to Gair and Slack (1980), their presence at Ducktown suggests a local zone in the depositional basin overlying a rift in the continental crust through which lava and solutions carrying silica, sulfur, and metals were extruded.

The Ducktown deposits occur in two or possibly three stratigraphic horizions. The deposits have undergone intensive deformation and recrystallization, which has produced thickening of the lenses in fold closures. The deposits are generally tabular in shape and conform to the regional trend of the strike and dip of the bedding. The general dip of schistosity and bedding is about 45^{0} east (Kinkel, 1968). The ore bodies range in size from 250 000 tons to about 20 million tons and contained a combined total of some 80 million tons of ore at a grade of 0.4-4% Cu and 0.8-6% Zn. The ore minerals are principally pyrrhotite, pyrite, chalcophyrite, sphalerite and magnetite, with minor galena, bornite, cubanite, molybdenite, and arsenopyrite, and traces of gold and silver.

Rankin (1975) has hypothesized that the Ocoee basin was a Late Precambrian marginal rift that formed in a fault-controlled basin produced by extension associated with a spreading center to the southeast. Thus the deposits of Ducktown, Tennessee, and of Fontana, Hazel Creek, Savannah, Wayhutta, and Chullowee, North Carolina, can be viewed as having formed in a Late Precambrian aulacogen that did not completely rift the underlying continental crust. Feiss and Hauck (1980) envisage that a Red Sea type geothermal system, driven by high heat flow along the continentward extension of the rifted arm, produced massive sulfide accumulation in an intracratonic, rifted basin without active volcanism of any volumetric signifcance. Isotopic studies by Addy and Ypma (1977) confirm the possibility of a Red Sea type of geothermal system for the source of the metalliferous solutions.

Deposits Associated with Precambrian-Cambrian Island Arc Systems

Another class of massive sulfide deposit in the southern Appalachians are those associated with the island arc system that formed adjacent to what is now Virginia and the Carolinas during Late Precambrian through Early Paleozoic time (Whitney et al., 1978; Hatcher, 1972; Pavlides, 1981). These deposits are associated with tholeiitic volcanics and volcaniclastics distal to known volcanic vents, both in the Carolina slate belt and in the central Virginia volcanic-plutonic belt (Fig. 36

and Table II). Recent work by Pavlides et al. (1982) has shown that contrasts in stratigraphy, geochemistry, and magnetic and gravity signatures between the two belts indicate that they are not directly related to each other as has widely been held in the past. However, the deposits of both belts are of the same genetic derivation.

The deposits of the Carolina slate belt are associated with an island arc assemblage that was active over a period of about 150 m.y. beginning in the Late Precambrian. The most important deposits in the slate belt have been the massive sulfide deposits, consisting of sphalerite, galena, pyrite, chalcopyrite, and magnetite, with minor sulfosalts; historically they have been mined for their silver and gold content. They are associated with metavolcaniclastic rocks of intermediate to felsic composition which, on the whole, are of low-potassium tholeiitic affinities (Whitney et al., 1978). The massive sulfides of the Carolina slate belt have not been mined for several decades, but there has been a significant history of mining in the area and current interest in base metals exploration is high.

Feiss (1982) recognizes four distinct types of metallic mineral deposits in the slate belt:

(1) Polymetallic massive sulfide deposits of "Kuroko affinities". These are strata-bound and stratiform deposits of galena-sphalerite-chalcopyrite-pyrite within sequences of extrusive, predominantly felsic, volcanics, and include the Cid and Gold Hill districts of central North Carolina, the Haile and Brewer deposits of central South Carolina, and the McCormic and Lincolnton districts of South Carolina and Georgia. These deposits exhibit typical Pb-Zn, Cu-Zn, and Pb-Cu zoning and are associated with extensive hydrothermal alteration as well as exhalites, including iron-formation and barite. The differences in detail of the above named deposits are thought to be due to differences in relative proximity to volcanic centers or details of basin dynamics. These deposits are not very large by Buchans, Newfoundland, or Bathrust, New Brunswick standards, but clusters of small, high grade deposits are known.

(2) Remobilized massive sulfide deposits. These deposits are presumed to be equivalents of those described above, which were remoblized during orogenic activity. In North Carolina the slate belt shows a general

increase in metamorphic grade from east to west, and near the border with the meta-igneous terrane of the Charlotte belt the Carolina slate belt rocks were deformed by ductile shearing and may show evidence of multiple deformation. It is in these rocks that mineral deposits such as the Gold Hill and the Smyrna districts in South Carolina exhibit metamorphic remobilization. The ores are recrystallized and pitch steeply into the nose of folds or into the plane of ductile shear. Discordant veins are locally common.

(3) Vein mineralization. Deposits of this type are the end members of the metamorphic remobilizaton of presumed syngenetic mineralization. These include gold-quartz vein deposits with minor base metal sulfides in the central North Carolina part of the belt, and the chalcocite-bornite-quartz-epidote veins of the Virgilina district. The Virgilina district is located in a synclinal trough of the slate belt on the North Carolina-Virginia border. Stein and Kish (1978, referenced in Feiss and Hauck, 1980) have suggested that the chalcocite-bornite mineralization in the quartz-calcite-albite-sericite-epidote veins was produced by metamorphic migration of pre-existing disseminated metals in the basaltic tuffs, flows, and breccias into shear zones of the Virgilina greenstones. These were small deposits which, when production ceased in 1917, had produced a mere 15 000 tons of ore at an average grade of 2.5-3% Cu. In the gold-quartz veins, fluid inclusion studies indicate that the filling temperatures of primary inclusions in gold-bearing veins match the temperatures expected from the pro-grade metamorphic event in the Carolina slate belt (Feiss, 1982), indicating remobilization in a like manner to the Virginlina sulfide deposits. Total gold production in the region from the many known lode-gold deposits is probably somewhat in excess of 150 000 ounces, with the heaviest production in pre-Civil War years, but with modest production continuing until the 1930's (Worthington and Kiff, 1970).

(4) Post magmatic hydrothermal veins. The Hamme tungsten district, North Carolina-Virginia contains the largest quartz-wolframite- type vein deposits in the US. More than 50 tungsten-bearing veins are found in 13-km-long by 2-km-wide northeast-trending belt. Mining terminated in 1971 after a sharp drop in the price of tungsten and the district is currently inactive, but more than 1 million short tons of WO_3 have been produced since World War II. The tungsten- bearing quartz veins that define the district are concentrated near the border of

the lower Paleozoic Vance County granodiorite pluton, along its western contact with greenschist facies metapelite and metavolcanic rocks of the Carolina slate belt (Fig. 39). The contact between the pluton and adjacent metavolcanic rocks is believed to be intrusive (Parker, 1963) and possibly comagmatic (Glover and Sinha, 1963). On the basis of textural and structural evidence (Foose et al., 1980) and isotopic evidence (Casadevall and Rye, 1980) it appears that the tungsten deposits are typical hydrothermal tungsten-bearing quartz veins that formed synchronously or soon after granitic intrusion.

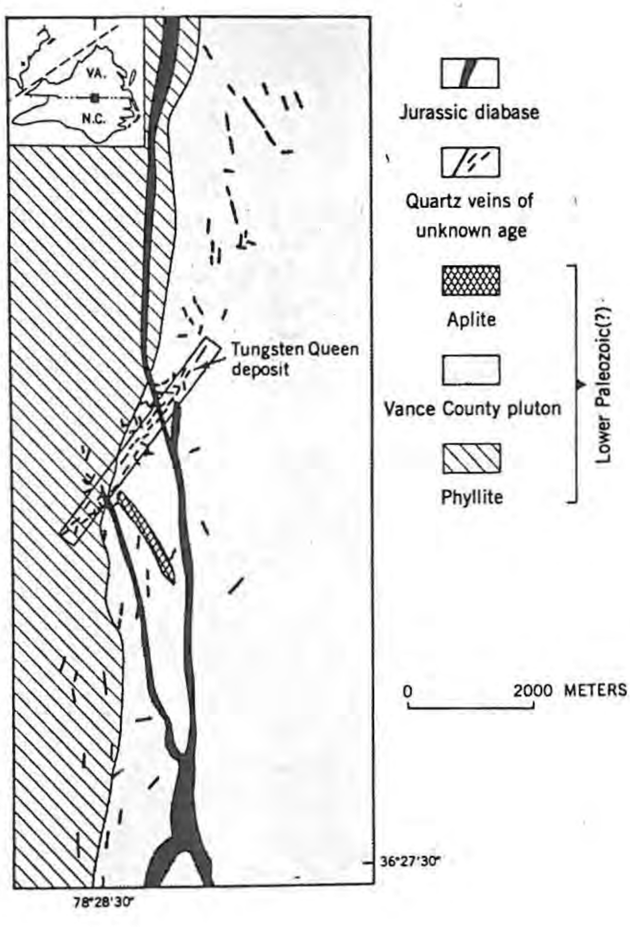


Figure 39 Index and geologic map of the Tungsten Queen deposit. From Foose et al., (1980).

The rocks of the central Virginia volcanic-plutonic belt are considered to be of Lower Cambrian (?) age. None of the deposits within the belt are currently in production, although exploration in the area is still continuing. Strata-bound massive sulfide deposits occur in the island arc volcanic rocks of the Chopawamsic formation on the northwest flank of the Quantico-Columbia synclinorium (Fig. 40), and in the Chopawamsic formation or its equivalent units on the flanks of the Arvonia syncline. The sulfide deposits are irregularly spaced along much of the 180 km length of the Chompawamsic belt from north central to south central Virginia. The sulfide deposits are northeast-trending strata-bound lenses, dipping generally steeply to the southeast, conformable with regional and probably local structures (Pavlides et al., 1982).

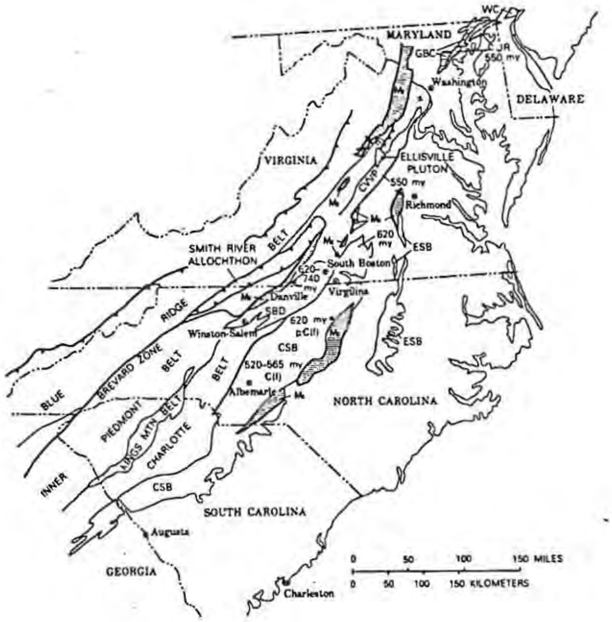


Figure 40 Generalized geologic map of the Piedmont showing the distribution of the Carolina slate belt (CSB), Eastern slate belt (ESB), central Virginia volcanic-plutonic belt (CVVP), South Boston-Danville area (SBD), James Run Belt (JR), and Wilmington Complex (WC). Also shown are Mesozoic basins (Mz), gabbro of the Baltimore Complex (GBC) of Maryland, melange zone (m), granitoid plutons (g), schists (s) stratigraphically and structurally beneath the Chopawamsic Formation, and other features as identified on the map. Isotopic ages reported for some of these metavolcanic rocks are also shown. From Pavlides et al., (1982).

The volcanic-plutonic belt consists of both island arc tholeiite and calc-alkaline mafic to felsic volcanic rocks, ranging from basalts to rhyolites. The principal sulfide deposits occur mostly within the felsic to intermediate volcanic rocks. The dominant sulfides are pyrite and pyrrhotite with subordinate chalcopyrite, sphalerite, and galena, with traces of gold and silver. Only three deposits, Valizinco, Allah Cooper, and Cofer, contain appreciable amounts of sphalerite (Pavlides et al., 1982).

Most of the sulfides in the Virginia volcanic-plutonic belt are contained within the Mineral district (Fig. 36 and Table II) where about 10 million tons of sulfides occurs in two and possibly three distinct belts, indicating that mineralization occurred at different stratigraphic levels in the Chopawamsic formation. According to Pavlides et al. (1982), many of the deposits in the Mineral district resemble deposits of the Kuroko type but differ in that they are not associated with domical eruptive enters.

Vein gold, similar to that found in the Carolina slate belt, also occurs within the Virginia volcanic-plutonic belt. The Virginia gold belt is a linear zone of gold-quartz veins crossing diverse rock types, including the Chopawamsic formation. The gold belt trends regionally at a small angle to and locally parallel with the outcrop of the Chapawamsic formation and associated massive sulfide deposits (Fig. 41). These deposits are generally lenses concordant with the schistosity of the enclosing rocks, striking northeastward, and dipping steeply to the southeast (Pavlides et al., 1982). These gold veins probably formed in the same manner as those of the Carolina slate belt, i.e., the gold was deposited syngenetically with the surrounding rocks, but was remobilized into veins when the gold belt as such formed.

Epigenetic Deposits in Rocks of Precambrian Age

Primary titanium deposits are found in the Precambrian rocks of the Blue Ridge province from central Virginia to southern North Carolina. Figure 42 shows the locations of the major occurrences and Table III gives a brief description of each. The geology of most of the deposits is not well known, but according to Herz and Eilertsen (1968) most are found in metamorphic rocks such as gneiss and schist, and a few are in intrusive ingneous rocks, such as syenite, gabbro, and pegmatite. Titanium is not presently being mined in the region, but historically the region has produced a considerable quantity of metal.

According to Ross (1941), the deposits in Nelson and Amhurst Counties, Virginia were at one time one of the world's principal sources of rutile and also a large source of ilmenite. Ross (1941) describes the

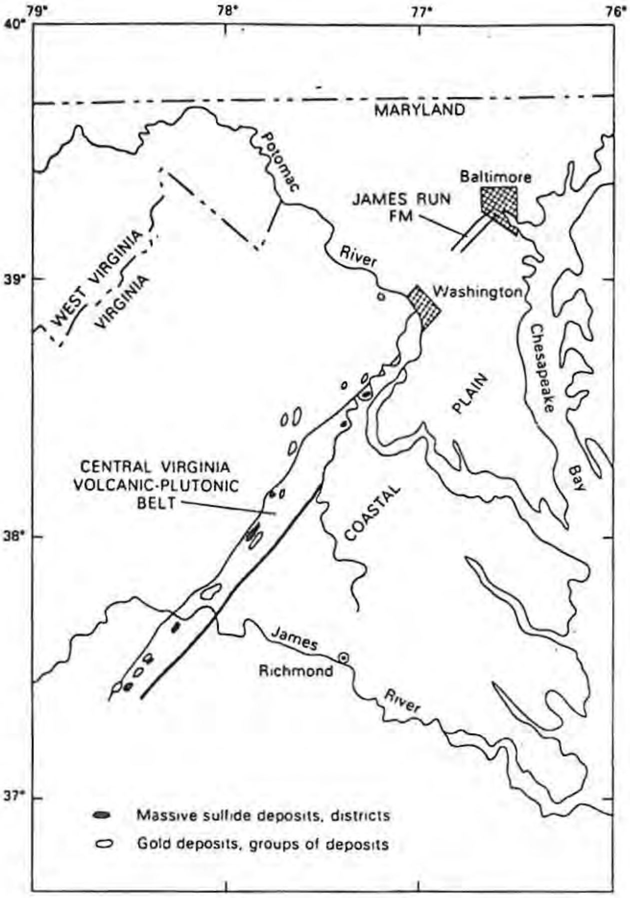


Figure 41 Generalized map showing the trend of the central Virginia volcanic plutonic belt and the distribution of deposits and groups of deposits of massive sulfides and gold. From Pavlides et al. (1982).

deposits: "The titanium minerals occur in deposits of two distinct types -- as disseminated deposits in ... anorthosite and as veinlike or dikelike masses of a rock known as nelsonite, which is characterized by rutile and apatite or by ilmenite and apatite. Most of these masses are within the anorthosite, but a few are outside of it... The titanium minerals in both disseminated deposits and nelsonites were introduced after granulation and consolidation of the anorthosite and are absent in the primary uncrushed feldspar. They are most abundant in the vicinity of shear zones, which evidently acted as feeding channels... The titanium and associated minerals are evidently the result of replacement and not of magmatic segregation or of pyrogenic processes."

