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GENESIS OF STRATABOUND ORE DEPOSITS IN THE MIDCONTINENT BASINS OF NORTH AMERICA. 1. THE ROLE OF REGIONAL GROUNDWATER FLOW

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ABSTRACT. Steady and transient flow models for regional brine migration have been constructed for quantifying the role of groundwater in the genesis of carbonate-hosted lead-zinc ore deposits in the U.S. Midcontinent region. Earlier theoretical studies suggested that ores of the Mississippi Valley type formed as deep groundwater was driven out of basins and onto platform margins by elevated topography (Garven and Freeze, 1984a, b). Several basins surround the major ore districts of the Midcontinent region, but it was the tectonic uplift after the Alleghanian orogeny of Late Pennsylvanian time that created the topography necessary for driving brines out of the basins and onto the adjacent domes where the ore deposits formed. A typical paleohydrologic reconstruction extending across the Arkoma basin and onto the Ozark dome shows that Cambrian-Ordovician strata acted as regional aquifers in focusing metal-bearing brines at Darcy flow rates of 1.0 to 5.0 m/yr in topography-driven flow systems. Numerical simulations of basin compaction and thrust-induced flow suggest a minor role for sediment compaction and the "squeegee" effect in ore formation, especially for the huge ore districts far-removed from the orogenic belts. Ore mineralization associated with topography-driven flow occurred in less than a few million years at temperatures between 80° and 130°C in broad discharge areas in southeast Missouri, although much warmer thermal transients may have lasted for about 100,000 yrs. Geothermal gradients in discharge areas were strongly elevated by regional flow associated with foreland uplift, yet lateral temperatures gradients are predicted to have been very small in the platform aquifers. Other hydrogeologic simulations predicted similar broad discharge areas in southern Wisconsin and southern Illinois with transient temperatures of ore formation between 150° and 220°C because of brine movement through the deep Illinois Basin and Reelfoot Rift, respectively.

Alleghanian uplift of the Appalachians evolved such that paleorelief probably reached a maximum first in the northeast and then migrated south, culminating with subaerial exposure of the Ouachita fold belt and Arkoma platform. Based on this tectonic interpretation,

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regional fluid migration pathways are likely to have varied considerably throughout the Late Paleozoic. For example, ores along the Old Lead Belt in Missouri may reflect a discharge pathway for brines driven to the west out of the Appalachian foredeep and Illinois sag as illustrated in two of the simulation models. A similar scenario probably applied for the ore districts in Tennessee. Later uplift in the southern Appalachians drove brines northwesterly out of the Black Warrior Basin and into southeast Missouri, perhaps adding another chemical signature to ore formation in the Old Lead Belt. Mineralization in the Upper Mississippi Valley District is most likely to have originated through the migration of brines out of the Appalachian foredeep and across part of the Illinois sag as a direct result of uplift of the Appalachian Mountains rather than later by uplift of the Pascola Arch in southern Illinois (Bethke, 1986). Uplift of the Ouachita Mountains and foreland platform resulted in the massive migration of brines to the north and in part to the northeast. Ores in the Tri-State District, Northern Arkansas, Viburnum Trend, and Central Missouri record this hydrologic system of which there is little dispute. Deep brines also would have moved easily along the axis of the Reelfoot Rift under a gravity-drive to form the fluorite deposits in southern Illinois. Ore genesis waned in the earliest Mesozoic as erosion dissipated the topography-driven flow systems. Emergence of the Rocky Mountains in the Tertiary resulted in easterly brine migration across the Denver and Forest City basins, but this flow system was too weak in Missouri to play a role in ore formation.

INTRODUCTION

Groundwater flow is ubiquitous in the Earth's crust and is an important, sometimes dominant, agent for heat and chemical mass transfer in a number of geologic processes (Bredehoeft and Norton, 1990). Large-scale fluid migration may reach depths of up to several kilometers, particularly in sedimentary basins where extensive hydrostratigraphic units provide conditions for aqueous mass transport over lateral distances of hundreds of kilometers (Bethke and Marshak, 1990; Cathles, 1990). Forces causing deep groundwater migration, such as the gravity-drive associated with topographic relief, fluid buoyancy associated with temperature and salinity gradients, and changes in stress fields associated with sediment compaction, erosion, and faulting, vary spatially and temporally as the structural and hydrologic framework of a basin evolves (Tóth, 1978).

In recent years, the genetic relationship between regional groundwater flow systems, basin tectonics, and stratabound ore mineralization has become better recognized. For example, carbonate-hosted sphalerite, galena, barite, and fluorite ore deposits of the greater Mississippi Valley type (MVT) are thought to have formed through the regional-scale migration of basinal brines (Leach, 1979; Anderson and Macqueen, 1982). Hydrologic modeling of regional brine migration in sedimentary basins has shown that tectonic uplift of foreland basins results in the development of topography- or gravity-driven flow systems capable of forming large stratabound ore deposits (Garven and Freeze, 1984a, b). Similar hydrologic systems appear to be responsible for the accumulation and entrapment of some of the world's largest oil fields (Garven, 1989; Bethke, Reed, and Oltz, 1991). The general role of deep groundwater flow as an agent for mineralization has also become more widely accepted because of the association with additional geochemical, geothermal, and geophysical observations, as reviewed by Hitchon (1984), Oliver (1986), and Bethke and Marshak (1990).

Despite these general understandings, quantitative hydrogeologic studies of specific ore districts and sedimentary basins have been limited: White (1971) studied the White Pine copper deposit in the Midcontinent Rift; Sharp (1978) considered the generation of overpressure in the Ouachita Basin as a mechanism for lead-zinc mineralization in northern Arkansas and southeast Missouri; Garven (1985) quantified the role of regional flow in the genesis of the Pine Point lead-zinc deposit in the Western Canada Basin; and Bethke (1986) placed hydrologic constraints on the formation of the Upper Mississippi Valley lead-zinc deposits near the edge of the Illinois Basin. Until now, no single comprehensive study existed that evaluated the hydrogeologic settings for ore genesis in the largest stratabound ore region in the world, the U.S. Midcontinent.

In this paper we present hydrogeologic calculations for simulating regional paleoflow systems associated with the genesis of all the major carbonate-hosted ore districts in Paleozoic strata of the Midcontinent basins of North America (fig. 1). For the purposes of this paper, the Midcontinent region broadly includes the entire area between the Appalachian Mountains and the Rocky Mountains and from the Great Lakes south to the Ouachita Mountains. It is generally agreed that Mississippi Valley Type (MVT) ore deposits such as those in the U.S. Midcontinent formed as a result of warm, saline fluids migrating through sedimentary basins (see reviews by Ohle, 1980; Anderson and Macqueen, 1982; and Sverjensky, 1986). But important questions regarding the origin of specific districts still remain to be resolved as does the relationship between ore districts at the basin scale. These questions include the driving mechanism of regional and local flow, the timing of groundwater flow and mineralization, the role of tectonics and basin structure, and the geochemical aspects of mobilization, transport, and precipitation. Controversy surrounds the general hydrologic picture for ore genesis: Cathles and Smith (1983) called upon episodic discharge of overpressured brines from the Illinois Basin; Bethke (1986) and Bethke and Marshak (1990) favored gravity-driven flow for the Arkoma and Illinois Basins; Oliver (1986) proposed tectonic squeezing for the Appalachian Basin; Clendenin and Duane (1990) conjectured seismic pumping along the Reelfoot Rift; Schedl and others (1992) proposed the involvement of metamorphic fluids derived from Piedmont thrust sheets; and Deming (1992) has suggested that free convection in the deep crust periodically releases heat, which is then transported by gravity-driven flow systems. Similar controversy exists over whether widespread fluid migration occurred as

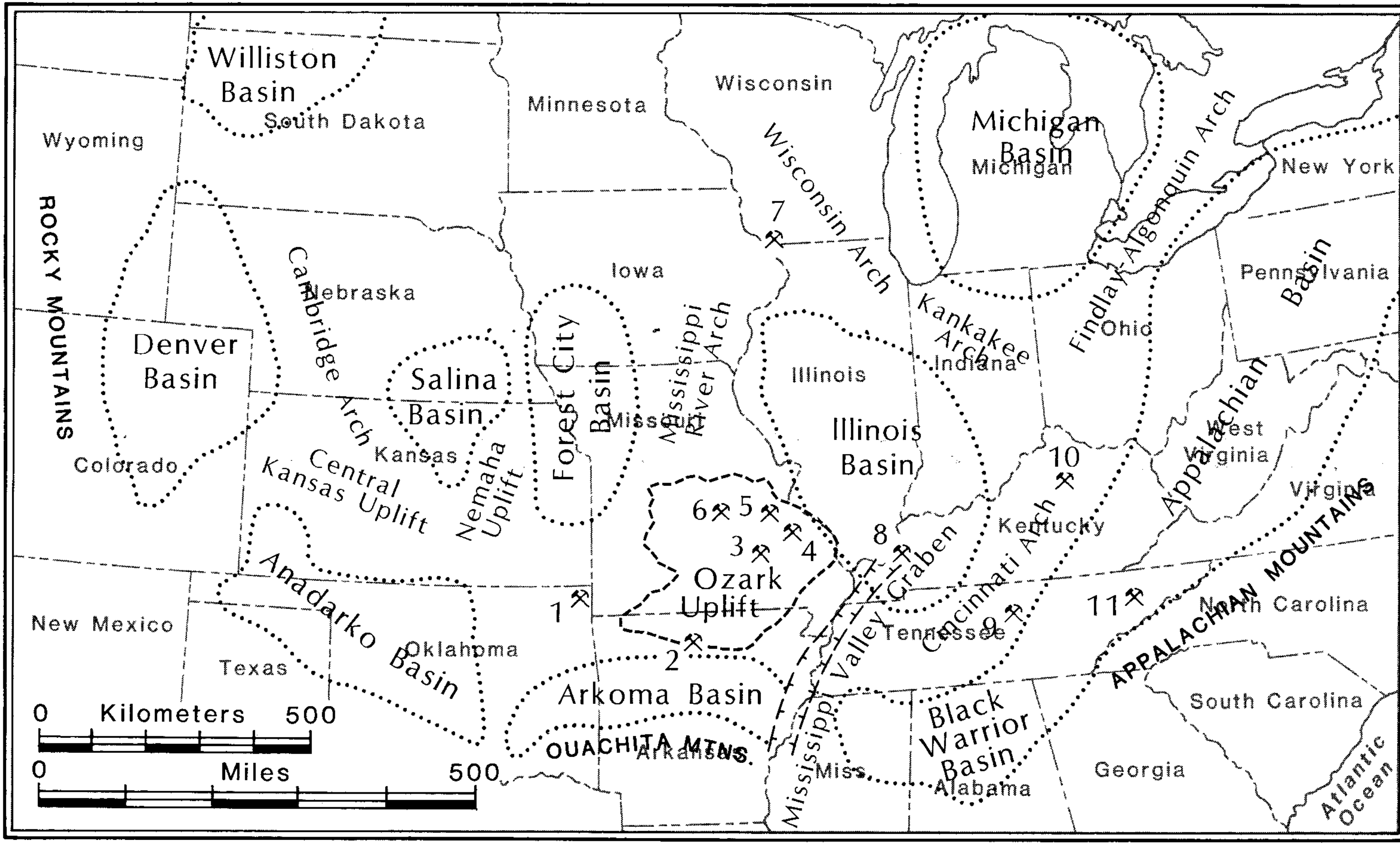

Fig. 1. Location map for the hydrogeologic study. Major Mississippi Valley-type ore districts include: (1) Tri-State, (2) Northern Arkansas, (3) Viburnum Trend, (4) Old Lead Belt, (5) Southeast Missouri Barite, (6) Central Missouri Barite, (7) Upper Mississippi Valley, (8) Illinois-Kentucky Fluorspar, (9) Central Tennessee, (10) Central Kentucky, and (11) Eastern Tennessee.

a single episode from a single basin source (Leach and Rowan, 1986) or as multiple episodes with multiple basin sources (Goldhaber and Church, 1989; Gregg and Shelton, 1989; Viets and Leach, 1990; Brannon and others, 1991; Shelton, Bauer, and Gregg, 1992), and over the timing of brine migration (Hearn, Sutter, and Belkin, 1987; Stein and Kish, 1991; Symons and Sangster, 1991).

To begin to answer such broad questions we present a review of the geologic and tectonic settings for the ore districts and basins and an overview of the physical and mathematical basis for our conceptual models of the role of regional flow systems. Sets of two-dimensional numerical simulations are then presented for constraining the hydrologic and thermal conditions for ore formation at the basin scale. We will present strong arguments for supporting the role of topography-driven flow as the primary mechanism for brine migration, but the effects of basin subsidence and tectonic squeezing are also considered. The two-dimensional calculations serve to illustrate likely hydrologic conditions that will provide constraints for geochemical mass transfer and three-dimensional flow calculations to appear in a later communication.

GEOLOGIC SETTING OF THE ORE DISTRICTS

Paleozoic strata of the Midcontinent region are hosts to major ore districts composed of sphalerite, galena, barite, and fluorite. Although the deposits differ in many details (Ohle, 1980; Sangster, 1983), several features are common to all (Anderson and Macqueen, 1982; Sverjensky, 1986):

1. Associated with basin-wide carbonate and sandstone aquifers.
2. Stratabound but epigenetic in carbonate host rock that probably never experienced local burial depths in excess of 2000 m.
3. Fluid inclusions contain Na–Ca–Cl type brines similar to present-day basinal brines. Hydrocarbon inclusions are not uncommon.
4. Homogenization temperatures for fluid inclusions suggest ore and gangue mineralization over a wide temperature range, but most deposition occurred between 80° and 150°C.
5. Ore mineralization was a regional phenomenon associated with other forms of thermal and chemical alteration.
6. Deposition commonly concentrated on the flanks, domes, and arches of foreland-type sedimentary basins.
7. Permeability changes caused by fractures, breccias, karst, lithologic facies, and basement structure appear to have controlled ore localization.
8. Sources of metals and salinity appear to be far removed and dispersed in basin foredeeps.
9. Isotopic and trace element systematics may suggest multiple fluid pathways or sources over time.
10. Dating studies indicate ore formation may be temporally associated with the uplift of orogenic belts and adjacent foreland basin platforms.

It appears to be well established that hot saline fluids similar to oil-field brines migrated out of sedimentary basins and were focused regionally by extensive aquifers, eventually forming ore deposits in sedimentary host rocks at the edges of the basins (fig. 1). Most ore production and exploration have been centered around the larger districts which include Southeast Missouri, Tri-State, Upper Mississippi Valley, Illinois-Kentucky, Central and Eastern Tennessee, and similar smaller districts and minor deposits are scattered throughout Paleozoic strata in the Midcontinent region:

Southeast and Central Missouri.—MVT ore deposits in southeast Missouri occur in Upper Cambrian and Lower Ordovician strata blanketing the Precambrian ridges and knobs of the St. Francois Mountains and Ozark Dome (fig. 2). Most lead and zinc ore in the huge Old Lead Belt and Viburnum Trend subdistricts occur in dolostones of the Upper Cambrian Bonneterre Formation. Pinchouts of the Lamotte Sandstone appear to have had an important control on mineralization patterns within the Viburnum Trend (Anderson, 1991). Barite and galena mineralization occur as veins within the Lower Ordovician Potosi Formation in the Palmer and Valle mines area. Farther north, barite mineralization dominates in the Ordovician Gasconade, Roubidoux, and Jefferson City Formations (Snyder and Gerdemann, 1968). In the Viburnum Trend, lead mineralization is strongly controlled by permeable facies of a reef complex and basement highs, where sphalerite precipitation ranged between temperatures of 90° and 120°C (Rowan and Leach, 1989). Temperatures for sphalerite in Ordovician and Mississippian rocks in the Central Missouri district fall between 80° and 105°C (Leach, 1979). The Southeast Missouri district is the world's largest producer of lead with total production since 1865 exceeding 500 million tons of ore (Hagni, 1989).

Northern and Northeast Arkansas.—The Northern Arkansas district is situated on the southern flank of the Ozark Dome where most ore mineralization occurs in the Ordovician Everton Formation, a coarse-grained dolomite with thin lenticular sandstones. Production also comes

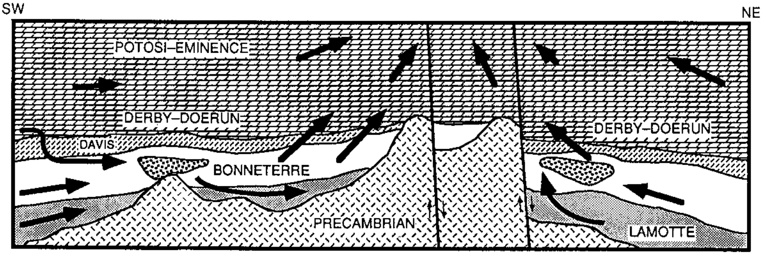

Fig. 2. Schematic section across Southeast Missouri lead districts (after Snyder and Gerdemann, 1968). Flow arrows suggest possible brine migration pathways during burial of the St. Francois basement high in the Late Paleozoic.

from the Boone Group of Mississippian formations that include the St. Joe, Reeds Spring, Keokuk, and Warsaw cherty limestones. Normal faults pervade the district although ore mineralization is often adjacent to faults as "runs" stratabound in coarser dolomite. Homogenization temperatures are commonly between 95° and 130°C but range up to 170°C in calcite cements (Leach, Nelson, and Williams, 1975). Northeast Arkansas is a small district where mostly sphalerite was mined from the Lower Ordovician Smithville Formation which is a cherty, brecciated dolomite (Snyder, 1968).

Tri-State of Missouri, Kansas, and Oklahoma.—The Tri-State district occurs in Mississippian formations on the southwest flank of the Ozark Dome (Brockie, Hare, and Dingess, 1968). Limestones of the Keokuk and Warsaw Formations contain flat-lying breccia zones of dolomite and jasperoid. Large amounts of jasperoid and chert occur with the ores. Mineralization is concentrated within breccia zones adjacent to structural "troughs" within the district, and normal faulting is pre-ore as well as post-ore. Sphalerite inclusion studies indicate precipitation temperatures from about 80° to 120°C. Total production in the district was in excess of about 500 million tons.

Upper Mississippi Valley.—Zinc and lead ore occur mainly in the Galena, Decorah, and Platteville Formations of Middle Ordovician age (Heyl, 1968), although minor deposits are found from Upper Cambrian sandstones through Silurian dolomite. Precipitated on the southwest flank of the Wisconsin Arch, sulfide mineralization occurs as vein fillings in fractures, breccia and vug fillings, and bedded replacements in gently flexed and faulted strata. The temperature of deposition for sphalerite ranges between 75° and 160°C and for calcite gangue between 50° and 78°C. McLimans (1977) reported 5 percent of his temperatures for main-stage ore between 160° and 220°C, whereas Kutz and Spry (1989) reported homogenization temperatures ranging from about 40° to 116°C for outlying sphalerite and calcite. The Upper Mississippi Valley district contains distinctive color banding due to Fe in the sphalerite ores which can be correlated across many kilometers (McLimans, Barnes, and Ohmoto, 1980). Ore production from 1798 to 1951 was in excess of about 100 million tons.

Illinois-Kentucky Fluorspar.—The Southern Illinois-Kentucky district differs from most of the other MVT deposits in the Midcontinent in that fluorite is the dominant ore mineral (Grogan and Bradbury, 1968). Veins and bedded ores occur in the Mississippian Renault and Ste. Genevieve Formations, although fluorite ore exists in formations from Devonian to Pennsylvanian in age. The district is situated on a northwest-trending structural high flanked on the north and west by the Shawneetown-Rough Creek Fault, a high-angle thrust zone. Fluid inclusions indicate mineralization temperatures of 90° to 150°C, with fluctuations as much as 15°C for growths of individual crystals (Spry and others, 1990). Sphalerite and quartz record slightly lower temperatures than fluorite. About

10 million tons of fluorspar concentrate was produced in the Illinois-Kentucky mining district between 1880 and 1965.

Central Kentucky.—Small amounts of barite, lead, zinc, calcite, and fluorite have been mined from mostly vein deposits in Middle Ordovician limestones of the Highbridge and Lexington Groups which disconformably overlie the St. Peter-Knox Groups of the Lexington Dome-Cincinnati Arch. The mineral veins consist of breccia replacement veins and simple fissure fillings with lateral zoning ranging from fluorite at the center to barite-galena-sphalerite on the periphery. Homogenization temperatures of fluid inclusions from Central Kentucky range from about 70° to 130°C (Roedder, 1969). The regional distribution of barite in the District suggests that barite deposition was localized by the presence of a fresh groundwater interface (Plummer, 1971; Kaiser and others, 1987).

Central and Eastern Tennessee.—The Central Tennessee district is situated near the apex of the Nashville Dome (fig. 3) where sphalerite–galena–fluorite–barite ores form veins in Middle Ordovician limestone and breccia deposits in the Lower Ordovician portion of the Knox Group (Jewell, 1947). Economic mineralization in the Knox Group is characterized by fine-grained crystalline dolomite of the Mascot Formation and the underlying Kingsport Formation and coarse, sparry, vuggy dolomite cement in the ore breccias. The Mascot Formation is truncated by an erosional unconformity, and karst penetrates into the erosion surface down to about 150 m (Stearns and Reesman, 1986). Early stage sphal-

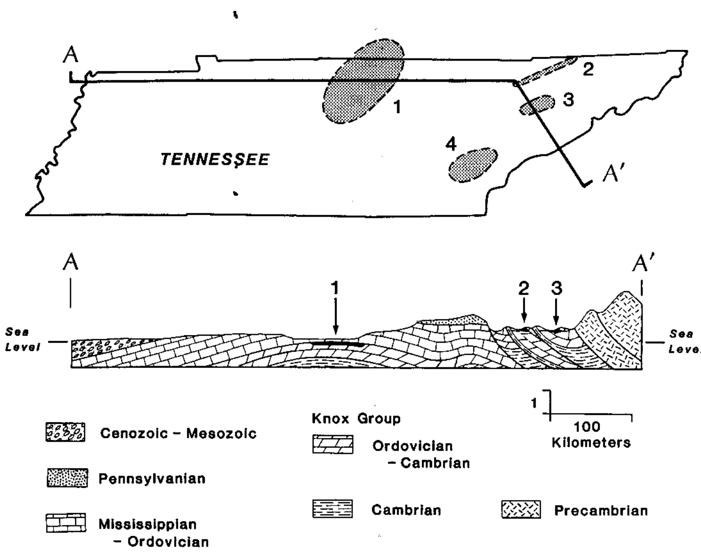

Fig. 3. Location of ore districts in Tennessee and regional stratigraphy (after Kyle, 1976). Numbers refer to individual districts: (1) Central Tennessee, (2) Copper Ridge, (3) Mascot-Jefferson City, and (4) Sweetwater.

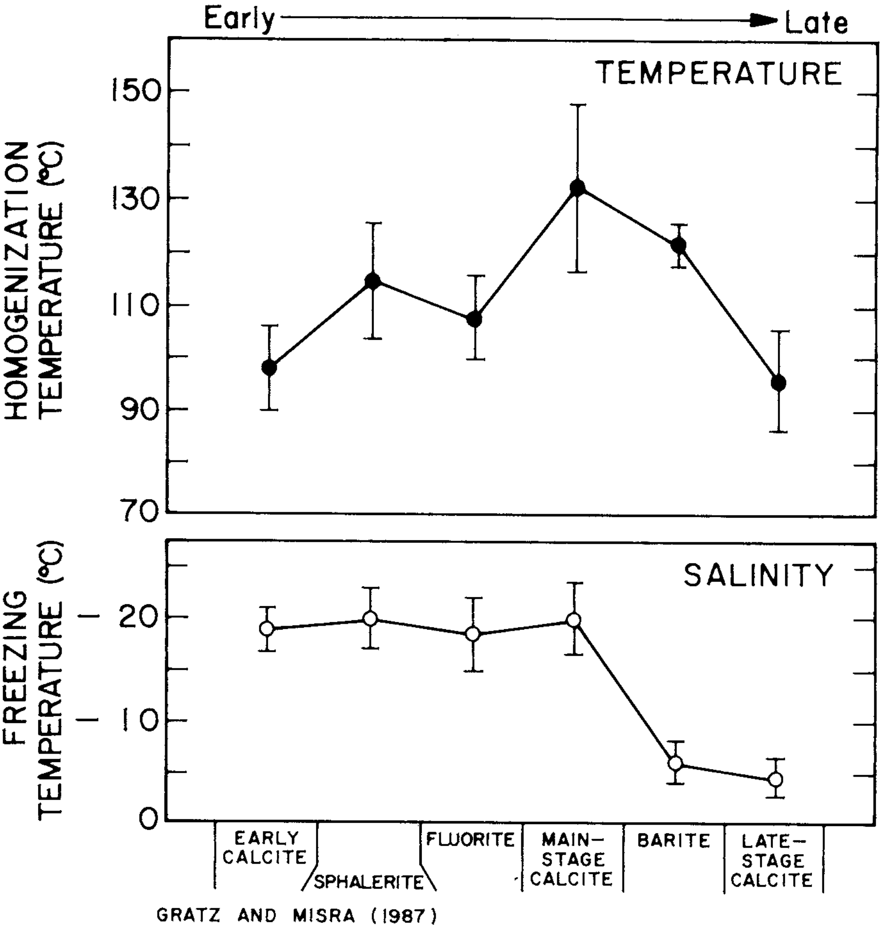

Fig. 4. Evolution of fluid temperature and salinity as a function of paragenesis in the Central Tennessee ore district (after Gratz and Misra, 1987). Patterns such as this may reflect thermal and salinity transients in MVT ore-forming groundwater flow systems.

erite, fluorite, and calcite were deposited at temperatures between 90° and 150°C, while later stage barite and calcite were deposited at somewhat lower temperatures by lower salinity groundwater (fig. 4).

MVT ores of Eastern Tennessee include sphalerite-fluorite-barite deposits of three major districts, Mascot-Jefferson, Copper Ridge, and Sweetwater, which are hosted by the Lower Ordovician-Cambrian Knox Group where it is exposed in thrust sheets of the Valley and Ridge province. The dominant ore controlling structures are breccia zones within the lower part of the Kingsport Formation, zones formed during the Lower to Middle Ordovician Knox unconformity interval. Karst features extend to depths of at least 250 m below the unconformity. Appalachian thrusting was later superimposed on the ore district. Fluid inclusions indicate temperatures in the 70° to 130°C range for Sweetwater, whereas ores in the Copper Ridge and Mascot-Jefferson City deposits formed in the 110° to 170°C range (Kesler, Jones, and Ruiz, 1988). Total zinc metal production from Tennessee during the period 1850 through 1964 was about 1.8 million tons with about 85 percent of the total derived from the Mascot-Jefferson City sub-district.

SEDIMENTARY BASINS OF THE MIDCONTINENT

Tectonics and paleohydrogeology.—The stratigraphy and structure of the greater Midcontinent region (fig. 5) reflect the influence of the Taconian, Acadian, Alleghanian, Ouachita, Wichita, and Laramide orogenies spanning the interval from the Early Paleozoic to Late Cenozoic (Sloss, 1988). Brine migration through the Paleozoic section of the Appalachian and Arkoma basins resulted in the formation of Pb–Zn–F–Ba deposits near the edges of the foreland basins and associated intracratonic sags and rifts (fig. 1). The tectonic history of the Midcontinent is too well documented in the literature to require additional review here, but some general comments can be made that have a direct bearing on understanding brine migrations and ore formation.