Herz and Eilertsen (1968) state that the ilmenite deposit of Yadkin Valley (Richlands), North Carolina are in gneiss of Precambrian age and is unique in being the only exploitable primary ilmenite deposit in the

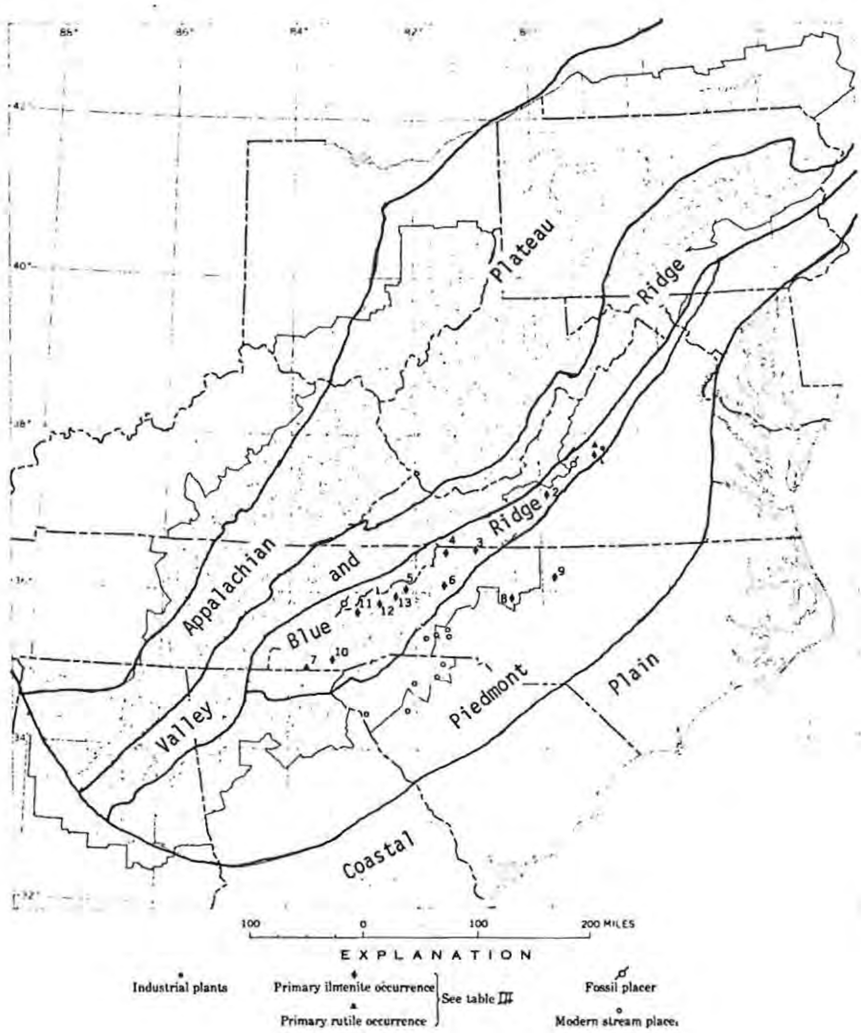


Figure 42 Location of ilmenite and rutile occurrences in the Appalachian Region. From Herz and Eilertsen (1968).

world not either in gabbro or anorthosite, and is also the only ilmenite deposit that has been exploited in the southern Appalachians. The orebody consists of a series of narrow, closely spaced lenses in a layered cataclastic gneiss, which form a nearly continuous vein about 300m long and about 60 m deep.

The rutile deposits at Shooting Creek, North Carolina are restricted to garnet mica schist of the Precambrian Carolina Gneiss, in a belt approximately 16 km long. Stringers of sugary-textured quartz associated with the rutile in many places suggest that the rutile was deposited by silicic solutions that pervaded the garnetiferous schist (Herz and Eilertsen, 1968).

State, county	No. (fig. 42)	Deposit	Ore minerals	Description of deposit
Virginia:				
Amherst, Nelson [1].	1	Piney River and others.	Largely ilmenite, some rutile.	Saprolite derived from nelsonite dikes and mafic rocks. Reserves greater than 20 million tons.
Roanoke [1]	2	Bush-Hutchins, Vinton.	Ilmenite	Nelsonite dikes, 8.4 percent TiO_2, with ilmenite-apatite-magnetite in syenite and greenstone.
North Carolina:				
Alleghany, Grayson (Va.).	3	Carrico Pits, Alleghany County Ti-magnetite belt.	Ti-magnetite, ilmenite.	Ti-magnetite and ilmenite disseminations, mineralized zone 2,000 ft long, lenses about 25 by 100 ft in hornblende schists locally altered to steatite. Ore has 4.9 percent TiO_2.
Ashe	4	Ashe County titanium belt.	Ti-magnetite, ilmenite, rutile.	Lenses are wide as 25 ft in belt 2.5 miles long in hornblende schist partly altered to asbestos. Ore has 4.7–9.2 percent TiO_2.
Avery, Mitchell, Carter (Tenn.).	5	Roan Mountain, Pumpkin Patch Mountain, Iron Mountain belts.	Ti-magnetite	Lenses as wide as 5.5 ft; about 12 deposits in hornblende gneiss, schist, and pegmatite; 4.5–6.8 percent TiO_2.
Caldwell	6	Richlands Cove, Yadkin River Valley.	Ilmenite, minor rutile.	Ore zone, 1,000 ft long and 20–50 ft thick, of ilmenite in small masses in talcose rock conformable to mica schist, quartzite, gneiss. Drilling shows zone to be continuous for at least 500 ft down dip and to average 35 ft thick. 215,400 tons concentrate produced 1942–52, with average of 51 percent recoverable TiO_2.
Clay, Towns (Ga.).	7	Shooting Creek	Rutile, minor ilmenite.	Rutile associated with sugary quartz in garnet mica schist in 10-mile-long belt. Deposits are residual and small placers. 68,000 tons TiO_2 recoverable reserves.
Davie	8	Near Mocksville	Ti-magnetite	Veins in hornblende-rich syenite, also placers. Ore has 8.0–10.3 percent TiO_2.
Guilford, Rockingham, Davidson [1].	9	Tuscarora-Shaw belts.	Ti-magnetite, ilmenite, rutile.	Two parallel belts 30 miles long, 3 miles apart, lenses few inches to 8 ft thick as segregations in gabbrol. Ore has 12.0–14.5 percent TiO_2.
Macon	10	Culasagee Creek	Ti-magnetite	Surficial residual float in a quartz and chlorite gangue. Ore 3.2–17.6 percent TiO_2.
Madison	11	New Found Mountain (Spring Creek).	do.	Vein 5–6 ft wide. TiO_2 is 7.4 percent.
	12	Ivy Creek	Ti-magnetite, rutile.	In float and placers, concentration averages 37.9 percent ilmenite.
Yancey	13	Hampton place and others.	Ti-magnetite, rutile or brookite.	Ore is in a vertical bed 6–10 ft thick; gangue is chlorite, quartz, feldspar; ore grade 11.9 percent TiO_2, nearby placers yield concentrates containing 14-20 percent ilmenite.

Table III Primary titanium (Ti) deposits and their secondary accumulations in the Appalachian Region. From Herz and Eilertsen (1968).

Deposits Associated with the Cambrian-Ordovician Carbonate Sequence

Appalachian Zinc-Lead Deposits

The carbonate hosted zinc-lead deposits of the Appalachians occur basically at two different stratigraphic levels. The deposits at Austinville-Ivanhoe, Virginia, and Embryville, Tennessee occur in the Lower Cambrian Shady formation where the mineralization is localized at a facies change in breccia and reef material. These deposits are characterized by zinc with subordinate but economically important lead mineralization. The most important and distinctive carbonate hosted zinc-(lead) deposits in the southern Appalachians occur in rocks of Lower Ordovician age and are related to the paleoaquifer system that developed in the Lower Ordovician carbonate sediments of the Appalachian miogeosyncline during the long period of uplift and erosion prior to deposition of Middle Ordovician sediments. It was during this period that the ground was prepared for mineralization by the formation of large debris-filled zones of dissolution. The deposits directly related to this unconformity include those of East Tennessee; Timberville, Virginia; and Friedensville, Pennsylvania (Fig. 43). These deposits are

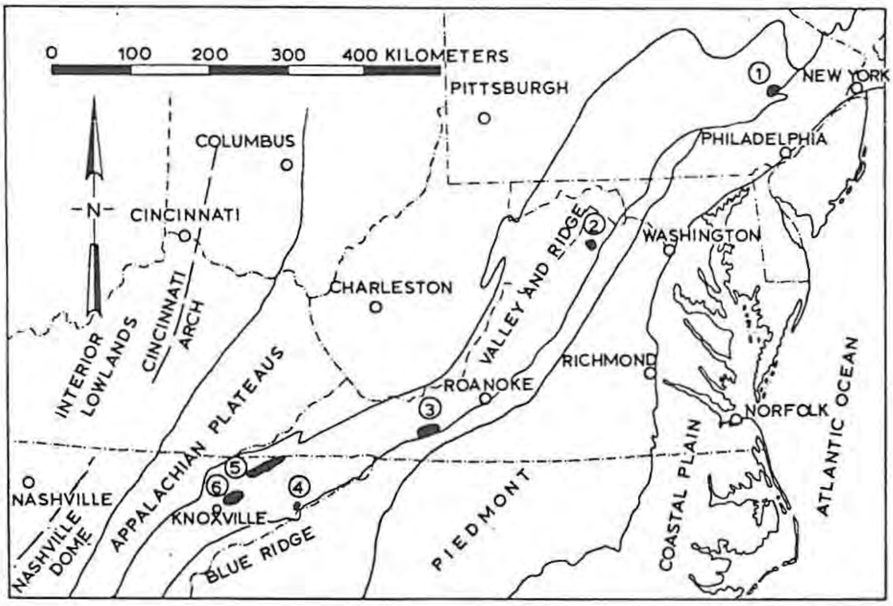


Figure 43 Major Appalachian-type deposits in eastern United States. 1 = Friedensville, Pa.: zinc in Lower Ordovician Beekmantown formation; 2 = Timberville, Va.: zinc in Lower Ordovician Beekmantown formation; 3 = Austinville-Ivanhoe, Va.: zinc-lead in Lower Cambrian Shady formation; 4 = Embreeville, Tenn.: zinc-lead in Lower Cambrian Shady formation; 5, 6 = east Tennessee districts, Copper Ridge and Mascot-Jefferson City, respectively: the zinc ore is in Lower Ordovician Mascot and Kingsport formations. Modified from Hoagland (1976).

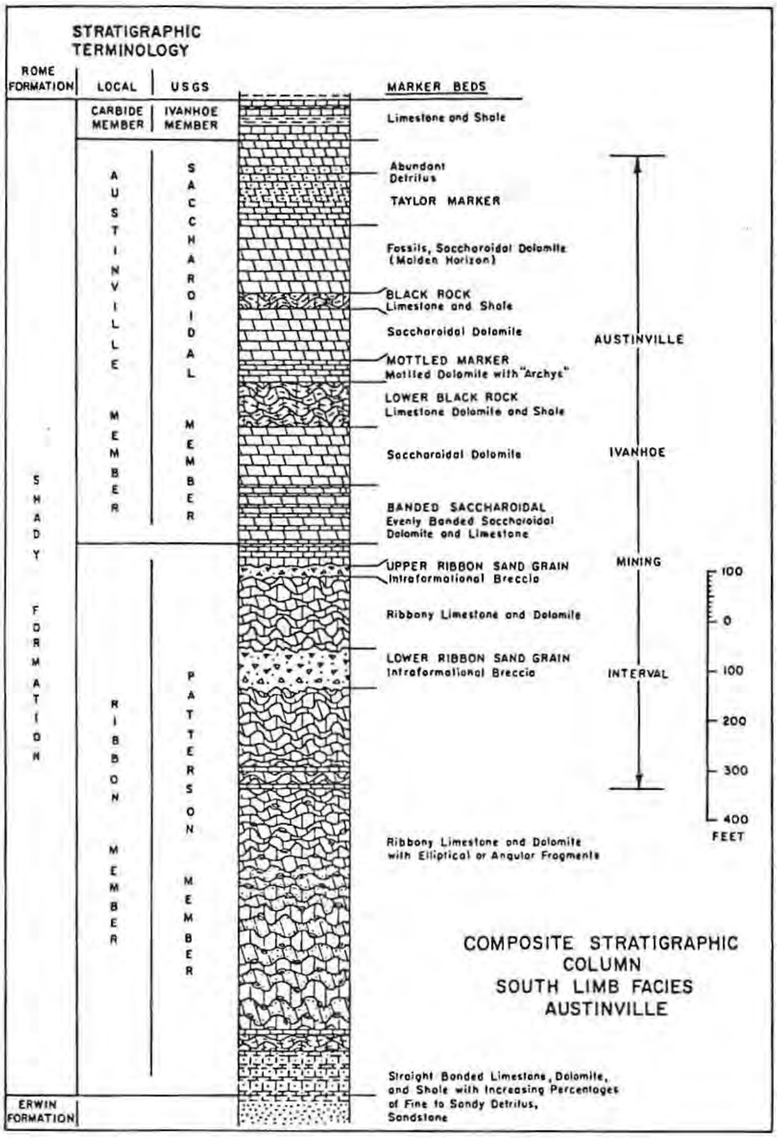
dinstinctive due to their essential absence of lead and comparable sedimentary and paleophysiographic environments in Lower Ordovician dolomite. The deposits are located within or close to the transition zone between the dominantly dolomite facies, believed to be of diagenetic origin, and the dominantly limestone facies on or near the edge of the continental shelf. The ore is commonly found in dolomitized limestone at or adjacent to the interface of limestone and dolomite.

Austinville-Ivanhoe The Austinville-Ivanhoe zinc-lead district lies near the southeast edge of the Valley and Ridge province of southwest Virginia (Fig. 43). Mining in the area began in 1765 and has continued, with minor interruptions, to the present. The district is estimated to have produced in excess of 1.2 million tons of zinc and lead (Hoagland, 1976). The chief ore minerals are sphalerite and galena, with a Zn:Pb ratio of about 5:1. Minor secondary minerals such as hemimorphite, smithsonite, hydrozincite, cerussite, and anglesite also occur. Pyrite is the second most abundant sulfide and is locally abundant but is disseminated ubiquitously (Brown and Weinberg, 1968). The most abundant gangue mineral is white dolomite, which is generally coarsely crystalline in the ore zone.

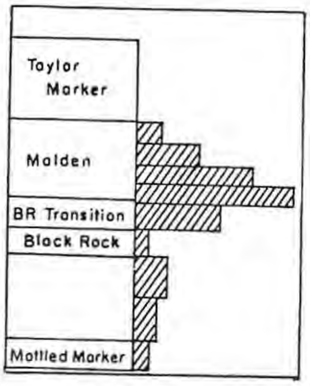
The folds in this portion of the Valley and Ridge province are relatively open, and they are broken by a complex series of imbricate thrust faults overriding to the northwest. Fold axes are tilted to the southeast, the southeast limbs of the folds dip at moderate attitudes, and the northwest limbs are steep or overturned (Brown and Weinberg, 1968).

The ore is hosted in the Lower Cambrian Shady formation which exhibits a high degree of lateral variability. Prominent archeocyathid reef structures and abruptly changing lithologies typical of reef complexes characterize the ore zone which, as shown in Figure 44A, is confined to certain zones of the Austinville and Ribbon members. Figure 44B illustrates that the Malden zone, and more specifically the basal part of that zone, is the most favorable ore horizion. According to Callahan (1964) the ore is localized at a facies change in breccia and reef material.

The Austinville-Ivanhoe ore zones extend over a distance of approximately 10 km along strike. The orebodies are pencil shaped with lens-like cross sections and are elongated along strike. The base of the orebodies is generally conformable with bedding whereas the upper portion is usually convex upward (Hoagland, 1976). Strike lengths of the ore zones are from less than 30 m to more than 2000 m. The deposits may extend 15 m to 120 m down dip, and thickness normal to bedding may exceed



A



B

Figure 44 (A) Composite stratigraphic column of the Austinville-Ivanhoe district.
(A) Stratigraphic distribution of the ore -- upper Austinville member. After Brown and Weinberg (1968).

30 m locally. Minor strike or diagonal faults disrupt the ore bodies in places by as much as 3 m or more. The ore zone has been modified by orogenic activity, but apparently received its essential form and structure during deposition of the unique archeocyathid reef facies. The nature and source of the ore-bearing fluids is problematical, Hoagland (1976), upon consideration of various lines of evidence, suggests that the mineralization was essentially completed in the Early Paleozoic, and probably before the end of the Cambrian.

Embreeville The Embreeville, Tennessee zinc-lead deposit, located on the extreme southeastern edge of the Valley and Ridge province (Fig. 43), is also hosted in dolomites of the Lower Cambrian Shady formation. Here, however, the dolomites are deeply weathered and the ore minerals are secondary oxides. Mining was conducted prior to 1945 during periods of high metal prices. Small patches of primary ore have also been found, but are too small for exploitation. Residual limonite and manganese deposits are also found in the area, the limonite presumably derived from pyritic dolomites and the manganese from the dolomites themselves. The structural and stratigraphic environment of the Embryville district is similar to that of the Austinville-Ivanhoe district, but the ore was formed on a significantly smaller scale; however, the ores of the two districts had a similar genesis (Hoagland, 1976).

Friedensville The Friedensville Mine lies in a small Lower Paleozoic reentrant in the Precambrian crystalline rocks of the Piedmont which borders the Valley and Ridge to the southeast (Fig. 43). The Friedensville deposit is unique in being the most strongly deformed of the Appalachian zinc deposits. The ore is lead free and averages about 6.5% Zn with a sphalerite:pyrite ratio of about 3:1. It occurs in a breccia zone approximately 30 m thick some 850 m above the Precambrian crystalline basement near the base of the Lower Ordovician Beekmantown dolomite. The breccia zone occurs about 300 m below the important pre-Middle Ordovician unconformity that separates the Beekmantown from the overlying Jacksonburg formation of Middle Ordovician age (Hoagland, 1976). Several limonite deposits that have experienced past production occur in the upper Beekmantown and are probably oxidized derivatives of pyritic deposits (Callahan, 1968).

The main structure at Friedensville is a northeast-trending saddle-shaped, doubly plunging anticline overturned to the north. A thrust fault repeats the south limb of the anticline. The scarcity of marker beds in the Beekmantown is a handicap in determining structural relationships, although a few key beds with floating sand grains have been useful (Hoagland, 1976).

Callahan (1968) describes the ore zone: "From the standpoint of mineralization, the most important unit in the Beekmantown formation is that designated 'Sedimentary Breccia'... The term 'Sedimentary Breccia' is used to emphasize that the breccia did not result from deformation but rather is composed of fragments derived from solution-collapse cemented by finer detritus resulting from the solution process... The mineralization generally is restricted to the sedimentary matrix of the breccia, and fractures in the fragments are post-mineralization."