Late Proterozoic rifting preceded creation of the Appalachian Basin (Cook and Oliver, 1981; Thomas, 1985). As rifting decayed, a passive margin developed along which a thick (4+ km) sequence of Cambrian-Ordovician platform carbonates were deposited over older Cambrian clastics. The passive margin in the central Appalachians was overthrusted during the Taconian orogeny (470-435 Ma), which resulted in the deposition of about 3 km of clastics, but the Taconian overthrusts are thought to have created only modest topographic relief (Slingerland and Beaumont, 1989). A second period of major convergence known as the Acadian orogeny (395-350 Ma) further loaded the Laurentia margin and produced the Catskill-Pocono clastic wedge in the foreland. Continental compression continued from the Mississippian to Permian and culminated with the Alleghanian orogeny (320-250 Ma) as thrust sheets moved up to 200 km over the eastern margin. Loading of the outboard margin throughout the later Paleozoic resulted in the series of foreland basins and peripheral arches and domes that characterize the Eastern Interior and Midcontinent (fig. 1). Intracratonic sag basins such as the Illinois, Michigan, and Forest City appear to have subsided for other reasons that are unclear (Quinlan and Beaumont, 1984). It is apparent that uplift and erosion characterized the Permian and early Mesozoic history of the Appalachian orogen, where the fold and thrust belt is exhumed by up to 12 km of post-Alleghanian erosion. Erosion also predominated on the arches and domes as these regions were uplifted once stresses relaxed in the lithosphere. Maximum elevation of the ancestral Appalchian Mountains probably occurred in the early Permian, a period when the Cincinnati Arch and associated domes were at maximum burial (fig. 6).

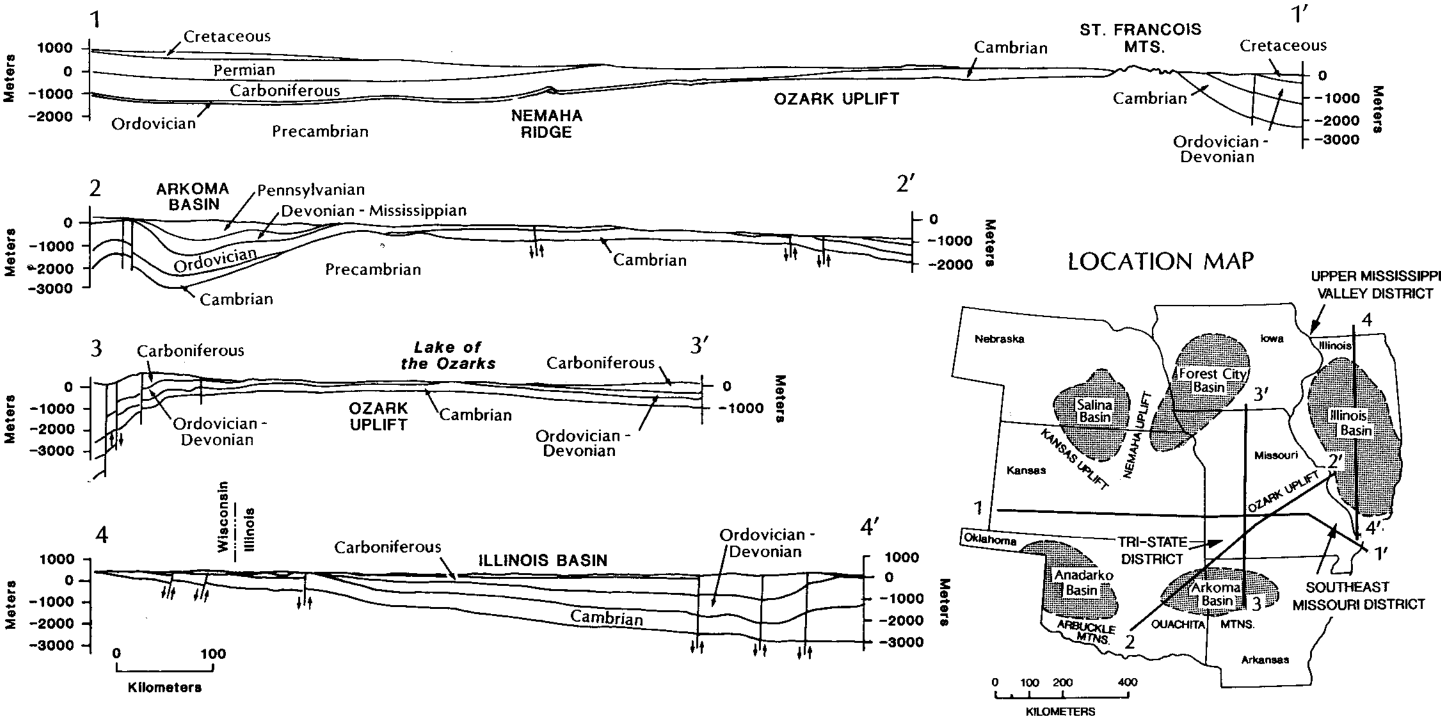

Fig. 5. Stratigraphy and structure in the Midcontinent (after Wu and Beales, 1981).

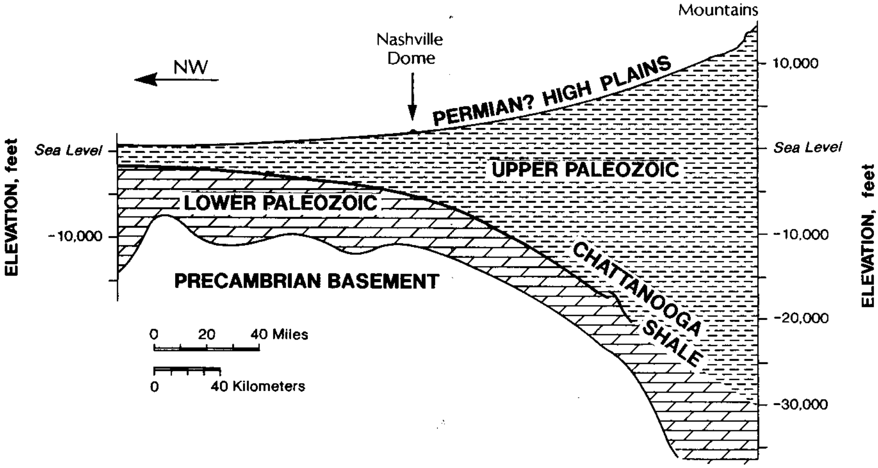

Fig. 6. Section across central Tennessee restored for the Late Paleozoic (after Stearns and Reesman, 1986). This profile extends from the ancient Appalachians northwest across the deeply buried Nashville Dome and adjacent foreland platform.

The Arkoma Basin is another foreland sag that developed in the late Paleozoic (350-250 Ma) in response to crustal downwarping and rapid sedimentation accompanying uplift, thrusting, and erosion of the Ouachita orogenic belt (Graham, Dickinson, and Ingersoll, 1975; Thomas, 1985). Beaumont, Quinlan, and Hamilton (1987, 1988) treat the geodynamic evolution of the Ouachita orogen as a southern extension of the Alleghanian orogeny that created the ancestral Appalachians. Unlike Appalachian thrusting which involved forward ramps rising across the complete Cambrian-Ordovician platform from basement décollements, frontal thrusts in the Ouachitas involved deep-basin, off-shelf facies of Cambrian to Lower Mississippian age. Sediments of the Pennsylvanian Atokan and Desmoinesian series comprise a typical coal-bearing molasse sequence where shallow marine, deltaic, and fluvial conditions dominated. A thick apron of Permian molasse covered the basin (fig. 7) although none of this remains, as subsequent uplift and erosion have beveled the stratigraphic profile so that only Pennsylvanian remnants still exist in northern Arkansas. Royden and others (1990) argue that the topographic elevation of the Ouachita Thrust Belt was low, never developing the very high mountains or thick crust typical features of true collisional mountain belts such as the Appalachians. The Ozark Dome borders the northern fringe of the Arkoma Basin, and it developed probably as a result of the flexural-related stress relaxation that produced similar structural highs such as the Findlay, Kankakee, Cincinnati, and Pascola Arches and the Wisconsin, Jessamine (Lexington), and Nashville Domes (Quinlan and Beaumont, 1984). Most of the arches and domes that separated various basins in the Cambrian-Ordovician period were normally submergent or only

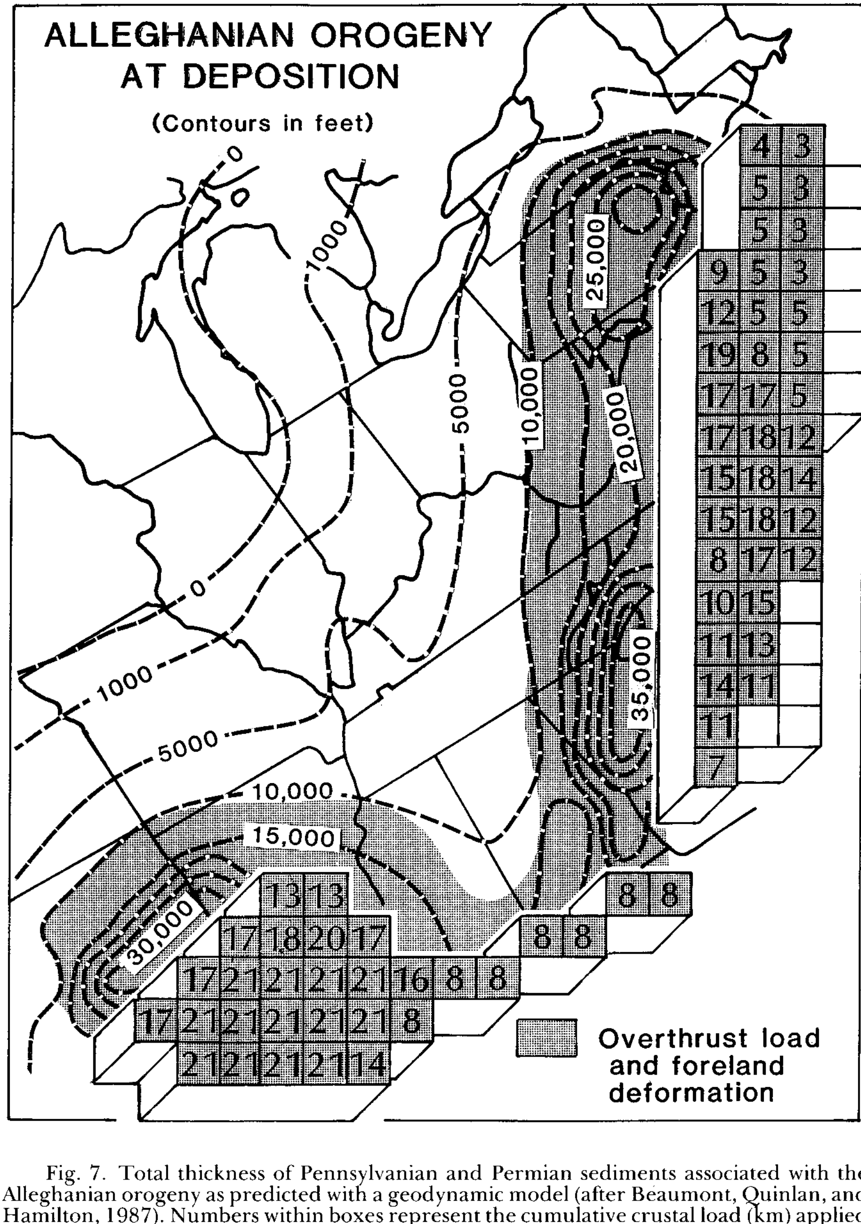

Fig. 7. Total thickness of Pennsylvanian and Permian sediments associated with the Alleghanian orogeny as predicted with a geodynamic model (after Beaumont, Quinlan, and Hamilton, 1987). Numbers within boxes represent the cumulative crustal load (km) applied to the orogenic belt which is required to replicate observed stratigraphy in the foreland basins.

intermittently emergent (Thacker and Anderson, 1977). Even after the earliest stages of the Ouachitan-Alleghanian orogeny (Lower Mississippian), Beaumont, Quinlan, and Hamilton (1987) predicted that the Ozark Dome would have submerged if its pre-existing height were less than 60 m. Stratigraphic considerations (fig. 7) suggest that Cambrian strata on the Ozark Dome were probably only buried by a maximum of about 1500 to 2000 m in the latest Permian, but some uncertainty surrounds these estimates.

The stratigraphic succession in the Anadarko is similar to that of the Arkoma and Appalachian Basins (Johnson, 1989). The Late Paleozoic Wichita and Ouachitan orogenies separated the Anadarko and Arkoma Basins in Middle Pennsylvanian time (Atokan) and produced a series of broad arches in northern Oklahoma. Regional uplift of the Rocky Mountains in Late Cretaceous to Early Tertiary time tilted parts of the southern Midcontinent and deposited Tertiary alluvial, aeolian, and lacustrine beds over Permian carbonates, exaporites, and red beds. The central Midcontinent contains a complex of arches and shallow sag basins of which the better known features include the Forest City and Salina Basins, the Central Kansas Uplift, the Nemaha Ridge, and the Chautauqua Arch (Bunker and others, 1988). In contrast to other intracratonic sag regions such as the Illinois Basin that displayed unidirectional subsidence throughout the Paleozoic, basin development in the central Midcontinent platform was transitory in nature. Late Cretaceous-Early Tertiary (Laramide) deformation created the modern Rocky Mountains and adjacent forelands such as the Denver-Julesburg Basin. Maximum uplift in Pliocene time initiated the general trend of erosion present today in the western interior.

It is difficult to anticipate with certainty patterns of regional brine migration or how flow systems evolved through time, although general features can be inferred from the tectonic history. Both the Taconian and Acadian orogenies could have produced some east-to-west brine migration driven by topographic relief, whereas sediment compaction or thermally-driven free convection may have been more important during the early Paleozoic in the passive margin sequences and compression-related flow in the fold and thrust belt. Regional migration of deep brines would have been strongest during the apex of the Alleghanian orogeny because of the elevated topographic relief imposed by uplift of the Appalachian and Ouachita Mountains. The basins were exposed to maximum paleotemperatures at the same time because of late Paleozoic burial (Arne, 1992). As deformation proceeded north to south along the Appalachian-Ouachita trend (fig. 7), regional flow patterns would have shifted gradually from predominantly east-west to south-north. The Illinois Basin and Mississippi Valley Graben (Reelfoot Rift) would have provided deep pathways for northward moving brines in the Late Paleozoic but likely saw only compaction-driven migrations or free convection prior to uplift of the Appalachian and Arkoma forelands. Flow systems would have evolved therefore throughout the Paleozoic-Mesozoic (fig. 8).

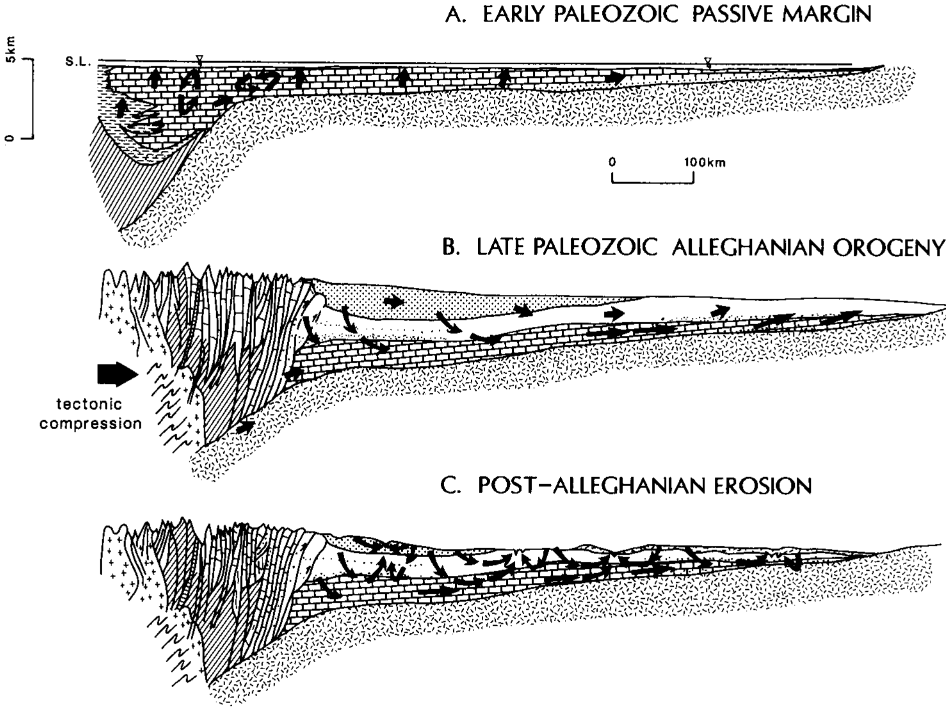

Fig. 8. Evolution of flow systems associated with foreland basins (after Garven, 1989). (A) Fluid migration is driven by sediment compaction and density gradients during subsidence of rifted margin and platform. (B) Maximum uplift of Appalachian and Ouachita Mountains occurs in the Permian after the apex of the Alleghanian orogeny. Deep groundwater flow is driven by gravity across the Midcontinent through regional aquifers. Enormous MVT ore deposits are formed as brines of variable temperature and salinity discharge near basin margins. (C) Basin-wide migration of ore-forming brines wanes in the early Mesozoic because erosion reduces topographic drive and partitions regional flow systems.

Slowing moving compaction-driven flow (mm/yr) and free convection (cm/yr) would have characterized the passive and rifted margin stages, with gravity-driven (m/yr), continental-scale flow systems appearing during major uplift of the foreland basins (Garven, 1989). Post-uplift flow systems (cm/yr) would have been less regional in nature as erosion and lower relief dominated the landscape. Maximum compression and uplift of the Western Interior Basin in the early Cenozoic would have imparted a stronger version of the west-to-east flow pattern observed in the Midcontinent today.

Present day hydrogeology.—Numerous studies have been conducted for the purpose of understanding the shallow groundwater resources in the Midcontinent region. Large mapping projects have been underaken over the past decade by the U.S. Geological Survey to document the distribution of regional aquifers and general flow patterns (Sun, 1986). Extensive carbonate and sandstone aquifers exist in all the sedimentary basins of the Midcontinent, particularly within the Cambrian-Ordovician strata but also within Mississippian and Cretaceous strata where they are present. Freshwater aquifers are prominent near the edges of sedimentary basin, along regional uplifts and basement arches. Local groundwater flow patterns are largely controlled by topography and hydrostratigraphy (Freeze and Cherry, 1979). In southeast Missouri, the Ozark Dome acts as a broad recharge area with shallow groundwater moving away from the plateau to discharge areas in the Arkansas, Missouri, and Mississippi River valleys (Jorgenson, Helgesen, and Imes, 1992). Quaternary incision of the Ohio and Mississippi Rivers has created a southward and westward hydraulic gradient for much of the shallow and deep aquifers in the Illinois Basin (Bond, 1972). A southeasterly flow direction dominates shallow groundwater movement in the Cambrian-Ordovician strata of the Forest City Basin of northern Missouri and Iowa (Imes and Smith, 1990; Young and others, 1989). In the Western Interior region, groundwater flow is largely from west to east along the regional topographic gradient (Darton, 1905).

Groundwater flow in deeper portions of the Midcontinent basins is rather sluggish, with present-day flow rates well below 1 m/yr in deep troughs such as the Illinois Basin (Bond, 1972). Except for part of the Anadarko Basin, the hydrodynamic systems are thought to be under "normal" fluid pressure regimes. Russell (1972) described near-hydrostatic pressure-depth relations in the Appalachian Basin, although no potentiometric or hydrodynamic maps have been published for this basin or for most of the Arkoma Basin. Potentiometric surface maps of the Ordovician and Pennsylvanian aquifers west of the Ozark Uplift and east of the Rocky Mountains are given by Larson (1971). These maps (figs. 9 and 10) indicate a mostly west to east flow pattern for the deeper formation water. Banner and others (1989) documented a similar flow pattern indirectly from isotopic measurements of brines discharging in springs of northern Missouri. In contrast to the overpressured brines in the deep Anadarko Basin, under-pressured, regional flow characterize the hydrologic system in the Denver Basin and Kansas platform (Belitz and Bredehoeft, 1988).

HYDRAULIC THEORIES ON MVT ORE GENESIS

It is now well established by petrographic and geochemical studies that Mississippi Valley-type ore deposits of the Midcontinent region formed from metal-bearing basinal brines some time after the lithification of their host rocks (Sverjensky, 1986). The general idea of deep and shallow groundwater circulation playing a major role in ore genesis has been around for over a century. Chamberlin (1882) recognized the disseminated nature of metals within the stratigraphic section and argued that descending groundwater could have formed ore deposits in the carbonates of southwestern Wisconsin. A similar conceptual model

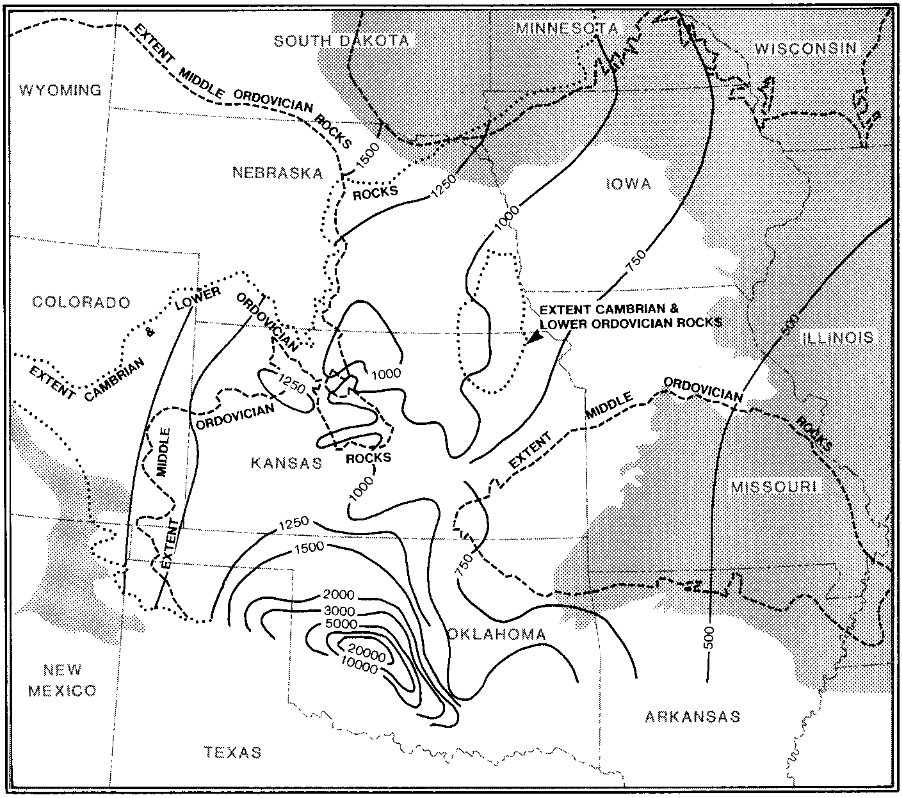

Fig. 9. Potentiometric surface map for Ordovician strata (after Larson, 1971).

was advocated by Van Hise and Bain (1902), Cox (1911), and Siebenthal (1915) in their later studies of lead-zinc ores of the Mississippi Valley and Tri-State region. Deep artesian flow appeared to be a prerequisite, however, as fluid inclusion data (Newhouse, 1933) indicated deep burial conditions for ore formation. Questions regarding the occurrence of deep groundwater flow and geochemistry of transport put the "meteoric hypothesis" in disfavor for most of the first half of this century, as sentiment swung back to even older theories associated with warm fluids of igneous derivation (Ohle, 1959). The role of "lateral secretion" or "artesian flow" in stratabound ore formation had not, however, been totally abandoned. Pelissonnier (1967) reasoned that deep groundwater could circulate through fractured basement under the hydraulic head created by topographic relief to form MVT ore deposits. He proposed that faults along basement highs would guide the deep fluids upward into the sedimentary basin. White (1971) suggested that paleorelief across the Lake Superior basin could have driven brines southward through the

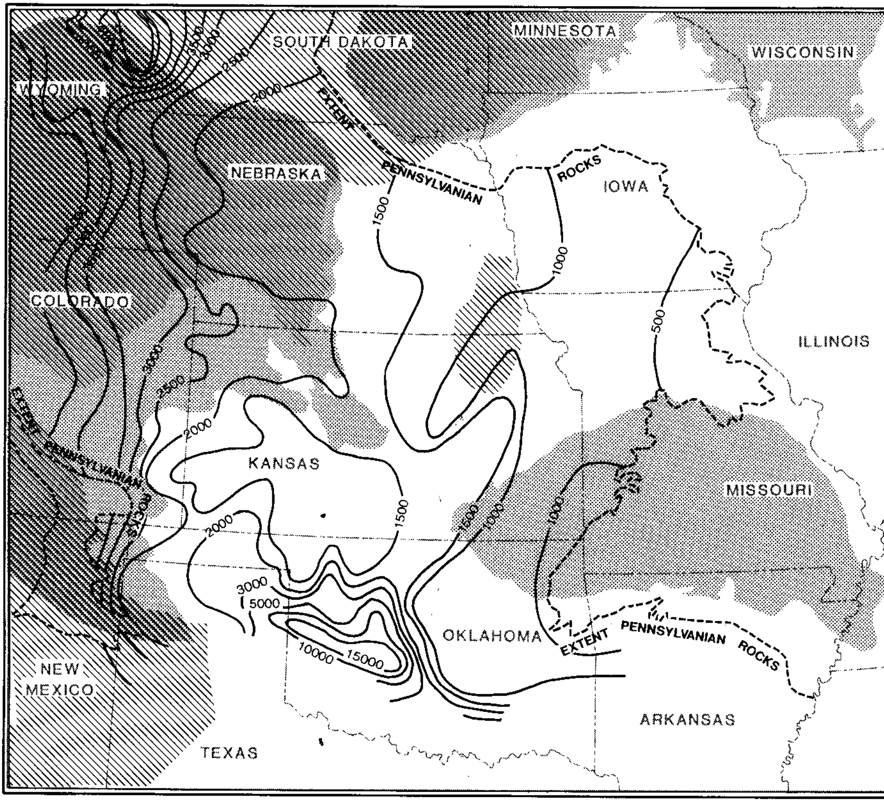

Fig. 10. Potentiometric surface map for Pennsylvanian strata (after Larson, 1971).

Precambrian midcontinent rift to form the White Pine copper deposit in northern Michigan.

Expulsion of basinal brines by compaction became a popular model for MVT ore formation after the articles by Noble (1963), Jackson and Beales (1967), and Dozy (1970). According to this theory, steady subsidence in the foreland and intracratonic basins would drive metal-bearing pore fluids out of compressible mudstones into more permeable sandstones and carbonates with lateral flow toward the edge of the basin. Sharp (1978) constructed a finite-difference model of the compaction history of the Arkoma basin and showed how rapid flow rates (1-10 m/yr) might be achieved if the sedimentary pile had become overpressured and subsequently ruptured by faulting. However, Cathles and Smith (1983), Bethke (1985, 1986), and Bethke and Marshak (1990) demonstrated mass balance limitations imposed by compaction-driven flow as a means for ore formation. Furthermore, flow rates generated by subsidence compaction appear to be either small or short-lived, and therefore the elevated thermal perturbations created by such flows are unable to explain the range of precipitation temperatures recorded in fluid inclusions.

Tectonic compression, thrusting, and dilation may also have induced brine migration across the Midcontinent, although the role of these mechanisms in MVT ore formation is less clear. Oliver (1986) proposed that deformation of the Appalachian and Ouachita orogenic belts in the late Paleozoic would have driven fluids away from the thrust belt toward the foreland platform to create both oil fields and ore districts. Duane and de Wit (1988) embraced the same mechanism for explaining Pb-Zn ore formation within the northern Caledonides. Kesler and van der Pluijm (1990) argue from petrographic observations that MVT-type ore mineralization in the Appalachian orogen must have been associated with middle Paleozoic fluid explusion and therefore cannot be the by-product of a late Paleozoic orogenic uplift event.

Hydrologic calculations of this "squeegee" effect by Ge and Garven (1989, 1992) and Bethke and Marshak (1990) suggest relatively slow rates of flow (less than 10 cm/yr) associated with compression in an orogenic belt. Subsequently, the effect of forced convection on the geothermal gradient in the adjacent foreland basin is limited (Deming, Nunn, and Evans, 1990). It has also been conjectured that heat may be released catastrophically during orogenesis as a result of free convection of fluids in permeable continental crust (Deming, 1992). A similar theory was proposed by Etheridge, Wall, and Vernon (1983) as a flow mechanism for regional metamorphism. But regional permeabilities in excess of 10^{-15} m^2 are required for even sluggish free convection, conditions that are unlikely to be duplicated over continental-scales in the deep basement (Valley, 1986; Ferry and Dipple, 1991).