East Tennessee Figure 45 shows the location of the main districts and mines in east Tennessee. The most important deposits are those of

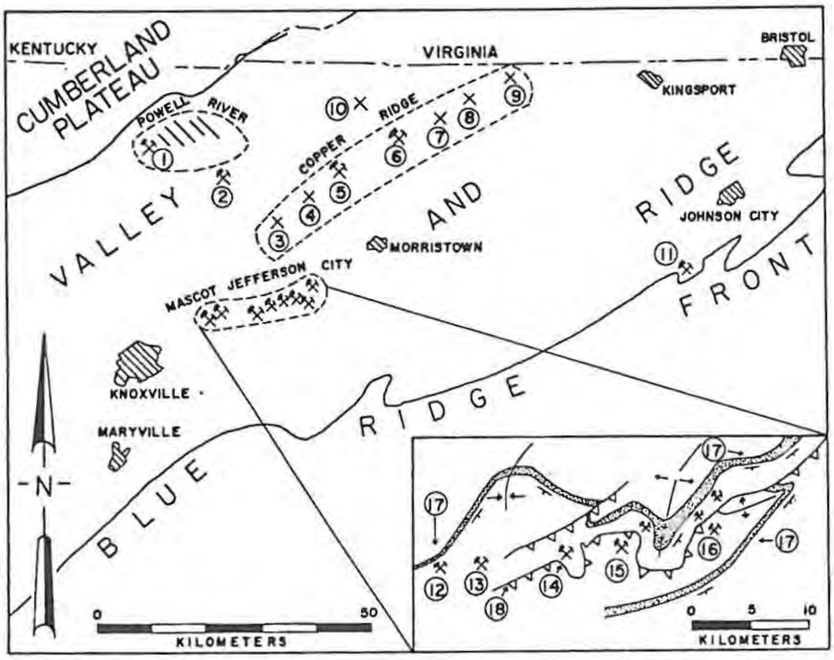


Figure 45 Appalachian deposits of east Tennessee. Inset of Mascot-Jefferson City district showing anomalous minor anticlinal and synclinal structures. 1, 2 = the New Prospect and Straight Creek Mines, respectively, in Powell River district with NW trending vein structures; 3, 4 = the Luttrel and Puncheon Camp prospects; 5, 6 = the Idol and Flat Gap Mines; 7, 8, 9 = the Shiloh, Eidson, and Independence prospects, all in the Copper Ridge district; 10 = the Evanston district, 11 = Embreeville. Inset : 12 = Mascot Mine; 13 = Immel Mine; 14 = Young Mine; 15 = New Market Mine; 16 = Jefferson City Mine; 17 = outcrop belts of the Lower Ordovician Kingsport Formation; 18 = Rocky Valley thrust fault. All of the important ore in the district lies in the northern Kingsport belt in the footwall of the Rocky Valley fault. From Hoagland (1976).

the Mascot-Jefferson City district which is the leading zinc producing district in the US. Zinc mining began in the Mascot-Jefferson City district in 1854, but large scale operations were not initiated until 1913.

The ore is essentially lead free. Sphalerite is the only primary metallic mineral of economic significance, and is notably low in iron and other contaminating elements. Pyrite is very scarce. Chalcopyrite and galena have been found, but are extremely rare. The ore grade ranges from less than 3% to 5% Zn and averages about 3.5% (Crawford and Hoagland, 1968).

The ore occurs essentially within a stratigraphic range of 60 m in the upper Long and lower Kingsport formations of Lower Ordovician age. The ore in the lower strata of the mineralized section is generally found in coarsely crystalline dolomite breccia containing silica and chert debris within a sequence of aphanitic limestone. The strata of the upper portion of the mineralized section are fine grained dolomites, which in the ore zone have been fragmented in mosaic patterns by solution collapse with the interfragmental space filled by white gangue dolomite and sphalerite. The orebodies are irregular in shape and occur in rubble breccia zones (Fig. 46) that were formed due to development of a mature karst system during the pre-Middle Ordovician erosion interval. This is believed to have been accomplished at a depth of from 150 to 250 m below the then existing surface (Crawford and Hoagland, 1968).

The structural features of the district were formed during the Alleghanian orogenic period. The structure of the area is dominated by extensive gentle folds, that are slightly overturned and dip to the southeast, and by extensive low angle thrust faults that dip gently to the southeast. These structures are modified by other faults, both normal and reverse, and by numerous minor folds and warps subsidiary to the larger structures (Crawford and Hoagland, 1968; Hoagland, 1976).

Mississippi Valley Lead-Zinc-Barite-Fluorite Deposits

Low temperature stratiform and vein deposits are widespread throughout the Mississippi Valley. The lack of any significant detailed genetic classification of these "sedimentogenic" deposits is due to the fact that each one is almost unique in its own right. The only unquestionable characteristic common to all these deposits is the fact that they are associated with shallow water platform carbonates. Because of their many geological and geochemical similarities, these deposits are all classed by many geologists as the Mississippi Valley type. Some

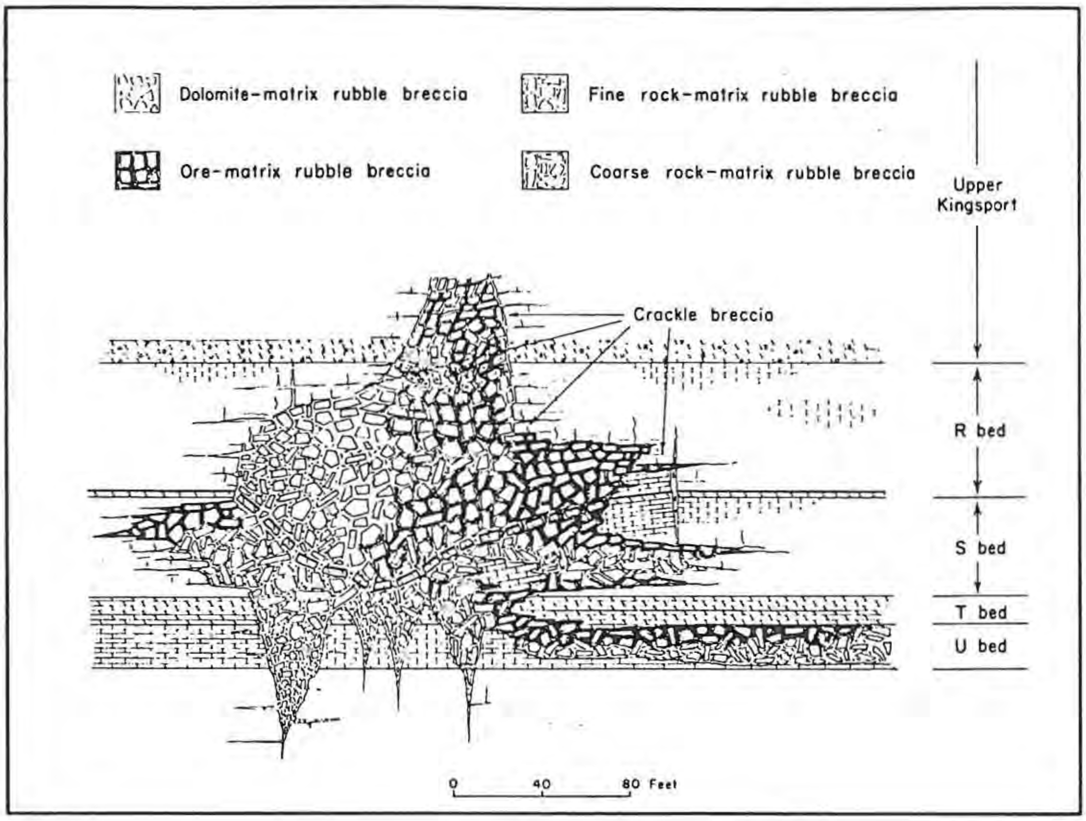


Figure 46 Generalized Section through a portion of the Jefferson City Mine. From Crawford and Hoagland (1968).

districts, such as the Southeast Missouri, Upper Mississippi Valley, and Central Tennessee districts, contain significant quantities of both stratiform and vein-type mineralization.

The commercial deposits of the Mississippi Valley type are shown on Figure 47. The deposits are clustered on the crests or flanks of gently flexed or fractured major domes or anticlines, which developed primarily during the course of the early and mid-Paleozoic. Paleoshorelines and paleohighs with superimposed tectonic features control the location and geometry of these deposits. The deposits occur to some degree throughout the Paleozoic sedimentary sequence, but the rocks with the bulk of the ore are limestones and dolomites of Cambrian and Ordovician age. The next rock units with significant quantities of mineralization of this type are those of the Mississippian period.

Southeast Missouri The Southeast Missouri mineral district includes an area of some 10 000 square kilometers on the northeast margin of the

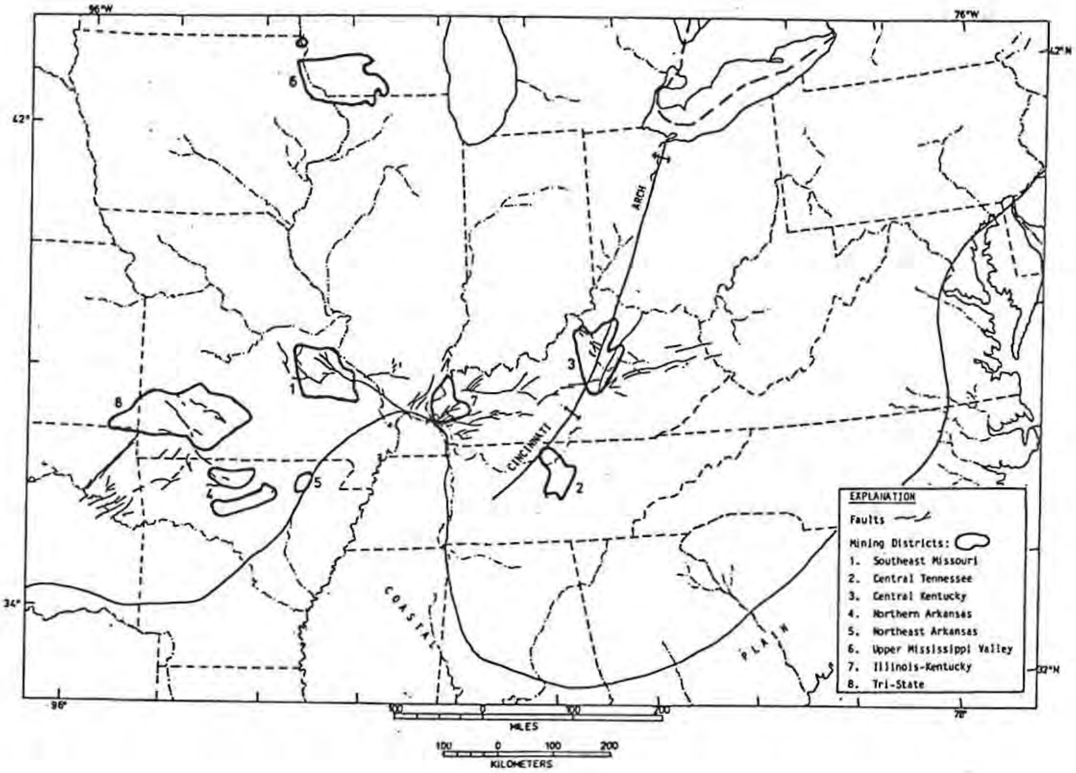


Figure 47 Location map for Mississippi Valley type deposits. After Heyl (1969).

Ozark uplift (Fig. 47). More precisely, the district is located on the flanks of the St. Francois Mountains, a Late Precambrian high that had a major influence in the localization of the deposits. A network of northwest-, east-, and northeast-trending faults and flexures have modified the St. Francois mountains and the northern side of the Ozark dome (Figs. 48 and 49) and many of the deposits lie within faulted and tilted blocks or occur along major fault zones.

The district contains three types of deposits. The Precambrian crystalline rocks of the St. Francois Mountains contain magnetite and hematite deposits which have been described in a previous section (p. 60). Surrounding the St. Francois Mountains on all but the southern side is an arcuate belt of lead deposits (Fig. 48) hosted in dolomites of the Upper

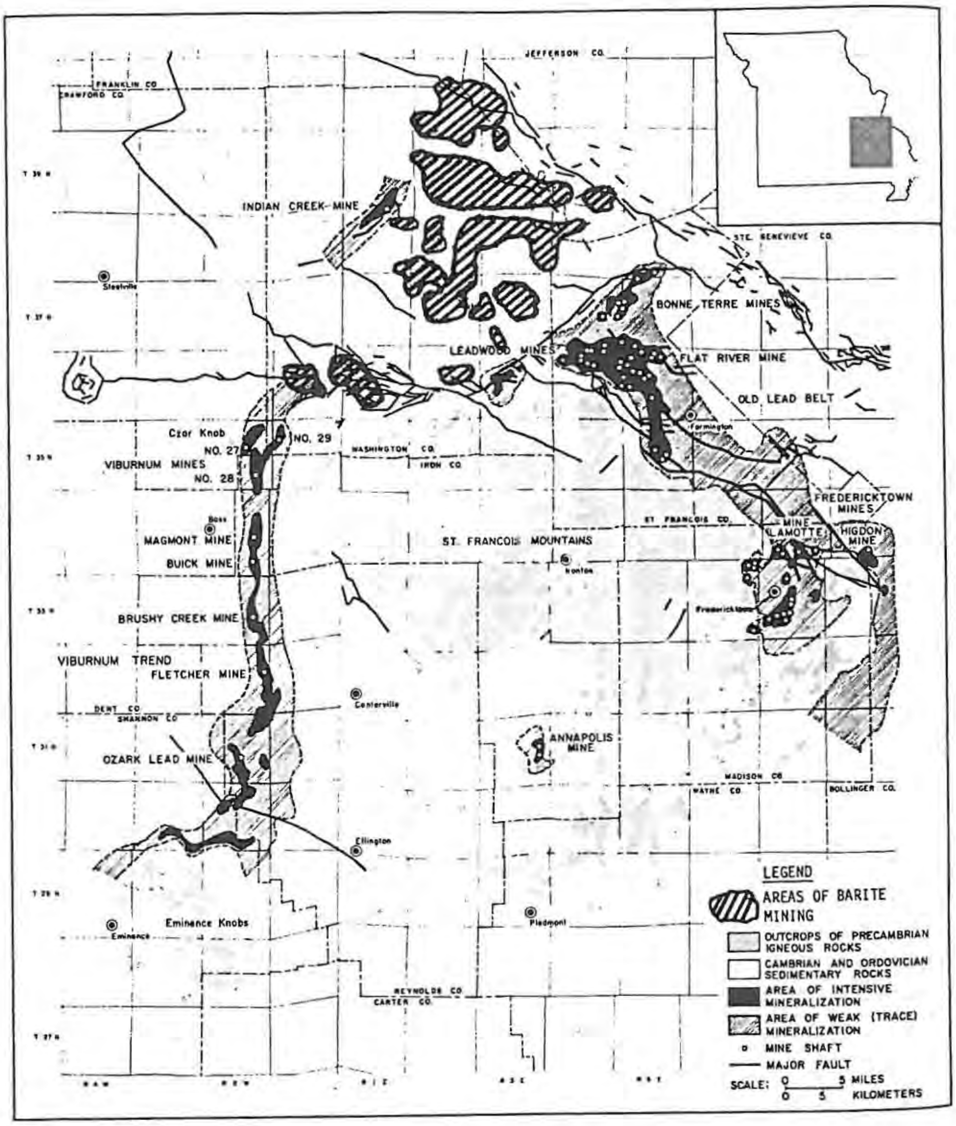


Figure 48 The southeast Missouri lead-zinc-copper and barite mining districts. Modified from Kisvarsanyi (1977); and Brobst and Wagner (1967).

Cambrian Bonneterre formation (Table IV). North and northwest of the St. Francois Mountains barite is mined from the residuum of weathered dolomites of the Potosi and Eminence formations, which are also of Late Cambrian age. To a considerable extent these deposits overlap the northern part of the lead mining district. The deposits of the lead district and those of the barite district will be described separately.

The lead district embraces four important subdistricts and several minor ones. The important subdistricts, in order of discovery are Mine La Motte, the Old Lead Belt, Indian Creek, and the Viburnum Lead Belt (Fig. 48). Historically, the Old Lead Belt has produced most of the ore from the district, but has been in production since at least 1864 and its economic life is nearly at an end. However, the Viburnum Lead Belt

Ordovician	Cincinnati	Orchard Creek Thebes Maquoketa Fernvale
	Champlain	Kimmswick Decorah Plattin Rock Levee Joachim St. Peter Everton
	Canadian	Smithville Powell Cotter Jefferson City Roubidoux Gasconade
Cambrian	Upper	Eminence Potosi Derby-Doe Run Davis Bonneterre Lamotte-Reagan
Precambrian		

Table IV Generalized stratigraphic chart of the Lower Paleozoic for the central and western midcontinent. From Snyder (1968).

promises to be as productive as the older area, and in 1974 accounted for 85% of the total US production of lead and 18% of the world total.

The ore deposits are stratiform in character and occur in the Bonneterre formation near or within a few kilometers of the Precambrian topographic highs that cut out the underlying Lamotte sandstone (Table IV). The orebodies are localized in a narrow carbonate bar and algal reef environment flanking the St. Francois Mountains. The Bonneterre formation is composed almost entirely of dolomite near and over basement highs, but grades into limestone in local basins. The dolomite contains numerous vertical and lateral facies variations indicative of shallow water deposition. Ore structures include a variety of primary features, such as disconformities, pinchout zones, ridge structures, reefs, and submarine gravity slides (Snyder and Gerdemann, 1968). Close to the basement highs the ore may also occur in the upper 30 m or so of the Lamotte sandstone.