Pumping fluids out of the Reelfoot Rift and into southeast Missouri along regional faults during seismic events has been advocated recently by Clendenin and Duane (1990), yet there is little field evidence linking ore mineralization to faulting in the Ozark region (Leach and Rowan, 1991). The mechanics of seismic pumping are well known (Nur and Booker, 1972; Sibson, Moore, and Rankin, 1975); flow volumes generated by this dilation effect can be on the order of 5×10^6 m^3. On the other hand, it is difficult to envision how seismic pumping could explain the widespread and pervasive geochemical and thermal alterations observed throughout the Midcontinent. Fracture networks are more likely to have affected regional and local permeability of the Paleozoic section than to have provided a driving force for regional brine migration.

Recognizing the possibility of other fluid-drive mechanisms, Garven and Freeze (1982, 1984a, b) proposed a new hydrologic model for fluid and heat transport in MVT ore formation at the basin scale. They argued for groundwater circulation at the scale of an entire basin in which the deepest, saline pore water would be driven updip toward the shallow edge of the foreland platform as a result of emerging topographic relief

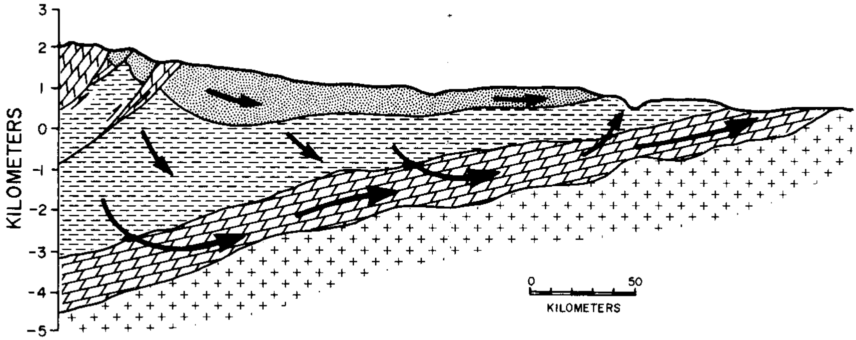

Fig. 11. Garven and Freeze (1984a, b) hydrologic concept for MVT ore formation. The cross section illustrates the style of continental-scale fluid migration in uplifted foreland basins, which are formed in front of mountain belts created by compressional tectonics. The arrows indicate the focusing of deep, briny groundwater through a Cambrian-Ordovician carbonate aquifer (slanted brick pattern) which is underlain by nearly impervious Precambrian basement and overlain by low permeability mudstones. Foreland sedimentary basins such as those in front of the ancient Appalachian and Ouachita Mountains provided the metal-bearing brines that were driven several hundreds of kilometers across the U.S. Midcontinent to form large ore deposits in discharge areas along the Mississippi Valley region. The hydraulic force responsible for brine migration is attributable to the newly elevated topography. This gravity-driven flow system decayed with erosion of the landscape, but flow rates of m/yr were capable of elevating heat flow at the basin margin for as long as a few million years.

alone (fig. 11). Hydrogeologic models of generic foreland basins were used by Garven and Freeze (1984b) to characterize a wide range of hydrologic, geologic, and geochemical conditions favorable and unfavorable for ore genesis. Deming and Nunn (1991) also present numerical simulations for a generic basin but were critical of the role of gravity-driven flow in MVT ore mineralization, unless focusing of flow and heat is provided by a basinal aquifer, a basic necessary requirement as evaluated in Garven and Freeze (1984b). Deming and Nunn also discuss the problem of the availability of salt and the inability of their numerical model to replicate the high temperatures inferred from some fluid-inclusion data without basement heat flows in excess of 100 mW/m^2.

As will be shown below, our calculations replicate thermal conditions for ore formation throughout the foreland platforms of the Arkoma and Appalachian Basin without imposing unrealistic thermal constraints. Hydrogeologic representation of the full scale of regional flow, better handling of boundary conditions, and consideration of transient flow conditions are the primary factors that provide a more realistic characterization consistent with basin history and ore mineralization.

The role of topography- or gravity-driven flow in stratabound ore formation has already been quantified for two major Pb-Zn districts. Garven (1985) documented the paleohydrogeology of ore genesis at Pine Point near the eastern edge of the Western Canada Basin with a two-dimensional finite-element model. He related basin-wide brine migration and associated heat transport to a regional flow system that probably formed Pine Point in less than a few million years, due to the Late Cretaceous-Early Tertiary emergence of the Rocky Mountains. Bethke (1986) applied a finite-difference model to simulate the regional flow that formed the Upper Mississippi Valley district during a period when deep groundwater may have been driven northward across the Illinois Basin as a result of uplift of the Pascola Arch in Permian to Cretaceous time. Bethke, Reed, and Oltz (1991) invoked a similar hydrogeologic model to explain patterns of oil migration within the Illinois Basin. A recent calculation by Bethke and Marshak (1990) also provides estimates on flow in the Arkoma Basin after uplift of the Ouachita foldbelt which may have implications for ore formation in the Tri-State district.

Regional flow systems driven by topographic relief appear to place most of the pieces in the puzzle of MVT ore genesis in their correct positions. For example, deep flow rates of 1 to 10 m/yr can be sustained for millions of years, albeit the rates will wane after hundreds of thousands of years as erosion wears down the elevated landscape. Because of the elevated groundwater flow rates, regional heat flow becomes elevated near the edges of foreland platforms and along intracratonic arches, thereby explaining the average deposition temperatures reflected by fluid inclusions, at least in the shallow platforms. Large-scale patterns of petroleum accumulation, cementation, and diagenesis associated with basin evolution also fit well under a general theory of gravity-driven flow. No other hydraulic theory merges all of these pieces of the puzzle together so well. For this reason, we have adopted topography-driven groundwater flow as our primary hydrologic model in order to reconstruct scenarios of ore formation in the Midcontinent basins of North America.

QUANTITATIVE EVALUATION OF BASIN-SCALE FLOW

Regional patterns of paleoflow in a sedimentary basin ought to place important hydrologic constraints on the sources of fluids, pathways of geochemical transport, rates of mineralization, and thermal environment for stratabound ore formation. We will present a number of numerical experiments to explore first the role of topography-driven flow. Additional experiments aimed at addressing the role of compaction- and tectonically-driven flow will follow. Our experimental procedure involves construction of mathematical models from a conceptual model of the hydrogeologic framework.

I. Conceptual Model

A basic premise of our study is that basin-scale brine migration across the Midcontinent region was strongly controlled by the structural and tectonic evolution of the Appalachians, Ouachitas, and Rocky Mountains. We will presume for the time being that the major phases of fluid flow were associated with periods of maximum topographic relief in the orogenic belts, when strong hydraulic gradients were most capable of driving deep saline groundwater away from foreland basins and into undeformed platform strata (Garven and Freeze, 1982, 1984a). In the Appalachian region, the Taconian (Ordovician), Acadian (Devonian), and Alleghanian (Permian) orogenies would have created gravity-driven flow systems. Uplift of the Ouachita Mountains (Pennsylvania-Permian) would have created similar flow in the Arkoma Basin and along the axis of the Mississippi Valley Graben. The latest phase of brine migration was probably associated with uplift of the Rocky Mountains (Tertiary) which drove basinal brines eastward across the Kansas platform.

Under gravity-driven flow, meteoric infiltration sustains subsurface flow such that groundwater recharge balances groundwater discharge across the basin, with the water table assuming a subdued configuration reflecting topography (fig 11). Establishment of the gravity-flow systems may have involved long-term transient changes associated with rapid uplift and emergence of the foreland. Transient pressure and thermal conditions would eventually dissipate as the basin adjusted to a quasi-steady state based on the new boundary conditions (Garven, 1989). Groundwater recharge would be concentrated in the elevated foreland in front of the fold-and-thrust belts where fluids could descend to several kilometers acquiring heat and salinity along the flow path. The hydraulic gradient created by topographic relief would drive deep groundwater toward the edge of the basin. Most importantly, regional aquifers would focus lateral groundwater flow and heat transport such that metal-bearing basinal brines could cool on ascending near the basin margin or along intracratonic arches and mix with fresh water at shallower depths. Circulation rates in the deep aquifers would eventually decline as erosion reduced the topographic relief, but the bulk of ore mineralization would be completed within a few million years after initial uplift. In contrast basin-scale flow patterns can be expected to fluctuate over tens of millions of years, perhaps even reversing occasionally, as topographic gradients varied temporally and spatially. Geochemical reservoirs for base metals ought to include all sediments in the thick foreland sag subjected to descending cross-formational flow, including the sandstone and carbonate aquifers focusing lateral flow, and even parts of the crystalline basement where the unconformity was sufficiently fractured and weathered to permit brine circulation. Sulfur could be derived mostly from organic sources and transported in reduced form by basinal brines or from inorganic sulfate and later reduced in discharge areas for ore formation (Anderson and Garven, 1987). Separate-phase methane could also have accumulated locally to reduce sulfate-bearing brines moving through ore sites (Anderson, 1991). Na–Ca–Cl brines would exist in the basins prior to uplift because of normal concentration processes acting in rifted margins of the continents (Hardie, 1990). The prolonged availability of salt would be aided through evaporite dissolution and through concentration processes such as membrane filtration (Hanor, 1979, 1987a, b).

II. Mathematical and Numerical Models

The region of flow has been defined by the conceptual model as a recently uplifted foreland basin bounded on one side by the fold and thrust belt of the orogen, which would create a barrier to lateral flow, and by the erosional, thin-edge of the basin on the other side. We can visualize a two-dimensional, vertical section where flow is limited at depth by the Precambrian basement and bounded at the top of the saturated zone by the water table which mimics broad features of the topography. The flow paths presumed here imply that groundwater flow in the third-dimension (along strike of the thrust belt) is taken to be negligible, an assumption aided by the large ratio of length to width of the foreland basins and the regional nature of the topographic slope. Strong lateral changes in permeability would create three dimensional flow fields, but the analysis of this feature is reserved for a later communication. Our model also is affected by buoyancy forces created by gradients in temperature and salinity. The temperature field depends on basement heat flow, thermal conductivity distribution, and heat advection caused by groundwater flow. We have assumed salinity increases linearly with depth in the basin below a chosen elevation level, but the concentration gradient is independent of groundwater flow in order to avoid solving yet another partial differential equation for aqueous salt transport, for which it would be nearly impossible to impose initial or boundary conditions, as no obvious source of bedded evaporites exists in the basins today, presumably because of dissolution.

Following the theory of Garven (1989), rates of variable-density groundwater flow are given with a modified form of Darcy's law

$$\mathbf{q} = -\mathbf{K}\mu_r(\nabla h + \rho_r \nabla Z) \tag{1}$$

where $\mathbf{q}$ is the Darcy velocity, h is hydraulic head, $\mathbf{K}$ is hydraulic conductivity, $\mu_r = \mu_o/\mu$ is the relative water viscosity, μ_o the reference state viscosity, μ the fluid viscosity at ambient conditions, $\rho_r = (\rho - \rho_o)/\rho$ the relative density where ρ_o is the reference-state density, and ρ is the fluid density at ambient conditions, and Z the elevation above a datum. The hydraulic head and hydraulic conductivity are defined the same as in a freshwater system (Freeze and Cherry, 1979):

$$h = \frac{p}{\rho_o g} + z \tag{2}$$

and

$$\mathbf{K} = \frac{\mathbf{k}\rho_o g}{\mu_o} \tag{3}$$

where p is fluid pressure and g is the gravitational acceleration constant. It should be noted that the hydraulic head in (2) is simply a convenient variable for mapping hydraulic gradients in a basin, and it should not be regarded as a "fluid potential" (mechanical energy per unit weight) in the classical sense (Hubbert, 1940).

A complete description of regional groundwater flow and heat transport in a sedimentary basin requires a mathematical solution to the coupled conservation equations for fluid mass and thermal energy, respectively:

$$-\nabla \cdot (\rho \mathbf{q}) = \rho S_s \frac{\partial h}{\partial t} \tag{4}$$

and

$$\nabla \cdot [\mathbf{E}\nabla T] - \rho c \mathbf{q} \cdot \nabla T = [\rho c \phi + \rho_s c_s (1 - \phi)] \frac{\partial T}{\partial t} \tag{5}$$

where S_s is the specific storage coefficient, **E** is the combined thermal conductivity-dispersion coefficient, T is temperature, and ρc and $\rho_s c_s$ are the heat capacities of the fluid and solid phases respectively. Eqs (4) and (5) are strictly applicable only to nondeformable, nonreactive porous media with a slightly compressible solid matrix and fluid in thermal equilibrium. The specific storage coefficient in (4) represents the volume of water released from storage per unit volume of porous medium for a unit drop in hydraulic head. Formally,

$$S_s = \rho g(\alpha + \phi\beta) \tag{6}$$

where α is the bulk compressibility of the solid matrix, and β is the isothermal compressibility of water. In thick compacting basins, S_s is dependent on pore pressure or depth (Neuzil, 1986), but we will assume here that it is nearly a constant for a given lithologic unit. This assumption results in overestimates in pressure and flow rates for compaction calculations (Bethke and Corbett, 1988).

Numerical solutions of (4) and (5) are necessary to preserve their physical coupling and to solve for hydraulic head and temperature in geologically realistic flow domains. Detailed explanation of the numerical technique is given in Garven (1989). Geologic cross sections are first simplified to depict basic hydrostratigraphic relations in the Midcontinent. Next, a finite element mesh is constructed for the 2-D flow region, and appropriate initial and boundary conditions are assigned, along with specified rock properties for the hydrostratigraphic units. A salinity-depth profile is also assigned, but in all cases this is assumed to be some simple linear profile, as actual paleo-conditions are unknown. Initial fluid density and viscosity are computed from the conductive temperature field and fitted equations of state (Kestin, Khalifa, and Correia, 1981). Finite element expressions for the groundwater flow and heat transport equations are solved numerically in a sequential iterative fashion, with fluid properties updated at each step as the solution is marched through simulation time. Time-stepping intervals are short in duration in early parts of the simulations to accommodate transients in the flow fields, but later these increase substantially as the system evolves to a steady state.

For some basin simulations, only the steady-state flow field was desired, therefore no time-stepping was required as the right sides of (4) and (5) are set to zero. Steady-state flowlines (streamlines) were obtained for all basin models by considering the Boussinesq approximation for fluid continuity (Phillips, 1991; Evans and Raffensperger, 1992):

$$\nabla \cdot (\mathbf{q}) = 0 \tag{7}$$

such that

$$\nabla \cdot \left[\frac{\mathbf{k}}{|\mathbf{k}|} \mu \nabla \Psi \right] = - g \frac{\partial \rho}{\partial x} \tag{8}$$

where Ψ is the stream function (volumetric flow rate per unit width), and $\mathbf{k}$ is the tensor for intrinsic permeability. Numerical solution of (8) provides the stream function as a field parameter that can be contoured for visualization of approximate flowlines in a basin near steady state.

III. Simulations of Gravity-Driven Flow

A suite of paleohydrologic simulations are presented here in order to document gravity-driven brine migration at the regional scale. We have considered several regional migration scenarios for the Midcontinent, all of which involve groundwater flow over hundreds of kilometers (fig. 12). Each flow model is of cross-sectional design, and each profile extends from the frontal thrust of a foreland orogenic belt to an arbitrary hydraulic divide near the platform edge of the basin, normally far-removed from the ore districts of interest to this study. Hydrostratigraphic units have been represented in the cross sections in as much detail as possible, but in many cases only broad generalizations could be made because of the large scales involved and the uncertainty in stratigraphic reconstruction. Regional stratigraphic data were obtained from published maps, atlases, cross sections from numerous sources, and some well logs obtained from commercial distributors. Figure 13 illustrates one example of how much of the Paleozoic stratigraphy inferred for the Ozark Dome and Arkoma Basin has been mapped into hydrostratigraphic units for modeling basinal flow systems. The classification of regional aquifers and aquitards used here is largely based on lithology and known hydrologic properties such as those presented by Jorgenson, Helgesen, and Imes (1992), and others. A similar style of hydrologic mapping is adopted for other regions in the Midcontinent. Assumed hydraulic properties for the hydrostratigraphic units will be cited as each simulation is presented. Assumed thermal properties for the units will not be cited as these have a very narrow range of variability. Values of thermal conductivity for sandstone, shale, carbonates, and crystalline basement were derived from the compilation in Garven and Freeze

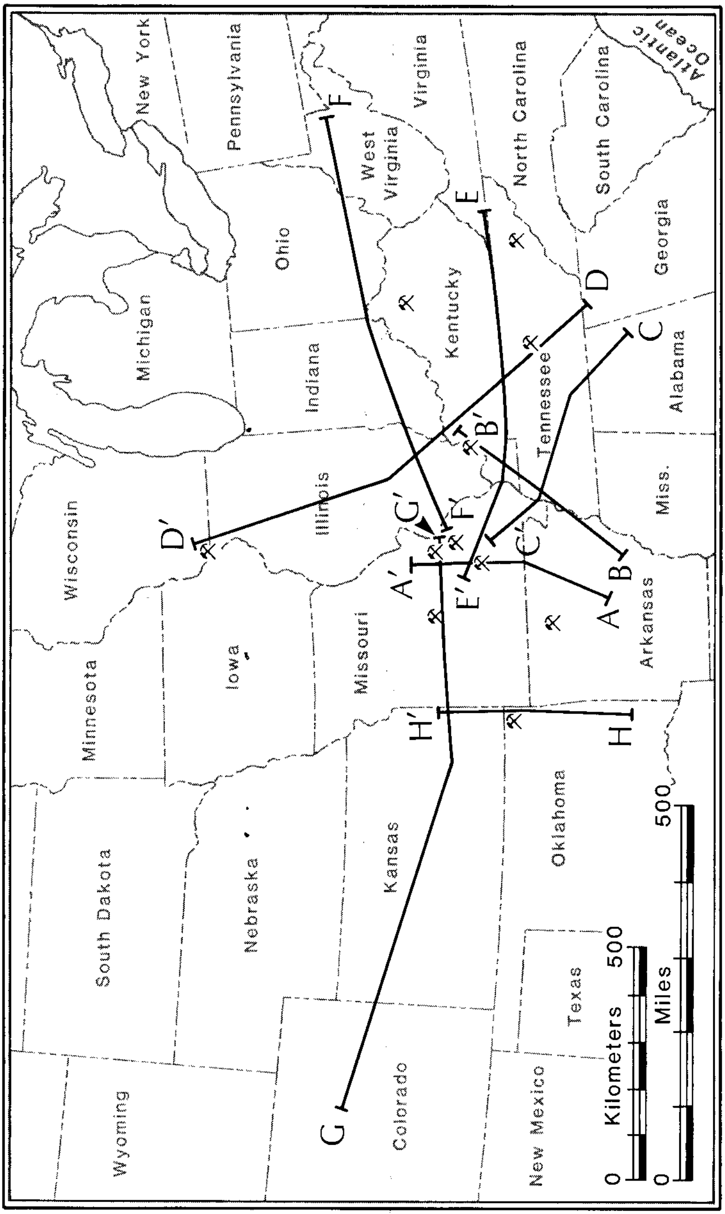

Fig. 12. Location map for hydrogeologic section models of the Midcontinent.

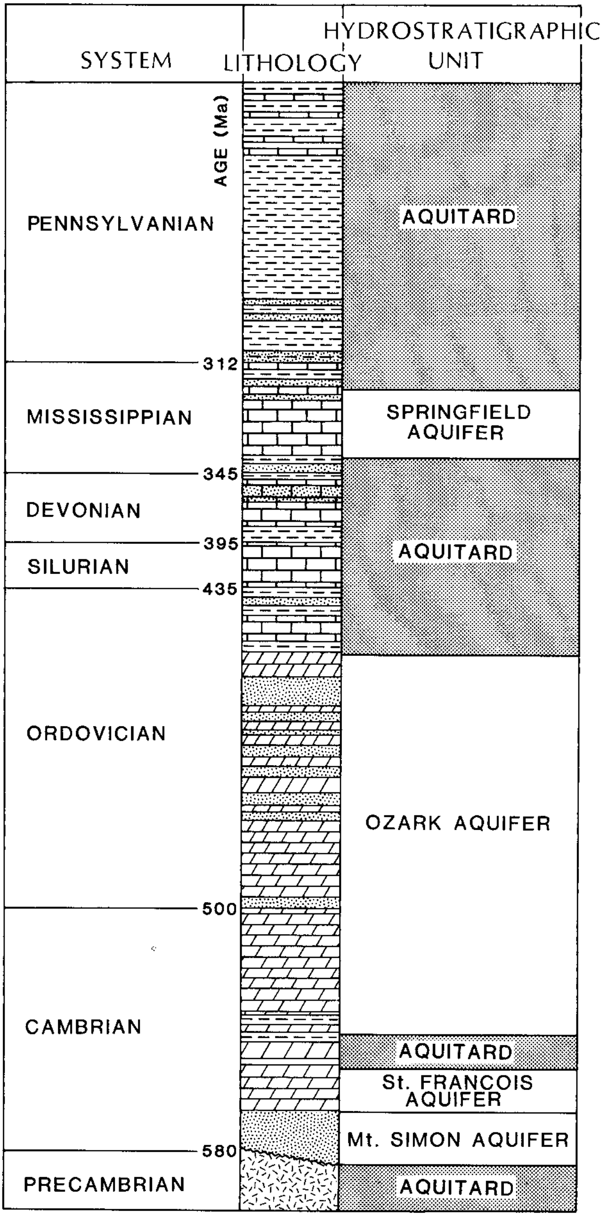

Fig. 13. Lithologic column and hydrostratigraphy for the Ozark region.

(1984b). No attempt has been made to compile sets of permeability-hydraulic conductivity or porosity field data for these rock units as this would be fruitless given the regional scale and age of the systems being modeled. Because of the scope of this project and space limitations, only a handful of simulation results can be presented, but we feel they are generally representative. Sensitivity studies on parameters such as permeability, thermal conductivity, salinity gradient, basement geometry, and grid density were conducted for each of the model sections described below. The effects of these features are described in the earlier works of Garven and Freeze (1984b), Bethke (1986), and Garven (1986, 1989).

Southern interior flow systems.—The Arkoma Basin, Mississippi Valley Graben, and Black Warrior Basin comprise the southernmost sources of mineralizing brines for ore districts in southwestern Missouri, southeastern Missouri, and southern Illinois-Kentucky (fig. 1). Section A–A′ in figure 12 cuts through the eastern half of the Arkoma Basin, along a transect that begins in the undeformed foreland north of Little Rock, Arkansas, extends northward over the Ozark dome, and terminates near the Missouri River, west of St. Louis. It is generally accepted by many that ores in northern Arkansas and southeast Missouri formed from basinal brines expelled from the Arkoma Basin (Leach, 1973, 1979), presumably along a flow path similar to A–A′. In figure 14, the hydrologic section of A–A′ is shortened as Cambrian through Mississipppian age sediments onlap the Precambrian St. Francois Mountains. Five hydrostratigraphic units are represented in this version of the model: Unit 1 (in black) is the crystalline basement of the St. Francois Mountains with a very low hydraulic conductivity $K_1 = 10^{-5}$ m/yr and a porosity $\phi_1 = 0.01$, Unit 2 represents a combined basal Lamotte sandstone and permeable Bonneterre dolomite (fig. 13) which eventually thins toward the Arkoma Basin. This unit is assigned a hydraulic conductivity along bedding planes $K_2 = 600$ m/yr and porosity $\phi_2 = 0.25$. A less permeable Ozark Aquifer, Unit 3, conformably overlies the basal units, and $K_3 = 300$ m/yr with $\phi_3 = 0.20$. Unit 4 contains low permeability carbonates and shale of Ordovician to Mississippian age which are overlain by a thick wedge of Pennsylvanian-Permian clastics of Unit 5. For both model units, $K_4 = K_5 = 10$ m/yr and $\phi_4 = \phi_5 = 0.10$. No attempt was made at characterizing the Mississippian group aquifer (Springfield Aquifer of fig. 13) which is so prominent in the western platform of the Arkoma Basin. All the sedimentary units within figure 14 are assumed to maintain a vertical hydraulic conductivity that is 1/100 of the along-bedding values cited above. We have adopted this hydraulic anisotropy factor for all the model simulations characterized in this paper. The effect of anisotropy on regional flow patterns is described by Garven (1989, see figs. 14 and 15). The flow region is discretized with a finite element mesh containing 17 rows and 73 columns with variable element sizes.

The base of the model is taken to be impermeable to groundwater flow, but a constant heat flow of 80 mW/m^2 is maintained along this basement surface. The frontal thrust of the Ouachita Mountains provides

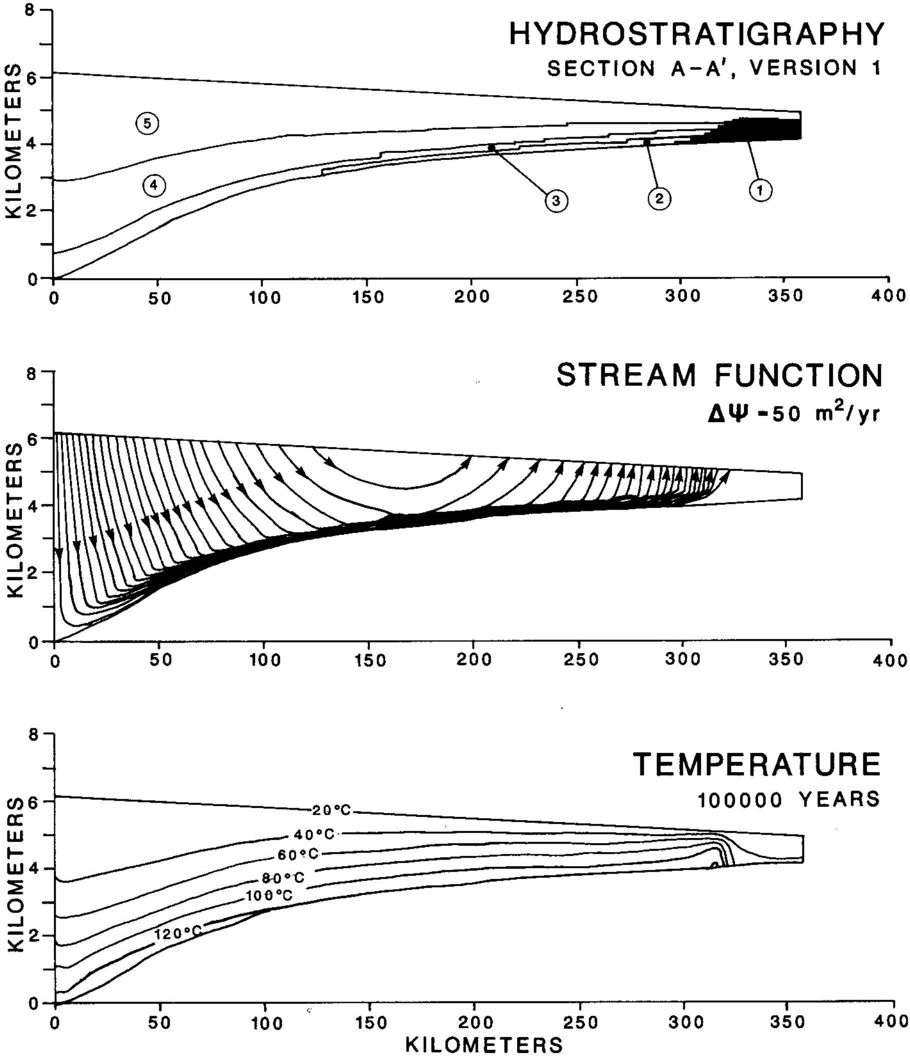

Fig. 14. Hydrogeologic model for section A–A′, version 1, across the Ozark Dome.

a near vertical hydraulic divide at the southern end of the section, and a similar divide is positioned at the thin northern end. The water table profile forms the top surface of the flow region, where it is assumed to follow a subdued replica of the topography. We have conjectured a near-linear drop in water table elevation of about 1200 m over 360 km (0.3 percent grade) for this late Permian representation of the basin. Salinity is assumed to increase linearly below the 5000 m elevation level to a maximum of 25 percent equivalent weight NaCl at the deepest point in the basin. Temperature along the water table was fixed at 20°C. Prior to the final stages of the subaerial emergence of the foreland basin and platform, we assume the basin profile is submerged or near sealevel and under hydrostatic conditions. After erosional unloading of the ancient Ouachita hinterland, the foreland basin and platform are uplifted to the gentle relief depicted in figure 14. This uplift occurs instantaneously in our numerical model, but new flow patterns and temperature fields emerge as the basin adjusts to the new boundary conditions. It takes about 10^5 to 10^6 yrs for both flow fields to adjust to a new steady state (Garven, 1988, 1989). For section A–A′ (fig. 14), regional brine migration is strongly controlled by the deep Cambrian-Ordovician aquifers in which flow is focused. The stream function map indicates that most of the section north of the Arkansas-Missouri border (near x = 200 km) was a regional discharge area, although most of the flow was forced upward near the pinchouts against the St. Francois basement where Darcy flow rates (eq 1) are the largest at about 5 m/yr. The temperature map at 100,000 yrs after uplift suggests a rather gentle rate of cooling for brines moving out of the foreland sag, but very rapid rates occur near the discharge margin. The history of cooling and heating is shown for two reference sites in figure 15 that illustrate how transient thermal pulses might advance through a near-steady groundwater flow system. The thermal pulse displayed here is related to the contrast in hydraulic and thermal diffusivities that control the rates at which hydrologic and thermal transients propagate across the basin (Garven, 1988, 1989). The extra heat transported through regional aquifers by forced convection results in elevated temperatures for 100,000 yrs, until conduction can dissipate the heat and temperatures stabilize at a new steady state for the uplifted foreland basin. Based on this model, brine temperatures range between 80° and 130°C in the vicinity of ore districts in northern Arkansas and southeast Missouri.