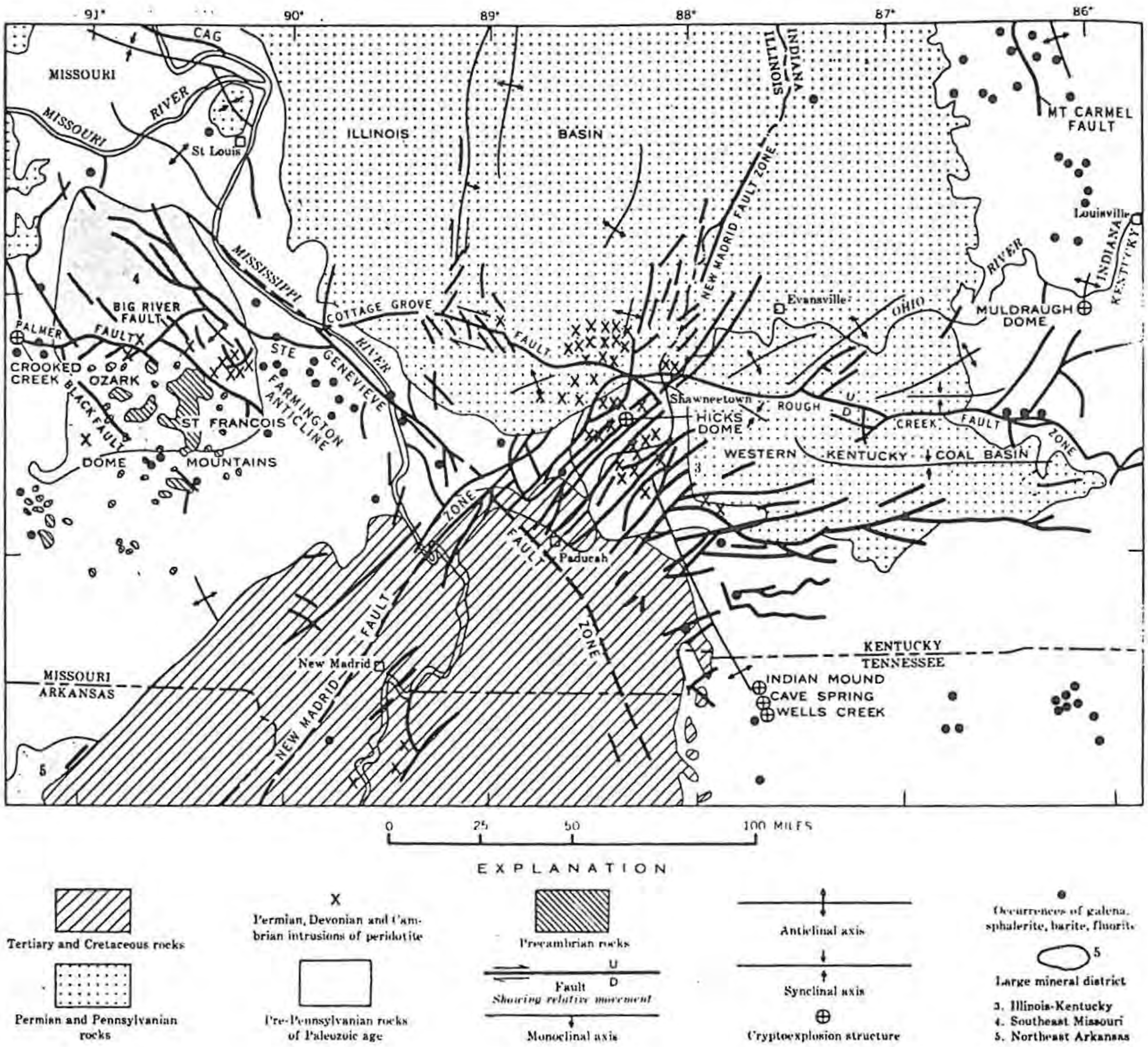


Figure 49 Cottage Grove and Rough Creek fault zones, Kentucky, Illinois, and Missouri, and associated structures and mineral deposits. From Heyl (1972).

The basement rocks of the Southeast Missouri district were subject to doming, corresponding marginal subsidence, block faulting, and to a long period of erosion in Late Precambrian time. The regional structure of these basement rocks that underlie the district had a strong influence on the paleogeography of the area during the period of Upper Cambrian marine transgression, and the paleotopography dictated the sedimentary facies patterns, the development of fringing algal reefs, and the distribution of primary and superimposed permeability of the Bonneterre formation, all of which served to localize the mineralization.

A complex network of faults also served to localize ore in the district. The Southeast Missouri district lies at the intersection of the Ste. Genevieve, Palmer, and Cottage Grove fault zones (extensions of the Rough Creek fault zone) and the Ozark dome (Fig. 49). Faulting prior to and during ore deposition conditioned the host rocks for mineralization and provided conduits for ascending mineralizing solutions. The more strongly fractured areas are much more intensively and pervasively mineralized than unfractured areas containing the same sedimentary structures. Fault movement began at least as early as Bonneterre time (Snyder and Gerdemann, 1968), and probably as early as Precambrian time (Heyl, 1972), but a major episode is thought to have occurred during post-Jefferson City time (see Table IV). Most mineralization is believed to have occurred during the post-Jefferson City faulting, but some of the ore appears to be prefaulting (Snyder, 1968). The fault zones within the district are still seismically active today.

Galena is the dominant sulfide mineral present; sphalerite and chalcopyrite are abundant locally. Silver occurs in minor quantities, as does cobalt and nickel which occur in the mineral siegenite (Snyder and Gerdemann, 1968). The ore is generally richer in copper, nickel, and cobalt minerals near the basement highs than in other parts of the mineralized areas. According to Kisvarsanyi (1977), other ore districts, which formed in stratigraphically higher and younger rocks at a distance from igneous rock sources (e.g., Tri-State and Upper Mississippi Valley), may contain only trace amounts of these metals.

In the Southeast Missouri barite district most of the ore occurs within zone 30 m thick that embraces the upper part of the Potosi formation and the lower part of the Eminence formation. Both of these formations are of Late Cambrian age (Table IV). Rock types include algal reef, and sand, silt, and clay size carbonate, now entirely dolomite. Preference for a particular lithology has not been recognized. Barite occurs in fractured bedrock and in the red clay residuum. Only the concentrations of barite in the residuum, which can contain up to 65 kg of barite per cubic meter, are of commercial importance (Brobst and Wagner, 1967). Galena and sphalerite occur in minor amounts with the barite. Pyrite, partially oxidized to limonite, is abundant in some pits.

Brobst and Wagner (1967) believe the barite deposits formed as follows: "After deposition and induration the host rocks were fractured and solutions permeating the fractures deposited chalcedony and drusy quartz. Renewed fracturing was followed by the deposition of pyrite and then barite, along with smaller amounts of galena and sphalerite from solutions that descended along steep fractures and moved out laterally in favorable host rocks. Weathering and the removal of many constituents left behind a clay residuum sufficiently rich in barite to be minable." The timing of mineralization is unknown, but it is probable that the ground was prepared for mineralization during the period of epeirogenic uplift that resulted in the retreat of the Sauk sequence in Early Ordovician time. Work by Leach (1980) indicates that the period of barite deposition was distinctly later than and unrelated to the lead-zinc mineralization in the Southeast Missouri lead district.

Central Tennessee The discovery in 1969 of a major zinc deposit near Elmwood Tennessee initiated a period of continuing exploration activity by numerous companies along the crest and flanks of the Cincinnati arch in central Tennessee and in central Kentucky. The deposits lie near the axis of the Nashville dome (Fig. 50) in stratabound breccias within the Lower Ordovician Mascot dolomite of the Upper Knox group. Fissure veins in Middle Ordovicain limestones containing barite, fluorite, sphalerite, and galena, similar to those found in the Central Kentucky mineral district, (as described in a later section) have been known in the district for many years; but the close spatial relationship of these veins with the deeper stratiform ores remains unclear (Kyle, 1976).

The dominant structural features of the Lower Ordovicain strata are extensive solution breccias formed by the great karst system that developed during the widespread pre-Middle Ordovician erosion. These solution breccias were enlarged by further dissolution during a subsequent period of the Paleozoic by enriched connate brines carrying zinc as the principal base metal. This was accompanied by dolomitization on a wide scale and minor silicification, but the conditions favorable for deposition of zinc sulfide only occurred in certain areas (Callahan, 1977).

These Mississippi Valley type deposits of Central Tennessee are geologically similar to the Appalachian type deposits of the East Tennessee district thus emphasizing the link between the mid-continent

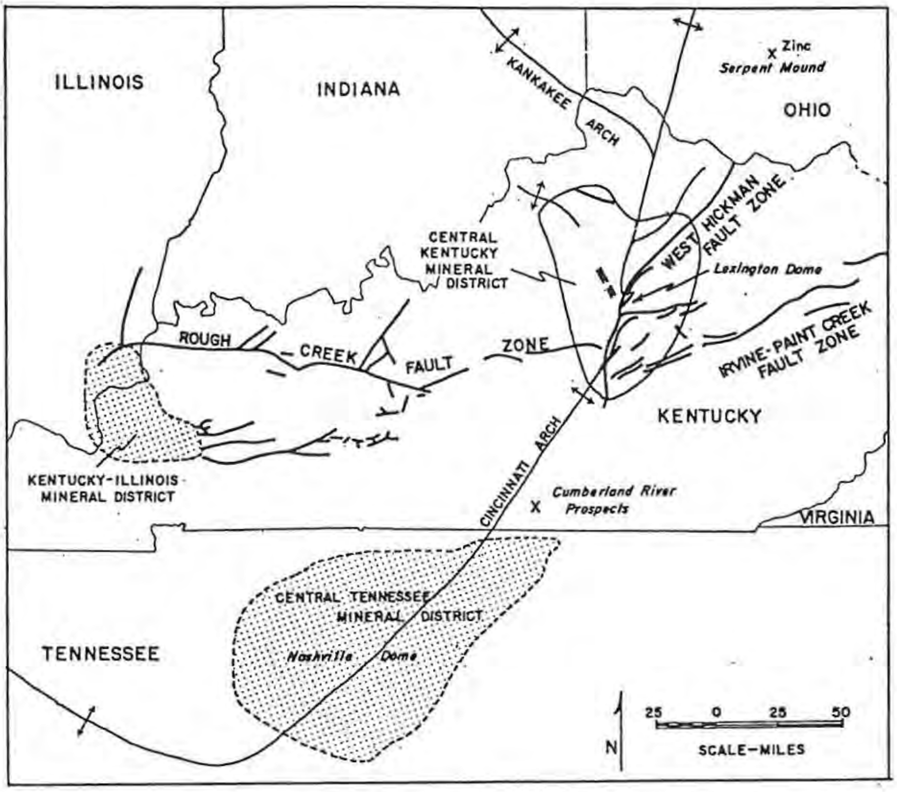


Figure 50 Index map showing location of the Central Kentucky, Central Tennessee, and Kentucky-Illinois mineral districts. From Jolly and Heyl (1964).

deposits of the Mississippi Valley type and those of the Appalachian type, but there are some distinct differences. Deposits of both areas occur predominantly as open-space fillings in carbonate rocks of the Early Ordovician Knox group. Sphalerite is the only ore mineral, but varying amounts of galena, fluorite, barite, pyrite and marcasite also occur. However, it is significant for exploration practices that the Knox group in the Central Tennessee district is unconformably overlain by from 200 to 400 m of Middle Ordovician limestone beds, whereas in the East Tennessee district the Knox dips from 10^{0} to 40^{0} to the southeast; therefore, the known mineral deposits in East Tennessee have some type of surface expression and lend themselves well to surface geological and geochemical investigations (Kyle, 1976; Callahan, 1977).

The deposits also differ in the timing of mineralization. According to Kyle (1976), sulfide mineral deposition in Central Tennessee was significantly later than than breccia formation and may have been as late as late Paleozoic. In East Tennessee sulfide mineralization took place in temporal proximity to limestone dissolution and dolomitization and occurred during the early Middle Ordovician.

Central Kentucky The Central Kentucky mineral district (Fig. 47) is an area of approximately 9000 square kilometers that approximately coincides with the Bluegrass lowland of Kentucky and lies astride the Lexington Dome and Cincinnati arch (Fig. 50). The ores occur primarily as vein deposits in the High Bridge and Lexington Groups of early Middle Ordovician age. Many of the 200 vein deposits of barite, calcite, sphalerite, galena, and fluorite were developed between 1900 and 1920, but none are being mined at present (Plummer, 1971).

The main structural feature of the area is the Lexington dome. Several major fault zones that have undergone several periods of movement intersect near the crest of the dome (Fig. 50). Jolly and Heyl (1964) state that the final uplift and major faulting probably took place in the Late Paleozoic, possibly extending into the Mesozoic. Most of the mineral deposits occur as fissure veins or open space fillings in and near the major faults, but replacement of fault breccia is found to varying degrees in the ore zone. Barite, calcite, and fluorite are the principal vein constituents and any one of these minerals may dominate. Locally sphalerite and galena may be the principal vein constituents. Minor chalcopyrite, pyrite, marcasite, and gypsum also occur.

Northern and Northeast Arkansas The Northern and Northeast Arkansas zinc districts (Fig. 47) lie on the southern flanks of the Ozark dome. Zinc mining in northern Arkansas began as early as the 1850's; small scale operations or prospecting have been carried out sporadically since that time. Literature giving a full description of the districts was unavailable to the author. The following brief summary of the districts is taken from Snyder (1968).

The deposits are hosted in Lower Ordovician dolomites. The Smithville formation and the Everton formation (Table IV) are the important host rocks in the Northeast Arkansas and the Northern Arkansas districts, respectively. The orebodies are both stratigraphically and lithologically controlled. Most of the mines are no longer accessible, but Synder (1968) noticed facies changes in the ore bearing bed at one of the mine portals.

Sphalerite is the main ore mineral; galena and chalcopyrite are present in minor amounts. The individual ore zones range in thickness from less than 1 m to about 6 m and may be up to 60 m in width, although usually less than 30. The ore zones may be up to 180 m in length.

Upper Mississippi Valley The Upper Mississippi Valley zinc-lead district covers an area of about 8000 square kilometers in southwestern Wisconsin, northwestern Illinois, and northeastern Iowa (Fig. 47) and has been one of the most important zinc producing regions of the US for many years. The district contains thousands of small lead mines, about 400 zinc mines, and a few small copper mines. About half of the zinc mines were mined primarily before the 1930's and were found to contain only a very few thousand tons of ore. The other half range in size from about 20 000 to 2 000 000 short tons; the average is about 280 000 short tons. The ores are chiefly in the Galena dolomite, and in limestones and dolomites of the Decorah formation and upper part of the Platteville formation, all of the Middle Ordovician age. The Platteville, Decorah, and Galena formations represent an unusually widespread and uniform marine environment of a relatively shallow water platform that had remarkable stability during deposition (Agnew et al., 1956). Reefs, bioherms, bars, channels and other unconformities are notably absent within the ore bearing formations (Heyl, 1968). No post-Precambrian igneous rocks are known in the area and the Precambrian basement unconformably underlies the district at depths of 450 to 600 m.

Heyl (1968) recognizes folds of three orders of magnitude in the district, and many related reverse, strike slip, and normal faults of small to moderate displacement are present. The gentle flexing and faulting of the strata are believed to be the result of gentle compressive rotational adjustment in the underlying crystalline basement, especially along lineaments between basement blocks.

Heyl et al. (1955) describe two types of orebodies (Fig. 51). The first orebodies mined in the district were gash veins containing galena. These are discontinuous veins filling joints in the Galena dolomite, often stratigraphically above the more productive sphalerite-galena deposits. The most productive deposits are the pitch and flat type, in

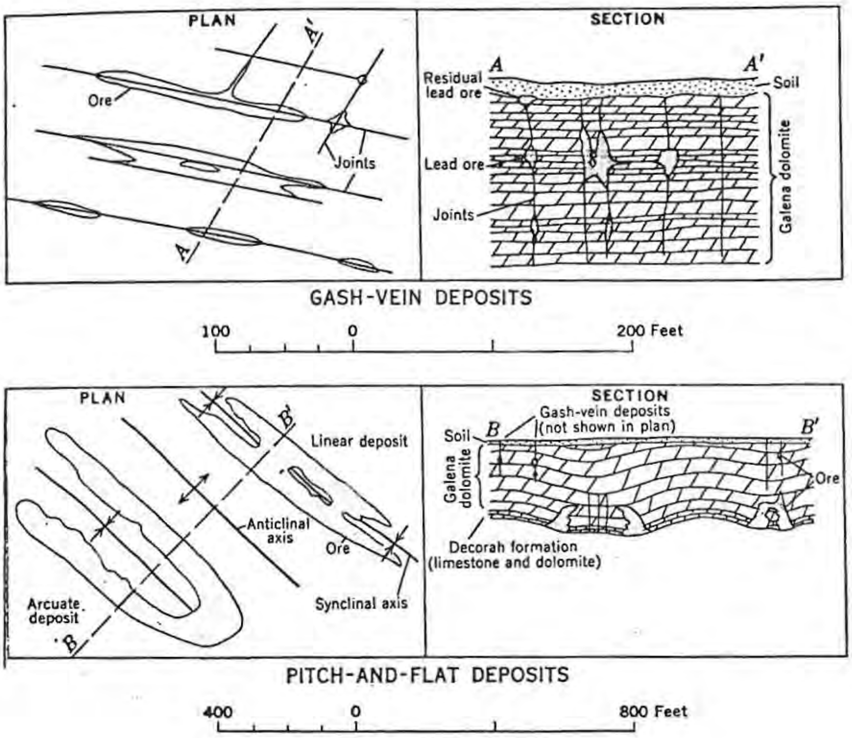


Figure 51 Diagrammatic plans and sections illustrating typical patterns of gash-vein lead deposits, underlying pitch-and-flat zinc deposits of the arcuate and linear types, and stratigraphic positions relative to one another. From Heyl et al., (1955).

which the pitch is a steeply inclined fracture and the flat is a bedding plane. Deposits of this type occur along reverse and bedding plane faults of small displacement, which are generally confined to the flanks of folds and tend to follow the outline of the folds to from arcuate or linear patterns. Sphalerite is the main ore mineral in this type of orebody, but galena or pyrite, and marcasite or barite may also be present. Reynolds (1958) concludes that solution thinning of minor limestone beds within the otherwise dolomitic Platteville and Decorah formations played the dominant role in the formation of the structures in which the ore occurs. A disconformity occurs at the base of the Silurian, about 100 m stratigraphicaly above the top of the Decorah formation, and dissolution of these limestone beds may have occurred at this time.