A modified version of section A–A′ is presented in figure 16, where the northern leg of the profile was moved to the west side of the St. Francois Mountains such that we could consider an unobstructed flow path along strike of the Viburnum Trend of the New Lead Belt in southeast Missouri. In this scenario there are seven hydrostratigraphic units: Unit 1 is a thin protrusion of crystalline basement at the apex of the Viburnum Trend ($K_1 = 10^{-5}$ m/yr, $\phi_1 = 0.01$); Unit 2 is the basal Lamotte Sandstone (Mt. Simon Aquifer), and Unit 3 the St. Francois Aquifer ($K_2 = K_3 = 500$ m/yr, $\phi_2 = \phi_3 = 0.20$); Unit 4 is the Davis Shale ($K_4 = 0.1$ m/yr, $\phi_4 = 0.15$); Unit 5 is the basal part of the Ozark Aquifer ($K_5 = 500$ m/yr; $\phi_5 = 0.15$); and Units 6 and 7 are less permeable Ordovician-Permian carbonates and shales ($K_6 = K_7 = 20$ m/yr, $\phi_6 = \phi_7 = 0.10$). The flow region is discretized with a finite element mesh containing 25 rows and 79 columns.

Once again the flow pattern is characterized by deep cross-formational flow in the foreland sag followed by broad, slow upward

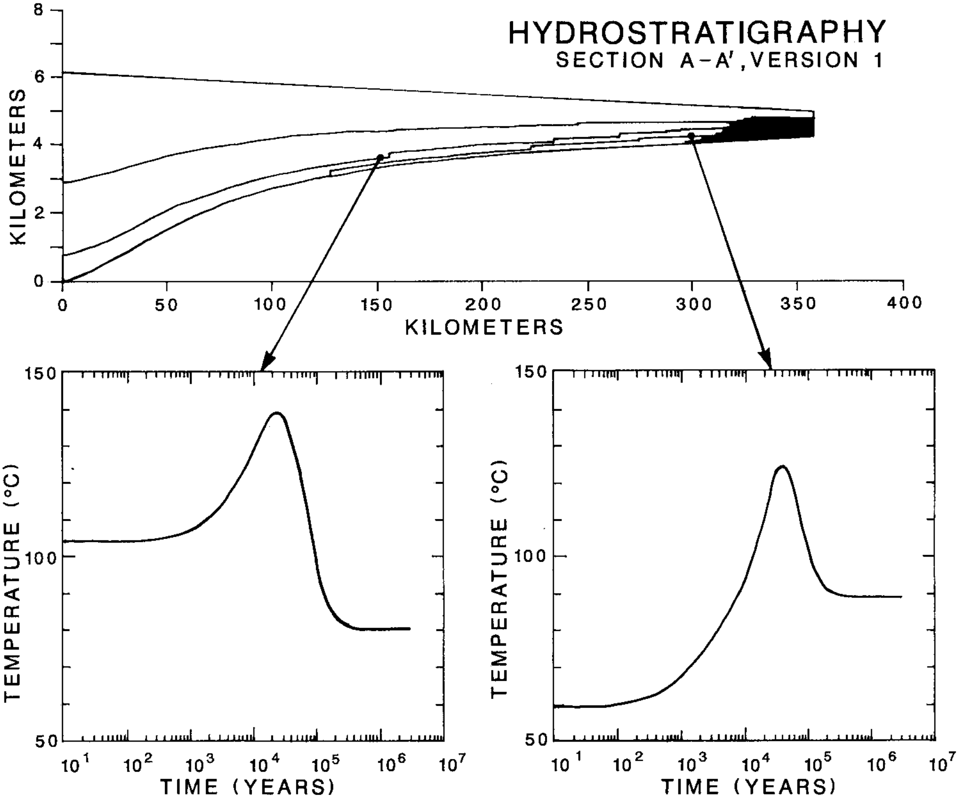

Fig. 15. Thermal history for reference points in section A–A′, version 1.

seepage in the platform with most regional flow focused by the deep Cambrian-Ordovician aquifers. Darcy flow rates of 3.5 m/yr occur in the paleoaquifers of the Viburnum trend, while vertical flow rates of 0.007 m/yr occur in the overlying less permeable strata. A lateral thermal gradient of 1.0×10^{-4}°C/m is predicted along the Viburnum Trend ore district in southeast Missouri, which suggests regional cooling might not have been important in ore deposition across the district. Even with a lower heat flux of 70 mW/m^2 assigned to the basement, there is ample evidence for the discharge of 100°C+ brines through the Viburnum Trend. Transient heat-flow adjustments may have allowed for temperatures in excess of 120°C for tens of thousands of years (fig. 17). It appears, however, that basement heat flow of about 80 mW/m^2 would be needed to explain the 100° to 120°C fluid inclusion range for mineralization if less stratigraphic cover existed than the thickness depicted here. Other geologic conditions could complicate this situation further, as in the scenario of a local topograhic high in southeast Missouri causing local

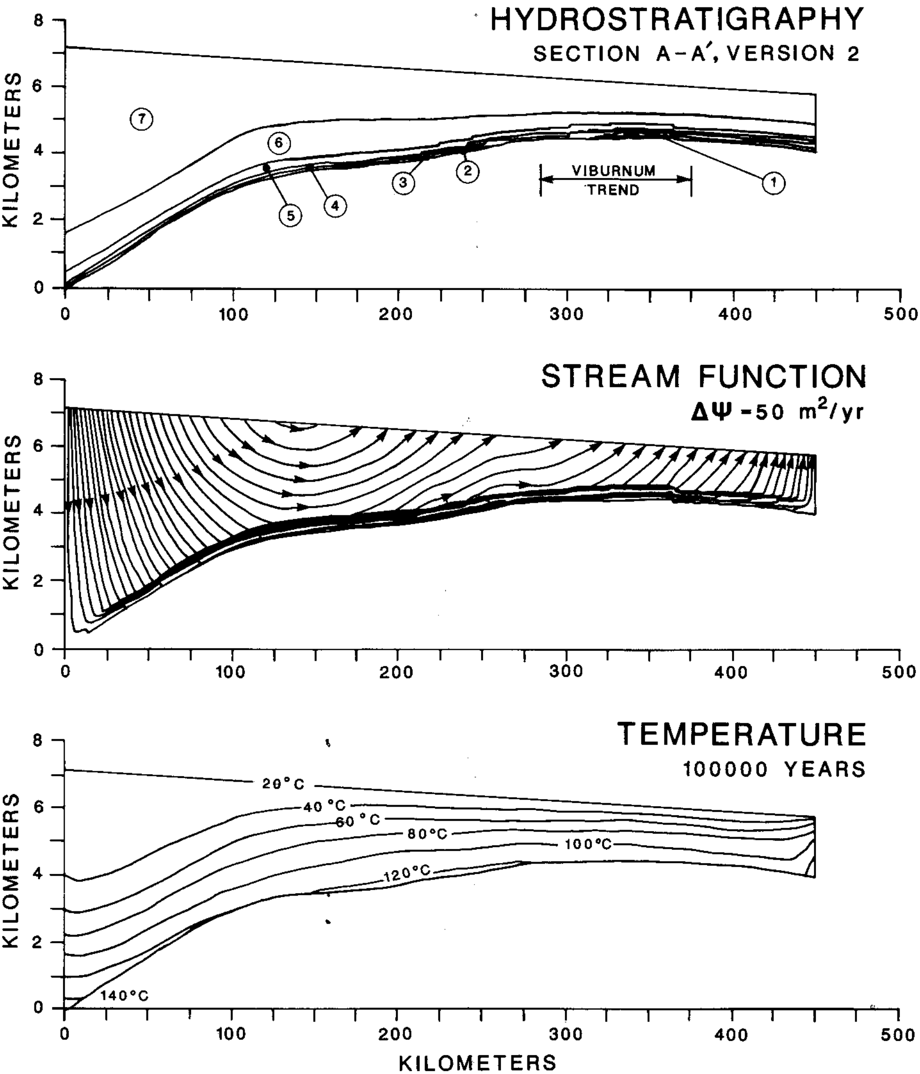

Fig. 16. Hydrogeologic model for section A–A′, version 2, across the Ozark Dome.

recharge and mixing along the Trend (figs. 18, 19). Such a scenario, however, may not have been feasible, as the Ozark Dome was mostly buried in the late Paleozoic (Beaumont, Quinlan, and Hamilton, 1988).

In section H–H′ we consider a flow profile in the west-central part of the Arkoma Basin that passes through the large Tri-State Pb-Zn district (fig. 20). Normal faulting of the Cambrian-Mississippian passive margin

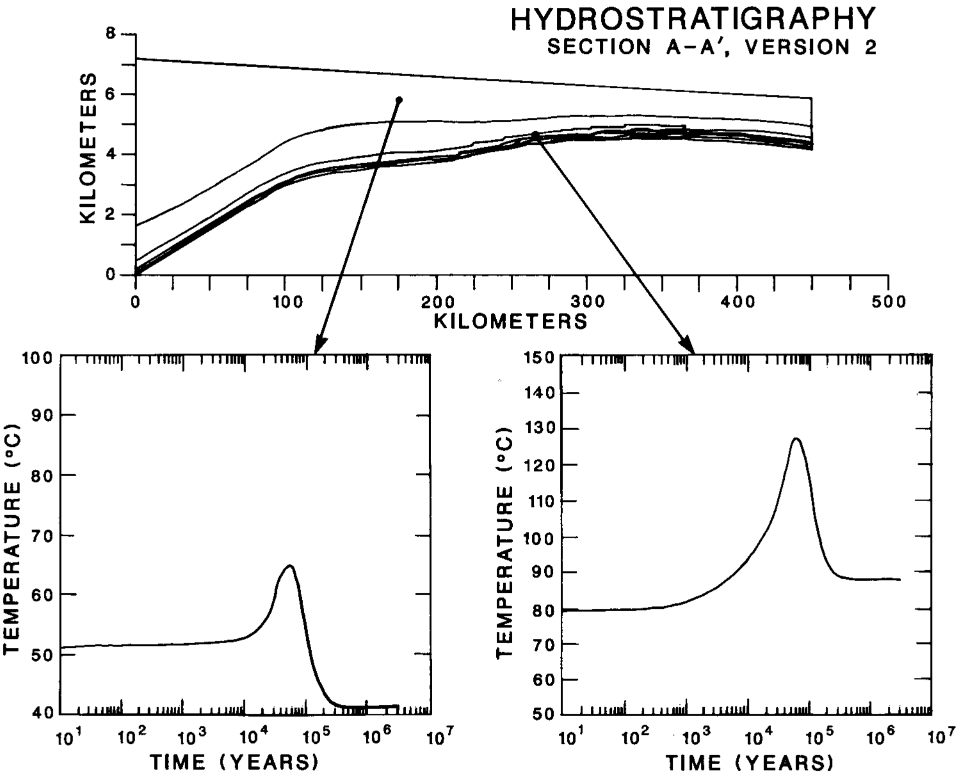

Fig. 17. Thermal history for reference points in section A–A′, version 2.

sequence has resulted in a staircase geometry in the deeper portion of the foreland. The flow region is discretized with a finite element mesh containing 17 rows and 79 columns. Salinity is assumed to increase linearly below the 9000 m elevation level to a maximum of 40 percent equivalent weight NaCl at the deepest point in the basin. Unit 1 (black) represents a slightly permeable crystalline basement, although $K_1 = 10^{-5}$ m/yr. Unit 2 is the combined Mt. Simon/St. Francois aquifer ($K_2 = 200$ m/yr, $\phi_2 = 0.20$), and Unit 3 consists of less permeable Upper Cambrian to Devonian shale and limestone, undifferentiated ($K_3 = 5$ m/yr, $\phi_3 = 0.15$). Unit 4 represents the thin Springfield Aquifer (fig. 13) with $K_4 = 200$ m/yr and $\phi_4 = 0.20$, but this layer is replaced by Unit 5 downdip in the basin with a much reduced hydraulic conductivity ($K_5 = 5$ m/yr, $\phi_5 = 0.15$). Unit 6 contains all post-Mississippian rocks ($K_6 = 5$ m/yr, $\phi_6 = 0.10$) that blanket the basin platform with over 1500 m of cover. As in the previous model, the water-table configuration represents a late Permian stage when the Alleghanian-Ouachita orogeny