The fracturing that has determined the location of the orebodies is tectonic in origin. A reasonable amount of faulting and readjustment in the basement rocks may have been responsible for much of the folding and faulting in the overlying sediments, and this is a plausible method for mineralizing solutions to gain access to the sediments in which the ore was deposited. Heyl (1968) states, "The age of the deposits cannot be definitely determined from any known relations in the Mississippi Valley. The rocks of the district were all gently warped during the main regional tectonic deformation, which was at least post-Middle Silurian in age, and, to judge from nearby regional relations, probably Pennsylvanian or later."

Residual Deposits of Barite, Manganese, and Iron

The deeply weathered Lower Cambrian Shady and Rome formations are host to residual deposits of barite, manganese oxides, and brown iron ore in the Carterville district in the Valley and Ridge province of Georgia (Fig. 52). Unfortunately, up to date information on the district is

Figure 52 Index map showing location of Cartersville district, Georgia. Modified from Kesler (1950).

unknown to the author and it is not known if the district is still in production, but figures available indicate that the district has been a major producer. Mining of brown iron ores (limonite) began about 1840 and the total output through 1943 was about 5 million tons. Mining of barite began about 1887 with a total output of concentrates through 1943 was about 1.83 million tons, or about 24% of the total US production for that period. The barite residual deposits were derived from low grade vein and cavity fillings within the Rome formation. The deposits of manganese and iron oxide were erosionally concentrated from syngenetic minerals in the associated rocks. The manganese is derived from the carbonates of the Shady formation which has been shown to contain from 0.2% to more than 1.2% Mn, and most of the iron ore production has been from surficial weathered zones of the Shady and Rome formations (Kester, 1950).

Bauxite

Many small bauxite deposits are found in folded rocks of Paleozoic age in the Valley and Ridge province from west-central Virginia to northeastern Alabama (Fig. 53). Most deposits occur in residuum that accumulated in sinkholes or other depressions in carbonate rocks of Cambrian or Ordovician age. Bauxite formation took place during the Paleocene-Eocene interval.

The bauxite deposits, as described by Overstreet (1964), are small pockets or lenses of bauxite that are enveloped by clayey and cherty residuum derived from weathering of the enclosing carbonate rocks. Deposits range in size from a few meters to 60 m across and may extend to depths of 60 m. Deposits in some districts are elongated along faults or joints, some of which extend through two or more neighboring deposits. The longest dimension of the deposits tends to be parallel the fractures.

The total reserves of bauxite in the southern Appalachians are not large. Overstreet (1964) estimated the total measured, indicated, and inferred reserves of metal grade bauxite in deposits in the Valley and Ridge province as of 1960 to be 50 000 tons.

Deposits Associated with Devonian (Taconic) Plutonism

The Baltimore-State Line peridotite complex lies within the Piedmont

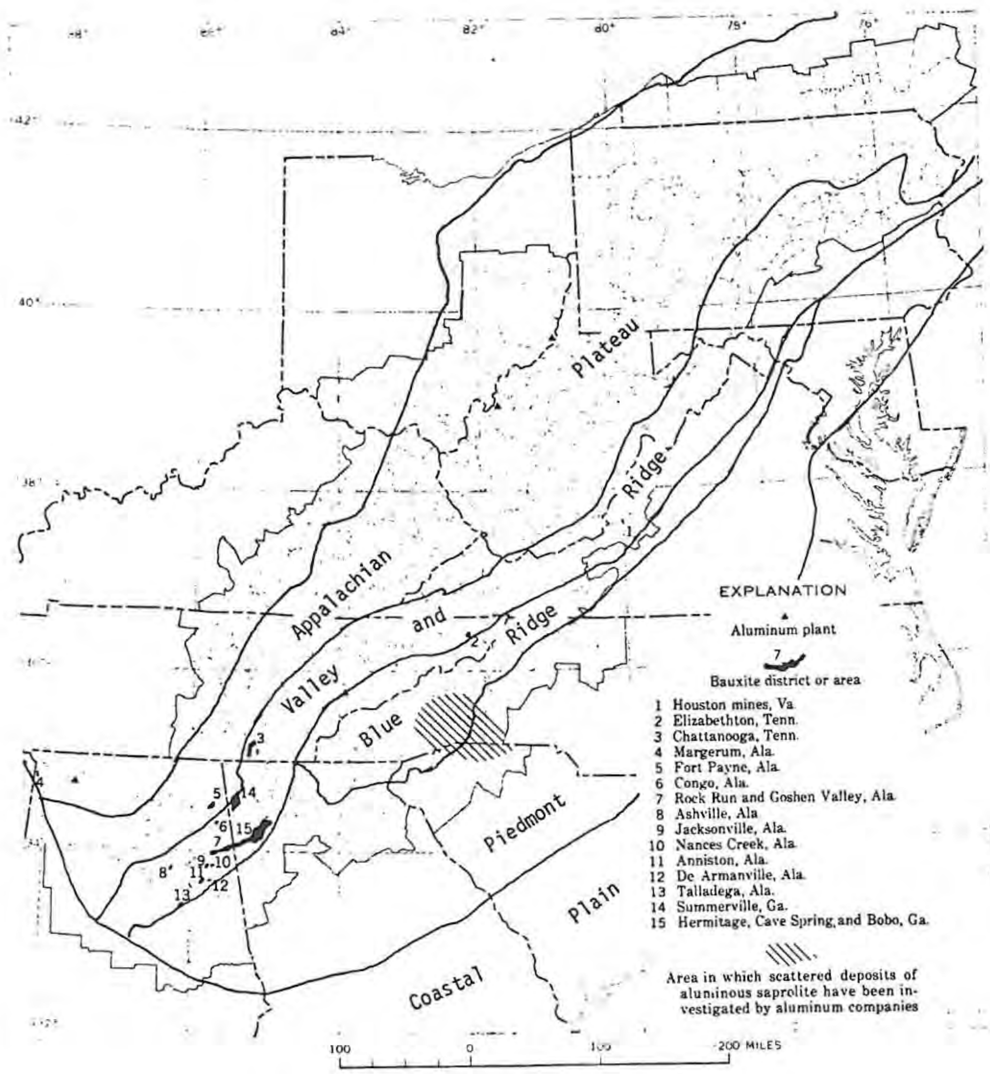


Figure 53 Bauxite deposits and aluminum plants in the Appalachian Region. Modified from Patterson and Sweeney (1968).

province of Maryland, Pennsylvania, and Delaware (Figs. 54 and 55). Deposits of chromite, titaniferous magnetite, rutile, amphibole asbestos, magnesite, and sodium-rich feldspar, have been mined or prospected for in serpentinized peridotites, pyroxenites, and dunites which were emplaced during Taconic orogeny. The serpentine has been extensively quarried for building, decorative, and crushed stone. Chromite was first discovered in the US at Bare Hills, Maryland (Fig. 55) about 1810. Large scale mining of chromite ceased before 1880, and small-scale, intermittent production ended in 1928. The largest of the 40 known chromite mines produced an estimated 200 000 tons of ore, while most of the others produced in the vicinity of 3000 tons (Pearre and Heyl, 1960). Estimates of production of the other commodities are not available.

The serpentinized ultramafics, as described by Pearre and Heyl (1960), are fairly small bodies elongate parallel to the regional

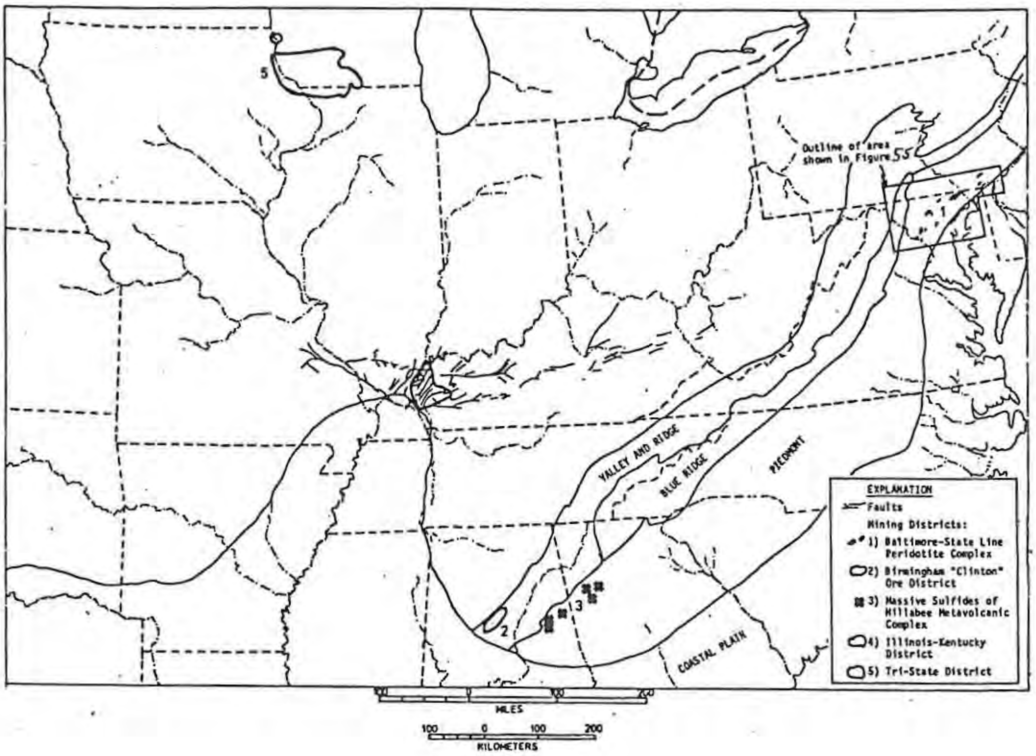


Figure 54 Location map for Devonian through Mississippian ore deposits in the southern Appalachian Mountains and Mississippi Valley.

northeasterly trend and are conformable with the enclosing rocks. The serpentinite bodies are apparently part of a group of plutonic rocks that intruded mica schists and Precambrian granites of the Piedmont during the Taconic orogeny.

Pearre and Heyl (1960) briefly describe the types of ore occurrences as:

1. Massive and disseminated orebodies that are concentrations or segregations of metallic oxides in serpentine (chromite and titaniferous magnetite).
2. Placer deposits in streambeds (chromite).
3. Products of metamorphic alteration of the entire serpentine rock or of one or more of its constituent minerals (talc and soapstone, possibly rutile).
4. Veins in serpentine, mostly small, commonly occupying faults or shear zones (amphibole asbestos, magnesite, and possibly some chromite).
5. In or directly associated with pegmatites intruded into serpentine (sodium-rich feldspar, corundum, and talc).

Analysis of mine dumps indicates that the chromite contains too much iron to be of the best metallurgical grade. The titaniferous magnetite deposits were mined for iron prior to 1900, but the titanium content was

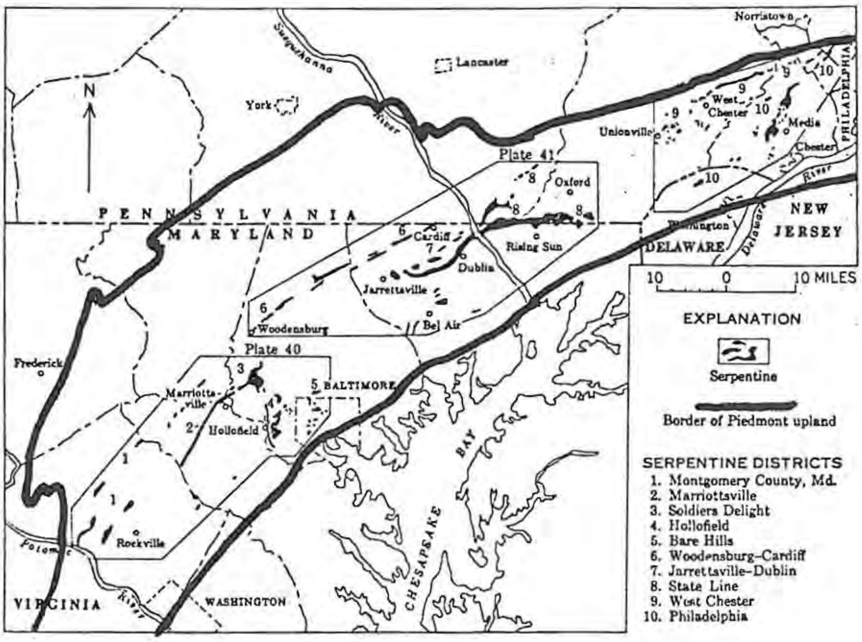


Figure 55 Index map of the Piedmont Upland in Maryland, Pennsylvania, and Delaware, showing serpentine districts. From Pearre and Heyl (1960).

a problem in furnaces, and their small size and relatively low titanium content limits their importance as a potential source of titanium. As of 1960, only talc and serpentine, and a very small quantity of asbestos as a byproduct, were being mined in the area.

Silurian Sedimentary Iron Ores

The sedimentary iron ores that lie within the Valley and Ridge provinces of the southern Appalachians constitute one of the largest reserves of iron within the US. These deposits are well described by Simpson and Gray (1968), and Wright et al. (1968).

Iron was deposited intermittently from Early Cambrian to Pennsylvanian time in the shallow seaway of the Appalachian miogeosyncline, but the most extensive deposition took place in Middle Silurian time when ferruginous beds were deposited from New York State to Alabama. The iron-bearing beds were deposited as elongate lenses near and roughly parallel to the northeast trending shoreline. The relation of the Silurian shoreline and reef zones of the eastern US is shown in Figure 56. In general, the ores near the southeastern paleoshoreline have more clastic quartz grains and are therefore more siliceous, whereas those farther from the shoreline have more calcite. The ores grade outwards, away from the shore, into ferruginous limestone. The Clinton ores are associated and interbedded with limestones, siliceous limestones, calcareous siltstones and shales, sandstones, and conglomerates.

The ore-bearing beds have been eroded away east of the easternmost beds shown in Figure 56, but this is also probably the easternmost limit of significant iron deposition in Silurian time. West and north of the line of outcrop the ore shows a decrease in iron content. Silurian beds are not preserved on the crest and flanks of the Cincinnati arch, but are present in central Kentucky and in Ohio and ferruginous beds have been mined in one small area in Kentucky.

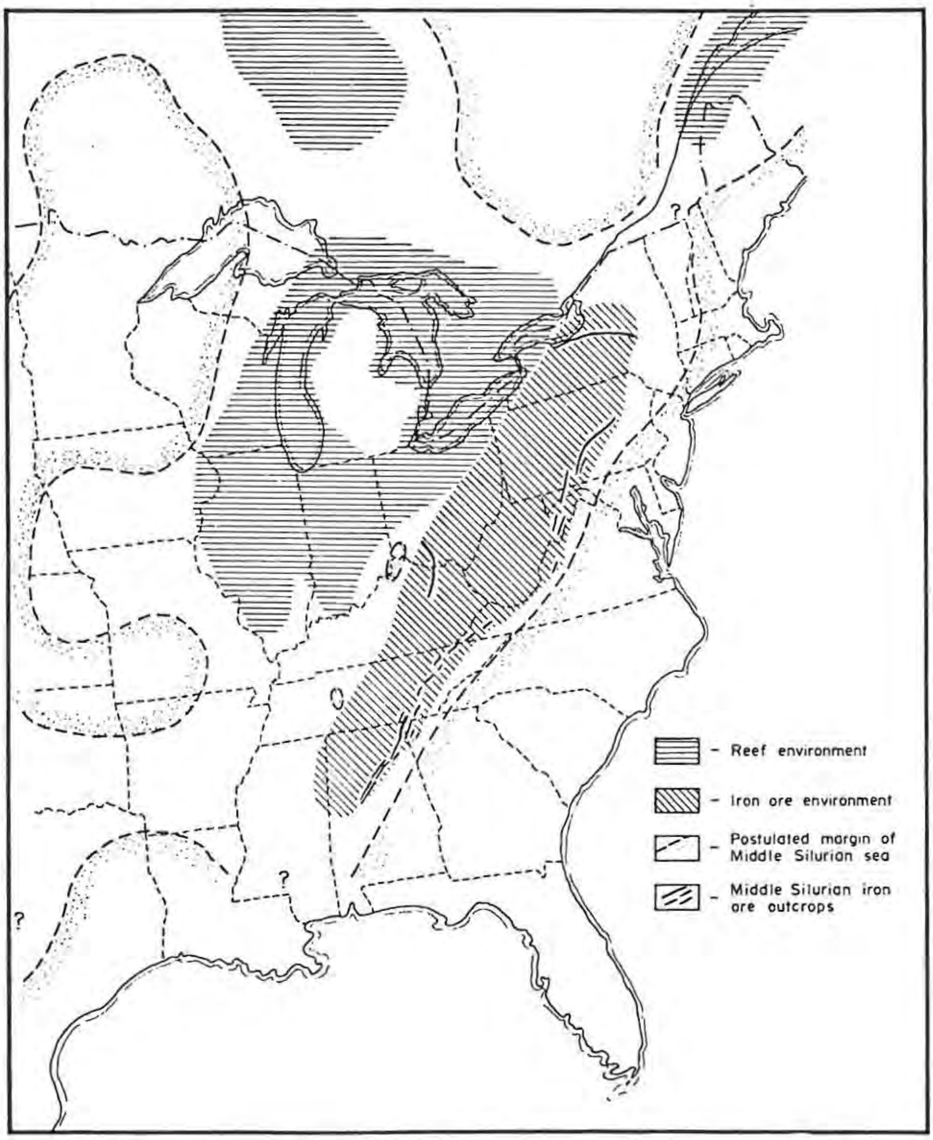


Figure 56 Distribution of the Silurian Clinton iron ores as related to Silurian paleogeography and marine environments. From Stanton (1972).

The principal iron mineral in Clinton ores is hematite which occurs in three forms:

(1) oolites,
(2) replacement of fossil remains, and
(3) cementing material coating and filling in around original oolites, sandgrains, and fossils.

The unweathered ore is hard and compact and contains from 25 to 50 weight per cent calcium carbonate. The silica and alumina content of the ore generally increases as the carbonate decreases and tends to be greatest in oolitic ores.

Weathered near surface ore is soft and generally of higher grade. The soft ores have been the most intensively mined, but many of these mines were abandoned when the lower grade, hard ores were penetrated at depth. However, some of the hard ores contain the proper proportion of carbonate and silica to be "self-fluxing" and can therefore be economically exploited even though the iron content is lower. Also, some ores with excessive carbonate have been blended with ores with the proper silica content to produce a viable product.

The Clinton ores attain their maximum development in Alabama, particularly in the Birmingham district (Fig. 54) where several seams and zones of ferruginous sandstone are present in the upper part of the Red Mountain formation. The ore occurs in lenticular beds and shows extreme textural variations and crossbedding, and is generally intercalated with sandstones, shales, and limestones. There are three seams of hematite ore. The Big Seam ranges in thickness from 5 to 10 m and is economically the most important, though only half is ore grade in most places. The Irondale Seam is 2 to 3 m thick and the Ida or "Hickory Nut" Seam is only about 1 to 2 m thick and has not been mined. The higher grade, softer parts of the seams were mined out long ago by open cut methods. The remaining oolitic and fossiliferous ore contains 35-39% Fe, abundant calcium carbonate, and is "self-fluxing."

The Birmingham district has produced steel from hematite ores since 1899. The mines generally produced more than 6 million tons of ore per year until the late 1950's. Production since then has declined to an annual rate of about 1.5 million tons of ore (as of 1968). Reserves in the district are enough to last several decades. Abundant nearby supplies of coking coal in overlying Pennsylvanian strata have helped to make Birmingham a major steel producing center.

In northeastern Alabama, northwestern Georgia, and eastern Tennessee the Clinton ores crop out along ridges and dip beneath younger rocks which are generally coal bearing. The soft, near surface ores have been mined by open cut along many miles of outcrop, and relatively shallow underground operations extracted hard ores where grade and thickness permitted. North of Tennessee the Clinton ores are generally thin and low grade, but crop out extensively. Small scale mining operations were conducted mostly in the 1800's and have long since been abandoned. Ferruginous sandstones of Silurian age in southwestern Virginia attain a thickness of 6 to 14 m, but average only about 20% iron, far to low a grade to be economic.

Deposits Associated with Devonian Island Arc Systems

Strata-bound massive sulfide deposits occur in the Hillabee metavolcanic complex within the extreme southern portion of the Piedmont province of northeastern Alabama and northwestern Georgia (Fig. 54). The occurrence of sulfide mineralization in the Hillabee greenstones has been known for more than 100 years and production of the ore has been intermittent for the last century.

Feiss and Hauck (1980) have classified these deposits as the Ore knob type on the basis of Rankin's (1976) speculation that a Precambrian salient might be present in northwestern Georgia and northeastern Alabama. The host rocks would, therefore, represent sediments, volcaniclastic sediments, and volcanic rocks associated with Late Precambrian intracontinental rifting.

Recent work by Tull and Stow (1982) has shown that the basal, dominantly pyroclastic portion of the Hillabee complex is interlayered with the upper portion of the Talladega group, which locally contains a Lower to Middle Devonian fossil assemblage. Moreover, Tull and Stow (1982) conclude that the Hillabee greenstone is apparently the distal continentward portion of a tholeiitic volcanic arc system that developed during the Middle Paleozoic in the southernmost Appalachian region. They further state that geochemical and stratigraphic data imply an ensialic island arc of the Andean-type continental margin. Stow and Tull (1982) interpret the sulfides as having been deposited on the sea floor, distal from the volcanic sources which were to the southeast. The Hillabee deposits are similar to the North Carolina and Virginia deposits with respect to geometry, structural history, associated rock types, base metal abundances, and igneous character of the host rocks (Tull and Stow, 1982), but the Hillabee deposits are anomalous with respect to age, and are the youngest greenstones yet found in the southern Appalachians.

Most of the prospecting and mining activity within the Hillabee greenstone has occurred in the Pyriton district in the north-central portion of the outcrop belt (Fig. 57). At Pyriton the sulfides occur in a layer up to 7.6 m thick which can be traced continuously for at least 2 km along strike. Stow and Tull (1982) list the sulfides, in decreasing order of abundance, as pyrite, chalcopyrite, sphalerite, and galena, with trace amounts of pyrrhotite and covellite. Pyrite and chalcopyrite exhibit evidence of metamorphic remobilization. Gair and Slack (1980) estimate that the district contained some 3 million short tons of ore to a depth of 150 m, with an average grade of 1.2% Cu and 0.5% Zn.

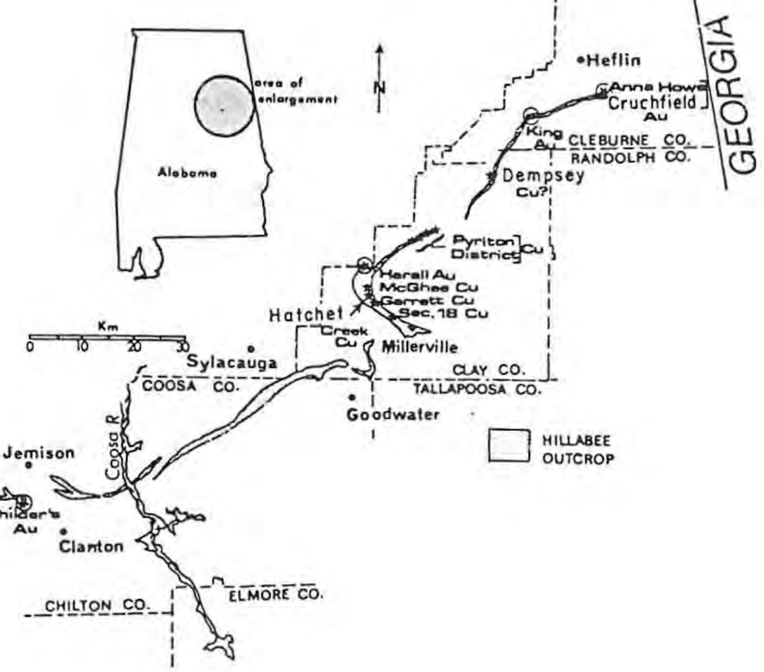


Figure 57 Locations of mines and mineralized areas reported for the Hillabee Greenstone. From Tull and Stow (1982).

Uranium in Devonian Shales

The Chattanooga shale is part of an extensive blanket of shale and other marine rocks that were deposited in the sea that covered large parts of the North America in Late Devonian-Early Mississippian time. It is less than 10 m thick and can be followed from Alabama to New York and Michigan, and westward to the midwest and Oklahoma.

Possibly the first economic use for which the shales were investigated was a secondary source of oil; however, the yield of the shale is only about 10 gallons per short ton of shale, which is much lower than that of some of the oil shales in the western US. Since 1946 the Chattanooga shale has been investigated as a large tonnage, low grade source of uranium. The uranium content of the shale ranges between 0.001% and 0.03% (Conant and Swanson, 1961). Glover (1959) concluded that the average uranium content of the shale is about 0.005%. The grade normally decreases where the thickness increases greatly or where the shale contains phosphate nodules. The current supply of, and demand for, uranium insures that the Chattanooga shale will not be mined for its uranium content for many decades, if ever. Other possible products that might be obtained from the shale include phosphate, black pigment, sulfuric acid, and light weight aggegrate for cement (Conant and Swanson, 1961).

The shale is composed of about 20-25% quartz, 25-30% clay and mica, 10% feldspar, 10-15% pyrite, 15-20% organic matter, and 5% miscellaneous constituents (Conant and Swanson, 1961). It was deposited in shallow seas and is underlain by a thin sandstone unit which was deposited on the Late Devonian erosional surface. The uranium is thought to have been removed from the sea water due to the affinity of organic substances for uranium.

Deposits Associated with Mississippian Carbonates

Unlike other Mississippi Valley type deposits in the US, which occur in Cambrian and Ordovician limestones and dolomites, the Illinois-Kentucky and Tri-State deposits occur in limestones and dolomites of Mississippian age which were deposited in the Kaskaskia seas which transgressed the continental interior during the Acadian Orogeny.

Illinois-Kentucky District

The Illinois-Kentucky mining district encompasses an area of some 2600 square kilometers (Fig. 54) and is the largest producer of fluorspar in the US. Since 1880 the district has accounted for 80% of all US production of fluorspar.

The earliest mining in the district was for lead in 1835. From this time to the early 1870's little fluorite was mined, but producton has increased since then. Zinc has been produced for many years, and since 1940 the district has been a major source of zinc, both as a byproduct and as a main product. Substantial quantities of barite have been produced at intervals. Prior to the 1930's almost the entire production from the district was from vein ores. Since that time the amount of production from the numerous bedding-replacement deposits near Cave in Rock, Illinois (Fig. 58) has risen, so that by the late 1960's this type of ore constitutes the largest proportion of ore mined.

The Illinois-Kentucky mining district is just south of the intersection of the Rough Creek - Shawneetown, Cottage Grove, and New Madrid fault zones (Fig 49). According to Heyl (1972), "The district is centered in the most complexly faulted area in the central craton of the United States. The district lies within a collapsed, faulted, and partly rotated domal anticline, the apex of which is Hicks Dome in southern Illinois. The major New Madrid fault zone slices the large domal anticline of which Hicks Dome is the apex... Unlike the Lexington dome to the east and the Ozark dome to the west, which have been positive domal uplifts from early Paleozoic or possibly Precambrian time to the present, Hicks Dome rose in late Paleozoic time and collapsed by Late Cretaceous."

The sedimentary rocks exposed in the district range in age from Late Devonian through Early Pennsylvanian. Igneous intrusive rocks occur as mafic dikes and, less commonly as sills; in Illinois, intrusive dike- or plug-like bodies of breccia occur.

Most fluorspar bodies in the district occur either as steeply dipping fissure veins along faults or as very gently dipping to nearly horizontal bedding-replacement deposits along certain limestone horizons of Late

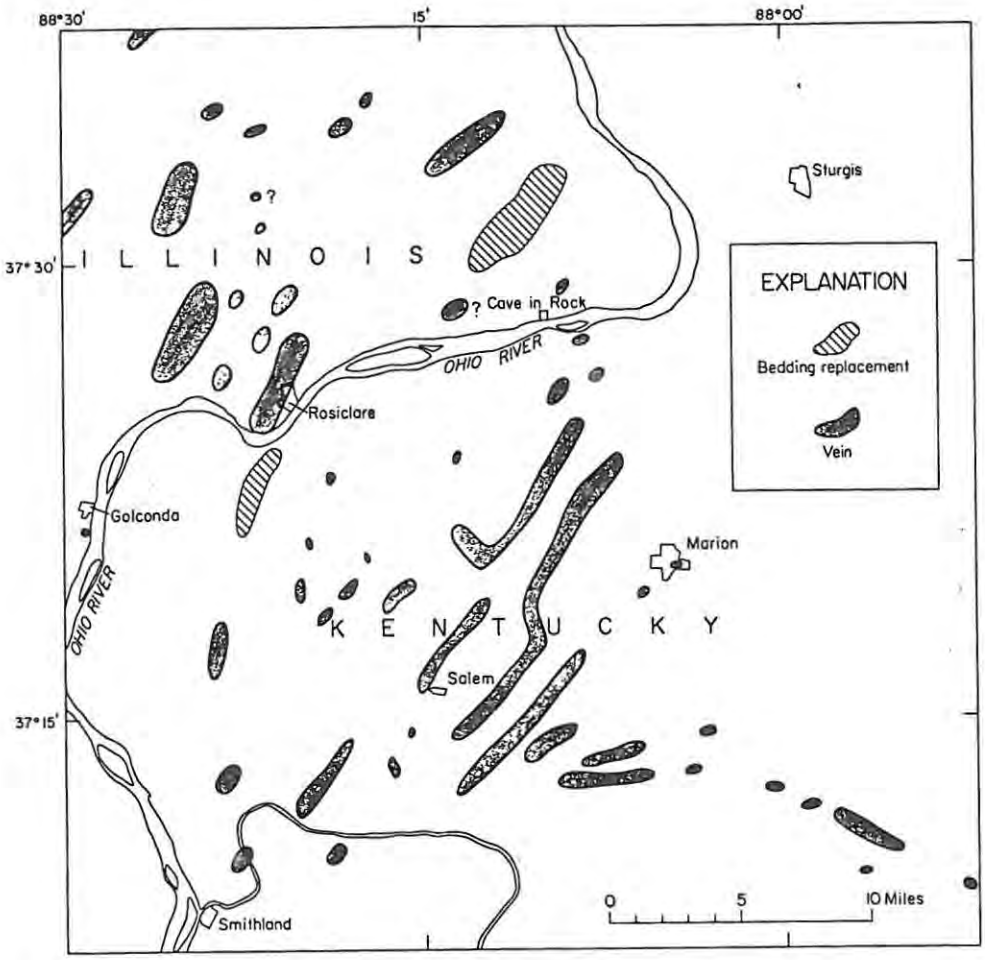


Figure 58 Illinois-Kentucky fluorspar district, showing mineralized area. Modified from Trace (1973).

Mississippian age (Fig. 59). A few of the deposits are comprised of a combination of both types.

The vein deposits occur in all parts of the mining district and consist of calcite which has been locally replaced to a greater or lesser degree by fluorspar. Most of the vein deposits occur along northwest- and north-trending normal faults. The workable veins average in width from 1 to 3 m and may reach a width of up to 14 m. The length of the ore shoots is generally from 60 to 120 m, and may extend 30 to 60 m down dip.

The known bedding replacement deposits are found only in two areas (Fig. 58). These deposits are elongated bodies that trend northeastward, and less commonly southeastward. According to Grogan and Bradbury (1968), "The bedding-replacement deposits follow the course of groups of joint-like fractures and minor pre-mineral faults trending N45^{o} to 60^{o}E and N30^{o} to 85^{o}W. The northeast-trending fracture zones clearly are the most persistent and support the largest orebodies...

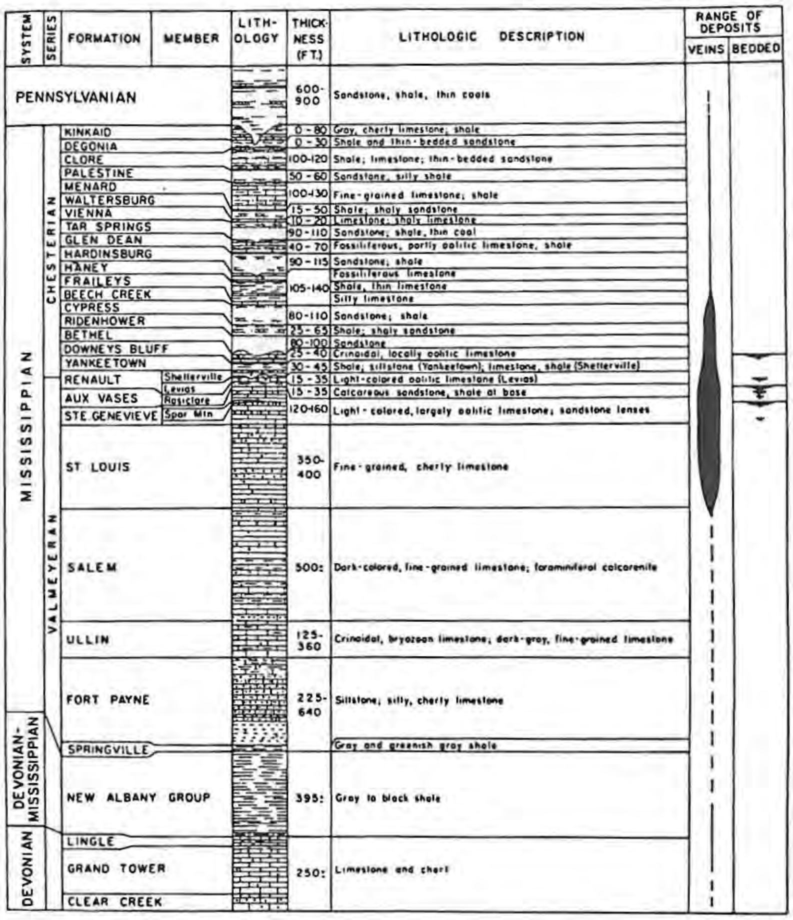


Figure 59 Stratigraphic column of exposed formations in the Illinois-Kentucky mining district. Range of deposits columns are scaled to correlate with lithology column, e.g., the three main bedded horizons are the top part of the Downeys Bluff, top part of the Ste. Genevieve, and the Spar Mountain Member. From Grogan and Bradbury (1968).

Although most of the ore formed by direct replacement of limestone along these fracture zones, certain features associated with the orebodies indicate that there also was solutional removal of limestone." The orebodies are commonly 15 to 60 m wide and 2 to 6 m in thickness. The length may range from 60 m to 2 km.

Calcite and fluorite are the dominant minerals in the deposits, although sphalerite, galena, and barite are very abundant locally. Chalcopyrite, marcasite, pyrite, witherite, strontianite, smithsonite, cerussite, and malachite also occur.

The general location of the Illinois-Kentucky district is probably structurally controlled by the intersection of the ancient major fault systems with a large northwest-trending structural uplift. Faulting was without a doubt the primary factor within the district that controlled the location of both vein and bedding-replacement deposits.

Tri-State District

The Tri-State zinc-lead district covers an area of about 5000 square kilometers in southwestern Missouri, northeastern Oklahoma, and southeastern Kansas (Fig. 54). Mining has been nearly continuous in the district from about 1848 to 1955. The district's combined production of zinc and lead concentrates has been valued at over 2 billion dollars (Brockie et al., 1968), ranking it as one of the world's greatest mining districts.

The Tri-State district is located on the northwestern flank of the Ozark uplift. The Mississippian and Pennsylvanian strata exposed here dip to the northwest at about 3-5 meters per kilometer, but folding and normal faulting may cause irregularities in the regional dip. The region is characterized by intersecting structural elements (Fig. 60). According

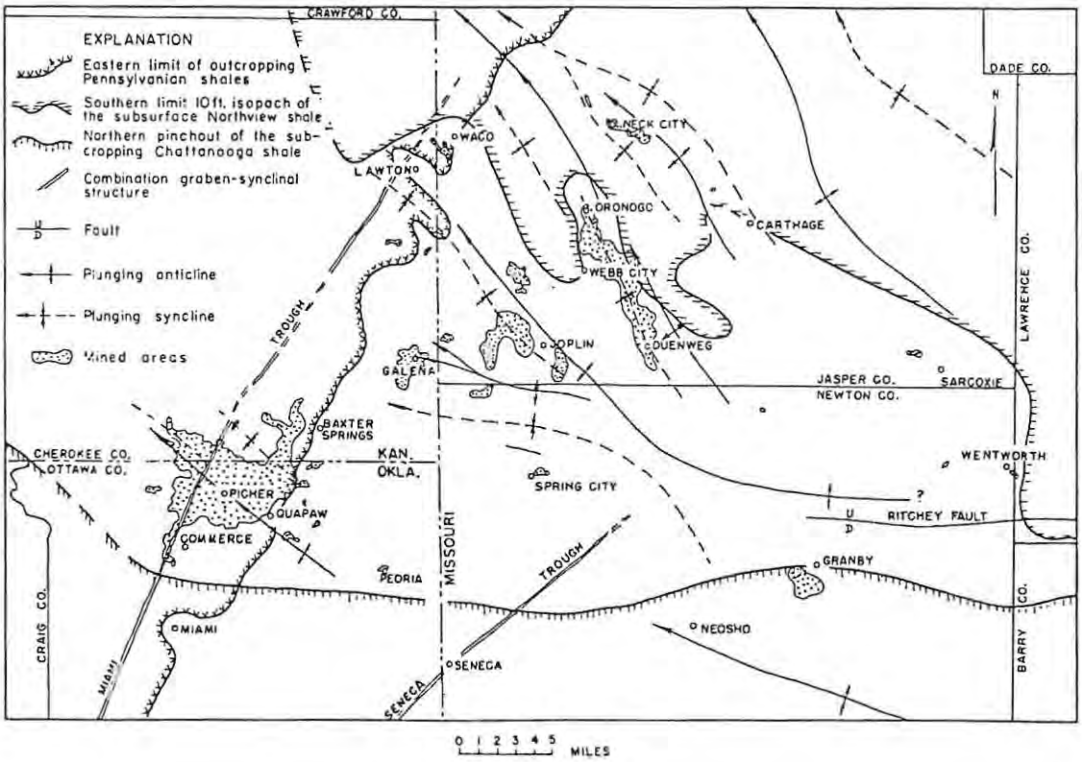


Figure 60 Map of the Tri-State District, showing the major structural and geological features. From Brockie et al. (1968).

to Hagni (1976), the major structures in the area appear to reflect a pattern of basement faulting. The faults are probably Precambrian age and have apparently experienced subsequent movement and periodic rejuvenation during repeated uplifts of the Ozark uplift.

Major production in the district has been obtained from 6 beds in the 60 to 120 m-thick Mississippian Boone formation, a dolomitized cherty limestone. The Mississippian limestones are unconformably overlain by the Pennsylvanian Cherokee shale, which is regarded to have acted as an impermeable barrier to rising mineralizing solutions which aided in the localization of these ore deposits (Brockie et al., 1968).

The ore bodies of the Tri-State district are divided into 3 groups of different shapes (Hagni, 1976):

1. "runs",
2. "circles", and
3. "sheet" deposits.

A "run" type orebody is an elongate, tabular body of chert breccia, which normally follows a stratum, but locally may break through from one to another. "Runs" vary from 3 to 150 m in width, may be more than 1000 m in length, and more than 30 m thick (Brockie et al., 1968). Most of the "runs" tend to follow the edges of elongate to roughly circular dolomitic masses, which gives the orebody an arcuate shape in plan view. The orebodies exibit a definite mineral zonal pattern. An elongated central dolomitic core is surrounded progressively outward by the main ore zone, a zone of jasperiod, a chert boulder zone, a sparry calcite limestone zone, and a fossiliferous limestone zone. One or more of the zones may be absent (Brockie et al., 1968).

"Circle"-type deposits are "runs" that form partial to nearly complete circular map patterns. These deposits have the same mineral zonal pattern as the "runs". The diameter of the circles ranges from 100 m up to 2.5 km.

The "sheet" deposits are stratified, partly broken, mineralized chert bodies. They are commonly 3.5 to 4.5 thick and have an areal extent of up to 1 km. The ore minerals and associated jasperiod are found in horizontal layers, 1 to 10 cm thick, intercalated with chert beds 15 to 30 cm thick, and are in partially broken ground resulting from slight folding and fracturing of the chert. There is little or no brecciation associated with these deposits.

The mineralogy of the deposits is similar to other Mississippi Valley deposits in their simplicity. Sphalerite and galena are the dominant sulfides, with lesser chalcopyrite, pyrite, and marcasite. The ore grade averages approximately 3% Zn and 1% Pb.

The fundamental control on the localization of the ore is the collapse breccias that developed during periodic uplift and erosion of the area in Mississippian time. Structural features have played a significant roll in determining the location and extent of many of the district's ore fields. For example, the Picher field (Fig. 60) is located at the intersection of the Miami trough and the Bendelari monocline. The folds, faults, breccias, and other open-space features in the rocks that are associated with these structures have provided channelways and sites of deposition for mineralizing solutions. Ore deposits occur several kilometers to the southwest along the Miami trough beyond the main Picher field, and to the southwest along the Bendelari monocline (Hagni, 1976). The 38th Parallel lineament lies about 40 km north of the Tri-State district, but bears no evident relationship to the deposits.

SUMMARY AND CONCLUSIONS

Plate tectonic theory provides logical explanations for the major tectonic events in the eastern US during Paleozoic time. The details of these tectonic events are becoming more apparent with the accumulation of new data, especially radiometric age dates. When plate tectonic theory is applied to specific tectonic events for which there is no substantial evidence, such as intracontinental hotspot rifting environments and Precambrian subduction zones, the proposed models may become very speculative.

A misconception concerning the geology of the central US is that this region is structurally stable. However, geologists are currently paying considerable attention to the interlocking network of faults that in a general way follow the 38th parallel of latitude from west-central Virginia into Central Missouri (and may extend farther to the east and west). Most of the displacement along this zone occurred during the Precambrian, but different parts have moved during several periods of post-Precambrian time. In the basement the lineament may be a wide fracture zone that extends deep into the crust and is thus responsible for the magmatic iron deposits of the Southeast Missouri and may be either directly or indirectly responsible for the localization of the Mississippi Valley type deposits that occur sporadically along its length. Whether or not plate-tectonic processes operated during the Precambrian is open to speculation and the lineament may or may not be related to plate tectonic activity, but it is obvious that throughout time inherent zones of weakness are important in the localization of ore deposits.

The occurrence of several major mineral districts at the intersections of the 38th parallel lineament with other major structural features, particularly in some uplifted areas and fault zone intersections, suggests that other similar structural uplifts and fault-zone intersections should be investigated for undiscovered new districts or extensions of known districts. Small uneconomic mineral occurrences along fault zones intersecting the lineament may merit further examination as they may be indications of undiscovered deposits at depth.

The overall tectonic environment in the Appalachian region was an important control on the localization of massive sulfide, gold, titanium, and tungsten deposits. The deposits occur in clusters, either in Late Precambrian spreading centers and associated rift systems related to the breakup of proto-Pangea, or in Eocambrian and Devonian low-potassium tholeiitic volcanic and plutonic rocks associated with the volcanic island arc systems which developed during the closing of the Iapetus Ocean. Feiss and Hauck (1980) are confident that moderate sized (1-10 million ton) massive sulfide deposits are yet to be found at depth in these regions of the southern Appalachians, but large (greater than 20 million ton) massive sulfide deposits are unlikely to exist.

The Mississippi Valley carbonate-hosted deposits of lead-zinc-barite-fluorite, that occur to some extent throughout the Paleozoic section, and the Silurian "Clinton" iron ores owe their origin and distribution to normal sedimentary and diagenetic processes resulting from the transgressions of the epeiric seas . Others, such as the residual deposits of managnese iron, and aluminum, owe their existence to the afore mentioned processes, but must also have had subsequent exposure to the concentrating mechanism of weathering in a stable environment.

The Mississippi Valley type occur primarily around paleo-basement highs and paleoshorelines; therefore, the formation of domes and arches within the continental interior during bathygenic episodes was a major factor controlling the localization of these deposits. These broad upwarps were preferential sites for reefal development and facies changes, and, during epeirogenic periods, these positive features have resulted in erosion and karsting of the the carbonate rocks by meteoric waters and have thus been prepared for mineralization. Deposits of this type are most common below a pre-Middle Ordovician unconformity and should be sought along major domes and arches, and along major lineaments. The association of Applachian type deposits with arches is indeterminate because a structure as subtle as an arch would be difficult to detect following overprinting by the deformation of the Alleghany orogeny; however, there is no reason to suspect that this type of positive feature did not play a role in their location.

In conclusion, plate movements were a major control on the Paleozoic tectonic history of the eastern US and were also the primary control on the localization of the base metal, gold, tungsten, chromite, and titanium deposits of the southern Appalachians. However, important sedimentary and diagenetic deposits were localized primarily by arch, dome, and basin development during bathygenic episodes. Whether these submergent episodes are the result of plate motion or whether plate motion is indirectly related to submergent episodes, as suggested by Sloss and Speed (1974), remains a problem that needs to be investigated and debated further.

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REFERENCES

Addy, S., and Ypma, P., 1977, Origin of massive sulfide deposits at Ducktown, Tennessee: An oxygen, carbon, and hydrogen isotope study : Econ. Geol., Vol. 72, No. 245, p. 1245-1268.

Agnew, A., Heyl, A. Jr., Behre, C., Jr., and Lyons, E., 1956, Stratigraphy of Middle Ordovician rocks in the zinc-lead district of Wisconsin, Illinois, and Iowa : US Geol. Surv. Prof. Pap. 274-K, p.251-312.

Bickford, M., Sides, J., and Cullers, R., 1981, Chemical evolution of magmas in the Proterozoic terrane of the St. Francois Mountains, southeastern Missouri, 1. Field, petrogaphic, and major element data : Jour. Geophys. Res., Vol. 86, No. B11, p. 10365-10386.

Bridge, J., 1955, Disconformity between Lower and Middle Ordovician series at Douglas Lake, Tennessee : Geol. Soc. Amer. Bull., Vol. 66, p. 725-730.

Brobst, D., and Wagner, R.J., 1967, Barite, in Mineral and Water Resources of Missouri, Vol. 43, Second Series : Missouri Dept. of Business and Administration, Rolla, Mo., p. 99-106.

Brockie, D., Hare, E., Jr., and Dingess, P., 1968, The geology and ore deposits of the Tri-State district of Missouri, Kansas, and Oklahoma, in Ore Deposits of the United States, 1933-1967, Volume 2, Ridge, J. (ed): Am. Inst. Min. Metall. Petrol. Engrs, New York, p. 400-430.

Brown, H., and Weinberg, E., 1968, Geology of the Austinville-Ivanhoe district, Virginia ,in Ore Deposits of the United States, 1933-1967, Volume 1 Ridge, J. (ed) : Am. Inst. Mine. Metall. Petrol. Engrs., p. 169-186.

Bryant, B., and Reed, J. Jr., 1961, The Stokes and Slurry Counties quartzite area, North Carolina -- a window?; US Geol. Surv. Prof. Paper 424D, p. D61-D63.

Bryant, B., and Reed, J., Jr., 1970, Structural and metamorphic history of the southern Blue Ridge, in Studies of Appalachian Geology : Central and Southern, Fisher, Pettijohn, Reed, and Weaver (eds) : Interscience Publishers, New York, p.213-225.

Callahan, W., 1964, Paleophysiographic premisis for prospecting for strata-bound base metal mineral deposits in carbonate rocks : CENTO Symposium on Mining Geology and Base Metals, Ankara, p. 191-248.

Callahan, W., 1968, Geology of the Friedensville zinc mine, Lehigh County, Pennsylvanian, in Ore Deposits of the United States, 1933-1967, Volume 1, Ridge, J. (ed) : Am. Inst. Min. Metall. Petrol., Engrs., New York, P. 94-107.

Callahan, W., 1977, The history of the discovery of the zinc deposit at Elmwood, Tennessee, concept and consequences : Econ. Geol., Vol. 72, No. 7, pp 1382-1392.

Carpenter, R., 1970, Metamorphic history of the Blue Ridge province of Tennessee and North Carolina : Geol. Soc. Am. Bull., Vol. 81, No. 3, p. 749-762.

Casadevall, T., and Rye, R., 1980, The Tungsten Queen deposit, Hamme district, Vance County, North Carolina : A stable isotope study of a metamorphosed quartz-huebnerite vein : Econ. Geol., Vol. 75, p. 523-537.

Clark, T., and Stearn, C., 1960, The Geological Evolution of North America : Ronald Press, New York, 434p.

Colton, G., 1970, The Appalachian basin -- its depositional sequences and their geologic relationships, in Studies of Appalachian Geology : Central and Southern, Fisher, Pettijohn, Reed, and Weaver (eds) : John Wiley and Sons, Inc., New York, p. 5-48.

Conant, L., and Swanson, V., 1961, Chattanooga shale and related rocks of central Tennessee and nearby areas; US Geol. Surv. Prof. Pap. 357, 91p.

Cook, F., Albaugh, D., Brown, L., Kaufman, S., and Oliver, J., Hatcher, R., 1979, Thin-skinned tectonics in the crystalline southern Appalachians, COCORP seismic-reflection profiling of the Blue Ridge and Piedmont : Geology, Vol. 7, No. 12, p. 563-567.

Cook, F., Brown, L., and Oliver, J., 1980, The southern Appalachians and the growth of continents : Sci. Am., Vol. 243, No. 4, p.124-138.

Crawford, J., and Hoagland, A., 1968, The Mascot-Jefferson City zinc district, Tennessee, in Ore Deposits of the United States, 1933-1967, Ridge, J. (ed) : Am. Inst. Min. Metall. Petrol. Engrs., New York, p. 242-256.

Davies, W., 1968, Physiography, in Mineral Resources of the Appalachian Region : US Geol. Surv. Prof. Pap. 580, US Govt. Printing Office, Washington, pp. 37-48.

Dewey, J., and Burke, K., 1973, Tibetan, Variscan and Precambrian basement reactivation : Products of continental collision : Jour. Geol., Vol. 81, p. 683-692.

Dewey, J., and Burke, K., 1974, Hot spots and continental breakup : Implications for collisional orogeny : Geology, Vol. 2, No. 2, p. 57-60.

Emery, J., 1968, Geology of the Pea Ridge iron ore body, in Ore Deposits of the United States, 1933-1967, Volume 1, Ridge, J. (ed) : Am. Inst. Min. Metall. and Petrol. Engin., Inc., New York, p. 359-369.

Emmons, W., and Laney, F., 1926, Geology and ore deposits of the Ducktown mining district, Tennessee : US Geol. Surv. Prof. Pap 139, 114p.

Ervin, C., and McGinnis, 1975, Reelfoot rift : Reactivated precursor to the Mississippi embayment : Geol. Soc. Am. Bull, Vol. 86, p. 1287-1295.

Faul, H., Stern, T., Thomas, H., and Elmore, P., 1963, Ages of intrusion and metamorphism in the northern Appalachians : Am. Jour. Sci., Vol. 261, pp. 1-19.

Feiss, G., 1982, Geochemistry and tectonic setting of the volcanics of the Carolina slate belt : Econ. Geol., Vol. 72, p. 273-293.

Feiss, G. and Hauck, S., 1980, Tectonic setting of massive-sulfide deposits in the southern Appalachians, U.S.A. : Proc. Fifth Quad. IAGOD Symposium, p. 567-580.

Fisher, G., 1970, Introduction, in Studies of Appalachian Geology: Central and Southern, Fisher, Pettijohn, Reed, and Weaver (eds) : Interscience Publishers, New York, p. 295-298.

Foose, M., Slack, J. and Casadevall, T., 1980, Textural evidence for a predeformation hydrothermal origin of the Tungsten Queen deposit, Hamme district, North Carolina : Econ. Geol., Vol. 75, No. 4, p. 515-522.

Fullagar, P., and Butler, R., 1979, 325 to 265 m.y.-old granitic plutons in the Piedmont of the southern Appalachians : Am. Jour. Sci., Vol. 79, No. 2, p. 97-128.

Gair, J. and Slack, J., 1980, Stratabound massive sulfide deposits of the US Appalachians : Geol. Surv. Ireland Spec. Paper No. 5, pp. 67-81.

Gary, M., McAfee, R., Jr., and Wolf, C., (eds), 1974, Glossary of Geology: American Geol. Inst., Washington, D.C., 805p.

Glover, L., 1959, Stratigraphy and uranium content of the Chattanooga shale in northeastern Alabama, northwestern Georgia, and eastern Tennessee : US Geol. Surv. Bull 1087-E, p. 133-168.

Glover, L., and Sinha, A., 1973, The Virgilina deformation, a late Precambrian to early Cambrian (?) orogenic event in the central Piedmont of Virginia and North Carolina : Am. Jour. Sci., Vol. 273-A, p. 234-251.

Goldrich, S., Muehlberger, W., Lidiak, E., and Hedge, C., 1966, Geochronology of the midcontinent region, United States, Part 1 : Jour. Geophys. Res., Vol. 71, No. 22, p. 5375-5388.

Grogan, R., and Bradbury, J., 1968, Fluorite-zinc-lead deposits of the Illinois-Kentucky mineral district, in Ore Deposits of the United States, 1933-1967, Ridge, J. (ed) : Am. Inst. Min. Metall. Petrol. Engrs., New York, p. 370-399.

Hadley, J., 1964, Correlation of isotopic ages, crustal heating, and sedimentation in the Appalachian region, in Tectonics of the southern Appalachians, Lowry, W. (ed) : Virginia Polytech. Inst., Dept. Geol. Sci. Mem. 1, p. 33-44.

Hadley, J., 1970, The Ocoee Series and its possible correlatives, in Studies of Appalachian Geology : Central and Southern, Fisher, Pettijohn, Reed, and Weaver (eds) : Interscience Publishers, New York, p. 247-259.

Hagni, R., 1976, Tri-State ore deposits : The character of their host rocks and their genesis, in Handbook of Strata-Bound and Stratiform Ore Deposits, Vol. 6, Wolf, K. (ed): Elsevier Scientific Publishing, Co., New York, pp. 457-490.

Ham, W., and Wilson, J., 1967, Paleozoic epeirogeny and orogeny in the central United States : Am. Jour. Sci., Vol. 265, No. 5, p. 332-407.

Harris, L., 1971, Lower Paleozoic paleoaquifer -- the Kingsport Formation and Mascot Dolomite of Tennessee and southwest Virginia : Econ. Geol. Vol. 66, No. 5, p. 735-743.

Harris, L., and Milici, R., 1977, Characteristics of thin-skinned style of deformation in the southern Appalachians, and potential hydrocarbon traps : US Geol. Surv. Prof. Pap. 1018, 40p.

Hatcher, R., Jr., 1972, Developmental model for the southern Appalachians : Geol. Soc. Am. Bull, V. 83, No. 9, p. 2735-2760.

Hatcher, R., Jr., 1978a, Synthesis of the central and southern Appalachians, U.S.A., in Caledonian Appalachian Orogen of the North Atlantic Region, Tozer, E., and Schenk, P., (eds) : Geol. Surv. Canada Paper 78-13, p. 149-157.

Hatcher, R., Jr, 1978b, Tectonics of the western Piedmont and Blue Ridge, southern Appalachians : review and speculation : Am. Jour. Sci., Vol. 278, No. 3, p. 276-304.

Hayes, W., and Guild, P., 1967, Iron, in Mineral and Water Resources of Missouri, Vol. 43, Second Series : Missouri Dept. of Business and Administration, Rolla, Mo., p. 74-88.

Herz, N., and Eilertsen, 1968, Titanium, in Mineral resources of the Appalachian region : US Geol. Surv. Prof. Pap. 580, p. 437-443.

Heyl, A., 1968, The Upper Mississippi Valley base metal district, in Ore Deposits of the United States, 1933-1967, Ridge, J. (ed) : Am. Inst. Min. Metall. Petrol. Engrs., New York, p. 431-459.

Heyl, A., 1969, Some aspects of genesis of zinc-lead-barite-fluorite deposits in the Mississippi Valley, U.S.A. : Inst. Mine., Metal. Trans./Section B, Vol. 78, No. 756, p. B148-B160.

Heyl, A., 1972, The 38th parallel lineament and its relationship to ore deposits : Econ. Geol., Vol. 67, No. 7, p. 879-894.

Heyl, A., Jr., and Brock, M., 1961, Structural framework of the Illinois-Kentucky mining district and its relation to mineral deposits : US Geol. Surv. Prof. Pap. 424-D, p. D3-D6.

Heyl, A., Lyons, E. , Agnew, A., and Behre, C., Jr., 1955, Zinc-lead-copper resources and general geology of the Upper Mississippi Valley district : US Geol. Surv. Bull. 1015-G, p. 227-245.

Hinze, W., Braile, L., Keller, R., Lidiak, E., 1980, Models for mid-continent tectonism, in Continental Tectonics : Nat. Acad. of Sciences, Washington, D.C., p. 73-83.

Hoagland, A., 1976, Appalachian zinc-lead deposits, in Handbook of Strata-bound and stratiform Ore Deposits, Volume 6, Wolf, K. (ed) : Elseivier Sci. Pub. Co., New York, p. 495-533.

Howell, B., Bridge, J., Deiss, C., Edwards, I., Lochman, C., 1944, Correlation of the Cambrian formations of North America : Geol. Soc. Am. Bull., Vol. 55, No. 8, p. 993-1004.

Hunt, C., 1974, Natural Regions of the United States and Canada : W.H. Freeman and Company, San Francisco, 725 p.

Irving, E., Emslie, R., and Ueno, H. 1974, Upper Proterozoic poles from Laurentia and the history of the Grenville structural province : Joun. Geophys. Res., Vol. 79, p. 5491-5502.

Johnson, J., 1971, Timing and coordination of orogenic, epeirogenic and eustatic events : Geol. Soc. Am. Bull., Vol. 82, No. 12, p. 3263-3298.

Jolly, J., and Heyl, A., 1964, Mineral paragenesis and zoning in the Central Kentucky mineral district : Econ. Geol., Vol. 59, No. 4, p. 596-624.

Kay, M., 1942, Development of the northern Allegheny synclinorium and adjoining regions : Geol. Soc. Am. Bull., Vol. 53, p. 1601-1657.

Kesler, T., 1950, Geology and mineral deposits of the Cartersville district, Georgia : US Geol. Surv. Prof. Pap. 224, 97p.

King, P., 1975, The Ouachita and Appalachian orogenic belts, in The Ocean Basins and Margins, Vol. 3, The Gulf of Mexico and the Caribbean : Plenum Press, New York, p. 201-241.

King, P., 1977, The Evolution of North America (revised edition) : Princeton University Press, Princeton, New Jersey, 197p.

King, P. (compiler), 1969, Tectonic map of North America, 1 : 5,000,000 - scale : US Geol. Surv., 2 sheets.

Kinkel, A., Jr., 1967, The Ore knob copper deposit, North Carolina, and other massive sulfide deposits of the Appalachians : US Geol. Surv. Prof. Pap. 558, 58p.

Kisvarsanyi, E., 1974, Operation basement : buried Precambrian rocks of Missouri -- their petrography and structure : Am. Assoc. Petrol. Geol. Bull., Vol. 58, No. 4, p. 674-684.

Kisvarsanyi, G., 1977, The role of the Precambrian igneous basement in the formation of the stratabound lead-zinc-copper deposits in southeast Missouri : Econ. Geol., Vol. 72, No. 3, pp. 435-442.

Kisvarsanyi, G., and Proctor, P., 1967, Trace element content of magnetites and hematites, southeast Missouri iron metallogenic province, U.S.A. : Econ. Geol., Vol. 62, No. 4, p. 449-471.

Kyle, J., 1976, Brecciation, alteration, and mineralization in the Central Tennessee zinc district : Econ. Geol., Vol. 71, p. 892-903.

Leach, D., 1980, Nature of mineralizing fluids in the barite deposits of central and southeast Missouri : Econ. Geol., Vol. 75, p. 1168-1180.

Lidiak, E., Marvin, R., Thomas, H., and Bass, M., 1966, Geochronology of the midcontinent region, United States, Part 4 : Jour. Geophys. Res., Vol. 71, No. 22, p. 5427-5438.

Magee, M., 1968, Geology and ore deposits of the Ducktown district, Tennessee, in Ore Deposits of the United States, 1933-1967, Volume 1, Ridge, J. (ed.) : Am. Inst. Min. Metall. Petrol. Engrs., New York, p. 207-241.

McCracken, M., 1971, Structural features of Missouri : Report of Investigations No. 49, Missouri Geological Survey and Water Resources, Rolla, Mo., 99p.

Morris, R.C., 1974, Sedimentary and tectonic history of the Ouachita Mountains, in Tectonics and Sedimentation, Dickinson, W. (ed) : Society of Economic Paleontologists and Mineralogists Special Pub. No. 22, Tulsa, Oklahoma, p. 120-142.

Muehlberger, W., Hedge, C., Denison, R., and Marvin, R., 1966, Geochronology of the midcontinent region, United States, Part 3 : Journ. Geophys. Res., Vol. 71, No. 22, p. 5409-5426.

Murphy, J., and Ohle, E., 1968, The Iron Mountain Mine, Iron Mountain, Missouri, in Ore Deposits of the United States, 1933-1967, Volume 1 : Am. Inst. Min. Metal. and Petrol. Engrs., Inc., New York, p. 287-302.

Overstreet, E., 1964, Geology of the southeastern bauxite deposits : US Geol. Surv. Bull. 1199-A, 19p.

Overstreet, W., 1970, The Piedmont in South Carolina, in Studies of Appalachian Geology : Central and Southern, Fisher, Pettijohn, Reed, and Weaver (eds) : Interscience Publishers, New York, pp. 369-382.

Overstreet, W., and Bell, H., 3rd, 1965, The crystalline rocks of South Carolina : US Geol. Surv. Bull. 1182, 126p.

Pardee, J., and Park, C., Jr, 1948, Gold deposits of the southern Piedmont : US Geol. Surv. Prof. Pap. 213, 155p.

Parker, J., 3rd, 1963, Geologic setting of the Hamme Tungsten District, North Carolina and Virginia : US Geol. Surv. Bull. 1122-G, 69p.

Patterson, S., and Sweeney, J., 1968, Aluminum -- metal and raw material, in Mineral Resources of the Appalachian Region : US Geol. Surv. Prof. Pap. 580, p.364-372.

Pavlides, L., 1981, The central Virginia volcanic-plutonic belt : An island arc of Cambrian (?) age : US Geol. Surv. Prof. Paper 1231-A, 34p.

Pavlides, L., Gair, J., and Cranford, L., 1982, Central Virginia volcanic-plutonic belt as a host for massive sulfide deposits : Econ. Geol., Vol. 77, No. 2, p. 233-272.

Pearre, N., and Heyl, A., Jr., 1980, Chromite and other mineral deposits in serpentine rocks of the Piedmont upland, Maryland, Pennsylvania, and Delaware : US Geol. Surv. Bull. 1082-K, p. 707-833.

Plummer, L., 1971, Barite deposition in central Kentucky : Econ. Geol., Vol. 66, p.252-258.

Potter, P., and Pryor, W., 1961, Dispersal centers of Paleozoic and later clastics in the upper Mississipi Valley and adjacent areas : Geol. Soc. Am. Bull., Vol. 72, No. 8, p.1195-1250.

Rankin, D., 1975, The continental margin of eastern North America in the southern Appalachians : the opening and closing of the Proto-Atlantic Ocean : Am. Jour. Sci., Vol. 275-A, p. 298-336.

Rankin, D., 1976, Appalachian salients and recesses : Late Precambrian continental break-up and the opening of the Iapetus Ocean : Journ. Geophys. Res., Vol. 81, No. 32, p. 5605-5619.

Reed, J., Jr., 1970, Introduction, in Studies of Appalachian Geology : Central and Southern, Fisher, Pettijohn, Reed, and Weaver (eds) : Interscience Publishers, New York, p. 195-197.

Reynolds, R., 1958, Factors controlling the localization of ore deposits in the Shullsberg area, Wisconsin-Illinois zinc-lead district : Econ. Geol., Vol. 53, p. 141-163.

Rodgers, J., 1967, Chronology of tectonic movements in the Appalachian region of eastern North America : Am. Jour. Sci., Vol. 265, No. 5, p. 408-427.

Rogers, J., 1970, The Tectonics of the Appalachians : Wiley-Interscience, New York, 271p.

Ross, C., 1941, Occurrence and origin of the titanium deposits of Nelson and Amhurst Counties, Virginia : US Geol. Surv. Prof. Pap. 198, 59p.

Simpson, T., and Gray, T., 1968, The Birmingham red-ore district, Alabama, in Ore Deposits of the United States, 1933-1967, Ridge, J. (ed) : Am. Inst. Min. Metall. Petrol. Engrs., New York, p.187-206.

Sloss, L., 1963, Sequences in the cratonic interior of North America : Geol Soc. Am. Bull., V. 74, No. 2, p. 93-114.

Sloss, L., and Nobles, L., 1972, Earth history : an illustrated syllabus in historical geology : Northwestern University Press (Circa 1972), 78p.

Sloss, L., and Speed, R., 1974, Relationships of cratonic and continental-margin tectonic episodes, in Tectonics and Sedimentation, Dickinson, W. (ed) : Soc. Econ. Paleon. and Mineral. Spec. Pub No. 22, p. 98-119.

Snyder, F., 1968, Geology and mineral deposits, midcontinent United States, in Ore Deposits of the United States Vol. 1, Ridge, J. (ed) : Am. Inst. Min. Metall. Petrol. Engin., New York, p. 257-286.

Snyder F., and Gerdemann, P., 1968, Geology of the Southeast Missouri lead district, in Ore Deposits of the United States, 1933-1967, Volume I, Ridge, J. (ed) : Am. Inst. Min. Metall. Engrs. p. 326-358.

Spooner, C., and Fairbairn, H., 1970, Relations of radiometric age of granitic rocks near Calais, Maine, to the time of the Acadian Orogeny : Geol. Soc. Am. Bull., Vol. 81, p. 3663-3670.

Stanton, R., 1972, Ore Petrology : Mc Graw Hill Book Co., New York, 713p.

Stearn, C., Carroll, R. and Clark, T., 1979, Geological Evolution of North America : John Wiley and Sons, New York, 566p.

Stein, H., and Kish, S., 1978, The Virgilina Mining district of North Carolina and Virginia -- preliminary evidence for a copper deposit of metamorphic origin : Geol. Soc. Am. Abstracts with Programs, Vol. 10, No. 4, p. 198-199.

Stewart, J., 1976, Late Precambrian evolution of North America : Plate tectonics implication : Geology, Vol. 4, No. 1, p. 11-15.

Stow, S., and Tull, J., 1982, Geology and geochemistry of the strata-bound sulfide deposits of the Pyriton district, Alabama : Econ. Geol., Vol. 77, No. 2, p. 322-334.

Summerson, C., 1962, Precambrian in Ohio and adjoining areas : Ohio Geol. Surv. Rept. Inv. 44, 16p.

Sundelius, H., 1970, The Carolina Slate belt, in Studies in Appalachian Geology : Central and Southern, Fisher, Pettijohn, Reed, and Weaver (eds) : Interscience Publishers, New York, p. 369-382.

Thomas, W., 1972, Regional Paleozoic stratigraphy in Mississippi between Ouachita and Appalachian Mountains : Am. Assoc. Petrol. Geol. Bull., V. 56, No. 1 p. 81-106.

Tilton, G., Wetherill, G., Davis, G., and Bass, M., 1960, 1000-million-year-old minerals from the eastern United States and Canada : Journ. Geophys. Res., Vol. 65, p. 4173-4179.

Trace, R., 1973, Illinois-Kentucky fluorspur district, in A Symposium on the Geology of Fluorspar, Hutcheson, D. (ed) : Proc. 9th Forum on Geol. of Indust. Min., Kentucky Geol. Surv., Spec. Pub. 22, Lexington, Ill., p58-76.

Tull, J., 1978, Structural development of the Alabama Piedmont Northwest of the Brevard Zone : Am. Journ. Sci., Vol. 278, No. 4, p. 422-460.

Tull, J., and Stow, S., 1982, Geologic setting of the Hillabee meta-volcanic complex and associated strata-bound sulfide deposits in the Appalachian Piedmont of Alabama : Econ. Geol., Vol. 77, No. 2, p. 312-321.

Van Schmus, W., and Bickford, M., 1981, Proterozoic chronology and evolution of the midcontinent region; North America, in Precambrian Plate Tectonics, Developments in Precambrian Geology 4, Kroner, A. (ed) : Elseiver Sci. Pub. Co., New York, p. 261-296.

Wetherill, G., Tilton, G., Davis, G., Hart, S., and Hopson, C., 1966, Age measurements in the Maryland Piedmont : Journ. Geophys. Res., Vol. 71, pp. 2139-2155.

Whitney, J., Paris, T., Carpenter, R., and Hartley, M., 3rd, 1978, Volcanic evolution of the southern slate belt of Georgia and South Carolina : A primitive oceanic island arc : Jour. Geol., Vol. 86, No. 2, p. 173-192.

Wilson, J.T., 1966, Did the Atlantic close and re-open? : Nature, Vol.211, p. 676-681.

Wright, W., Guild, P., Fish, G., Jr., and Sweeney, J., 1968, Iron and Steel, in Mineral Resources of the Appalachian Region : US Geol. Surv. Prof. Pap 580, p. 396-416.

Worthington, J., and Kiff, I., 1970, A suggested volcanigenic origin for certain gold deposits in the Slate Belt of the North Carolina Piedmont : Econ. Geol., Vol. 65, No. 5, p. 529-537.