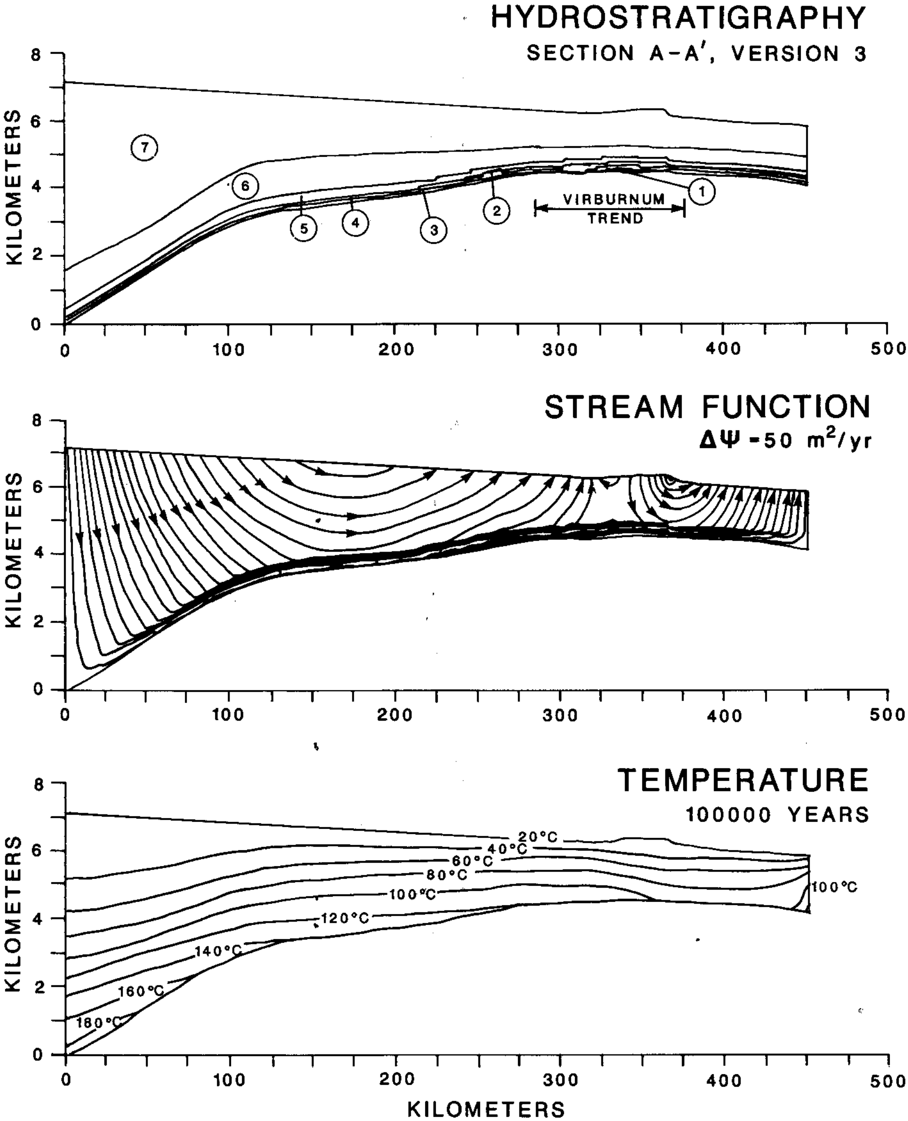

Fig. 18. Hydrogeologic model for section A–A′, version 3, across the Ozark Dome.

had created maximum relief across the foreland. Nearly two-thirds of the basin profile is characterized by groundwater discharge with both the Cambrian and Mississippian aquifers conducting large amounts of brines out of the foredeep. Maximum fluid flow velocities occur in the deep aquifers at rates of about 4 m/yr. The largely horizontal flow field results

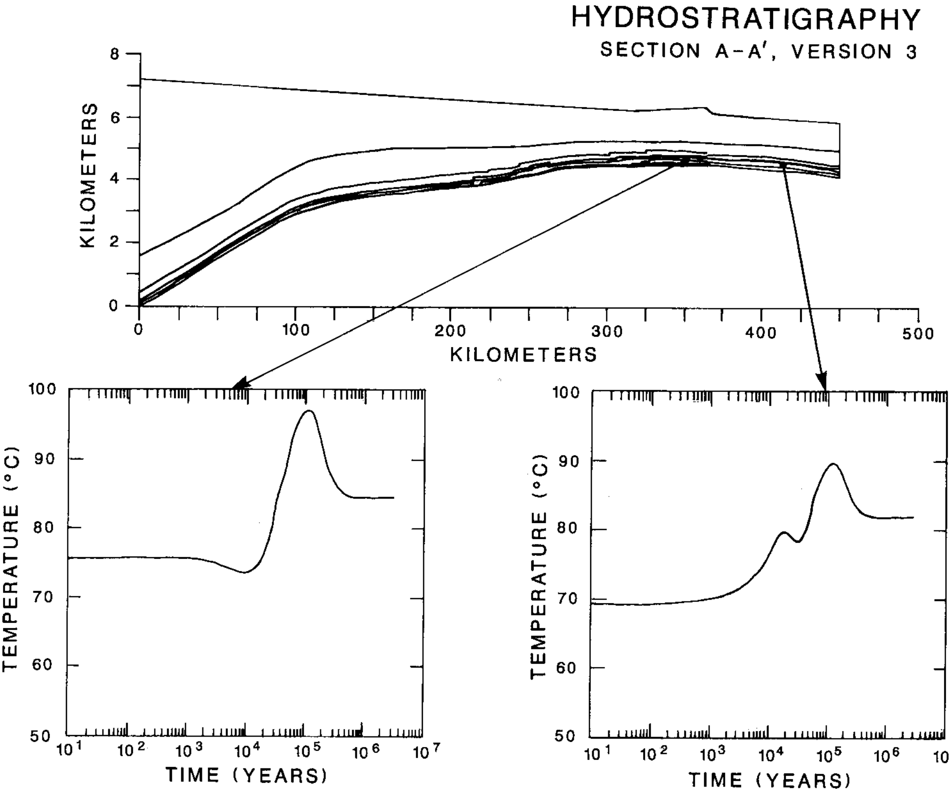

Fig. 19. Thermal history for reference points in section A–A′, version 3.

in a less dramatic influence on basin temperatures. With an assigned heat flux of 70 mW/m^2 from the basement, transient fluid temperatures appear to vary between 90° and 135°C at a depth of 1500 m on the platform (fig. 21). Ore mineralization in the Tri-State District occurred in this temperature range, but little thermal control on deposition is apparent from the regional simulation.

Compression of the Ouachita orogen resulted in deep thrusts that abutted the southern stretch of the Reelfoot Rift (Mississippi Valley Graben, fig. 1). Section B–B′ has been configured to test the theory that uplift of the Arkoma foreland by emergence of the Ouachita Mountains could have driven deep brines northward along the axis of the graben. In figure 22, six hydrostratigraphic units are chosen to represent the geology along central axis of the Graben, although these are approximate in part because of limited data. Units 1 and 2 represent Cambrian clastics, with a coarser basal unit being the most permeable (K_1 = 100 m/yr, ϕ_1 = 0.25, K_2 = 50 m/yr, ϕ_2 = 0.20). Parts of Unit 2 and all of Unit 3 are

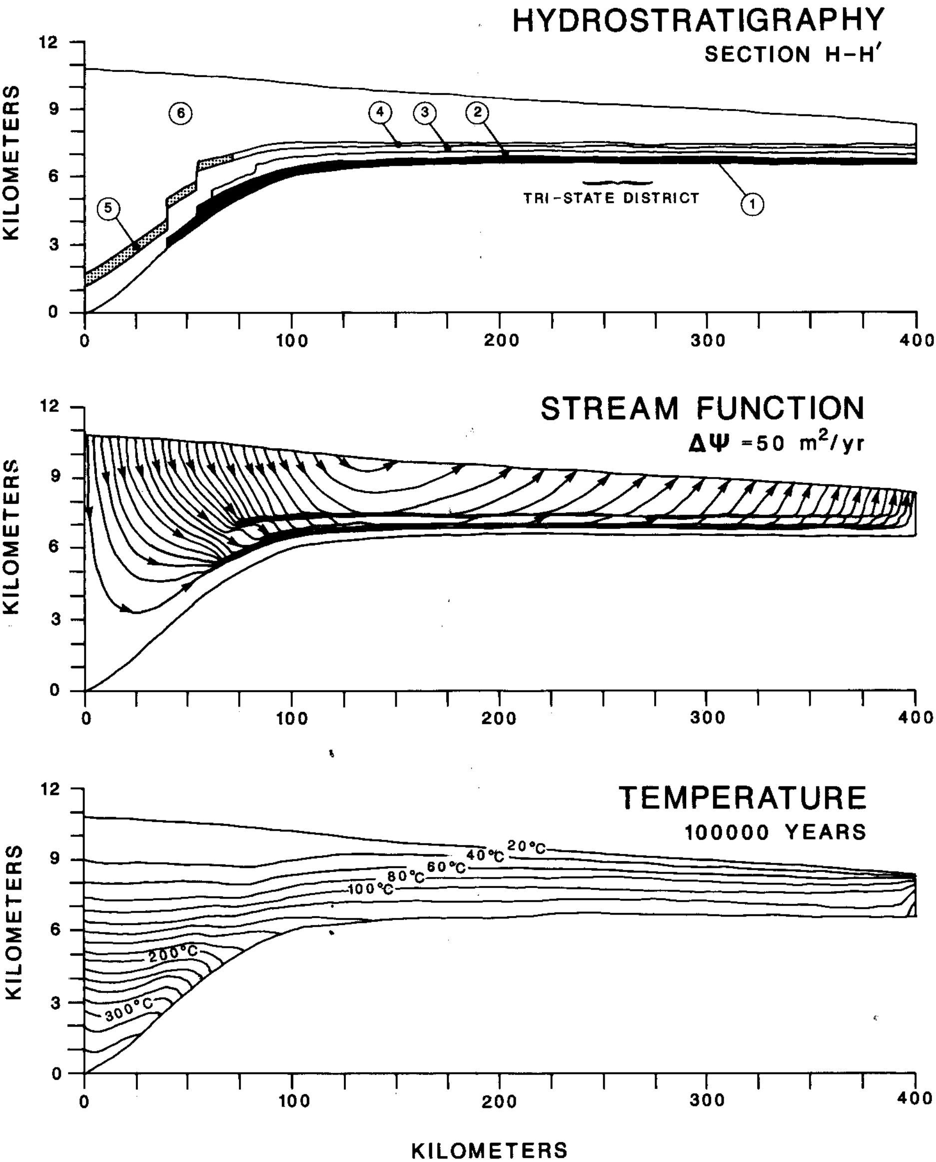

Fig. 20. Hydrogeologic model for section H–H′ across the Tri-State District.

Cambrian-Ordovician carbonates and minor clastics ($K_2 = 50$, $\phi_2 = 0.20$, $K_3 = 20$ m/yr, $\phi_3 = 0.15$). Unit 4 is a Silurian to Devonian shale sequence of relatively low permeability ($K_4 = 5$ m/yr, $\phi_4 = 0.15$). Very permeable Mississippian carbonates comprise Unit 5 ($K_5 = 100$ m/yr,

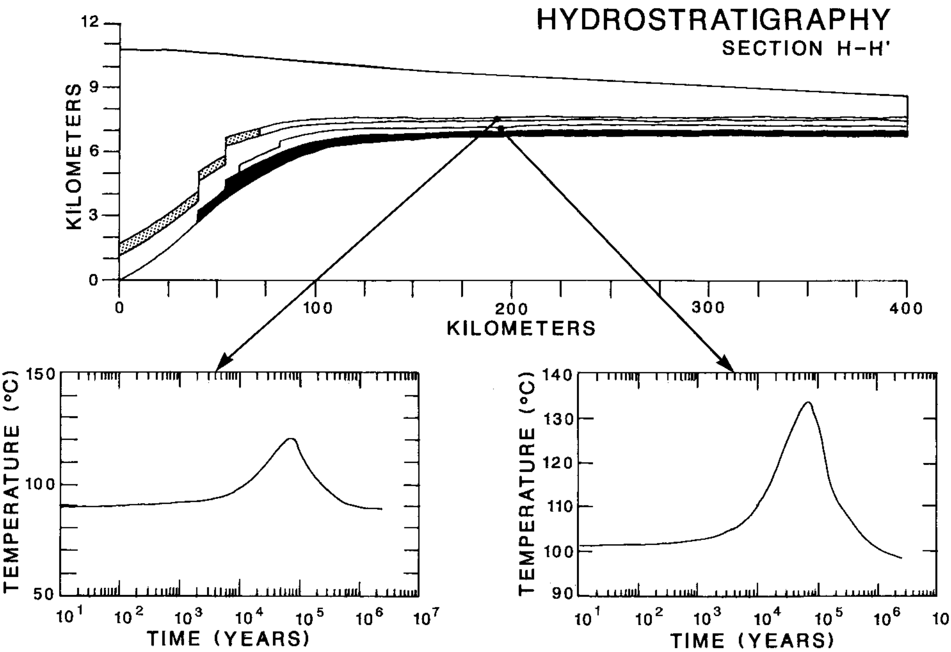

Fig. 21. Thermal history for reference points in section H–H′.

ϕ_5 = 0.20), but they exist only in the northern reaches of the basin. Overlying these strata is a very thick sequence of Pennsylvanian-Permian shale and redbeds with a gentle topographic slope. The structural dome on the basement reflects present-day relief surrounding the Pascola Arch, as no attempt was made to restore paleorelief. The south end of section B–B′ is a hydraulic divide (no-flow barrier) created by the leading frontal thrust of the Ouachita orogen, while the north end of the section is bounded by the Rough Creek-Cottage Grove fault. Faults of this type may behave as either horizontal barriers to flow or as nonbarriers depending on whether the fault zone is more permeable than adjacent aquifers (Bredehoeft, Belitz, and Sharp-Hansen, 1992). We have assumed that this major reverse fault system, which exhibits structural displacements in excess of 1 km, would form a barrier to lateral flow. No specific data exist to constrain the hydraulic properties of the fault system itself, so it is only treated as a no-flow boundary in the model. Despite the possibility of additional heat sources due to intrusions of magma along the rift, only a constant heat flow of 70 mW/m^2 is assigned to the basement contact. Salinity is assumed to increase linearly below the 9000 m elevation level to a maximum of 20 percent equivalent weight NaCl at the deepest point in the basin. The flow region is discretized with a finite element mesh containing 20 rows and 65 columns of elements.

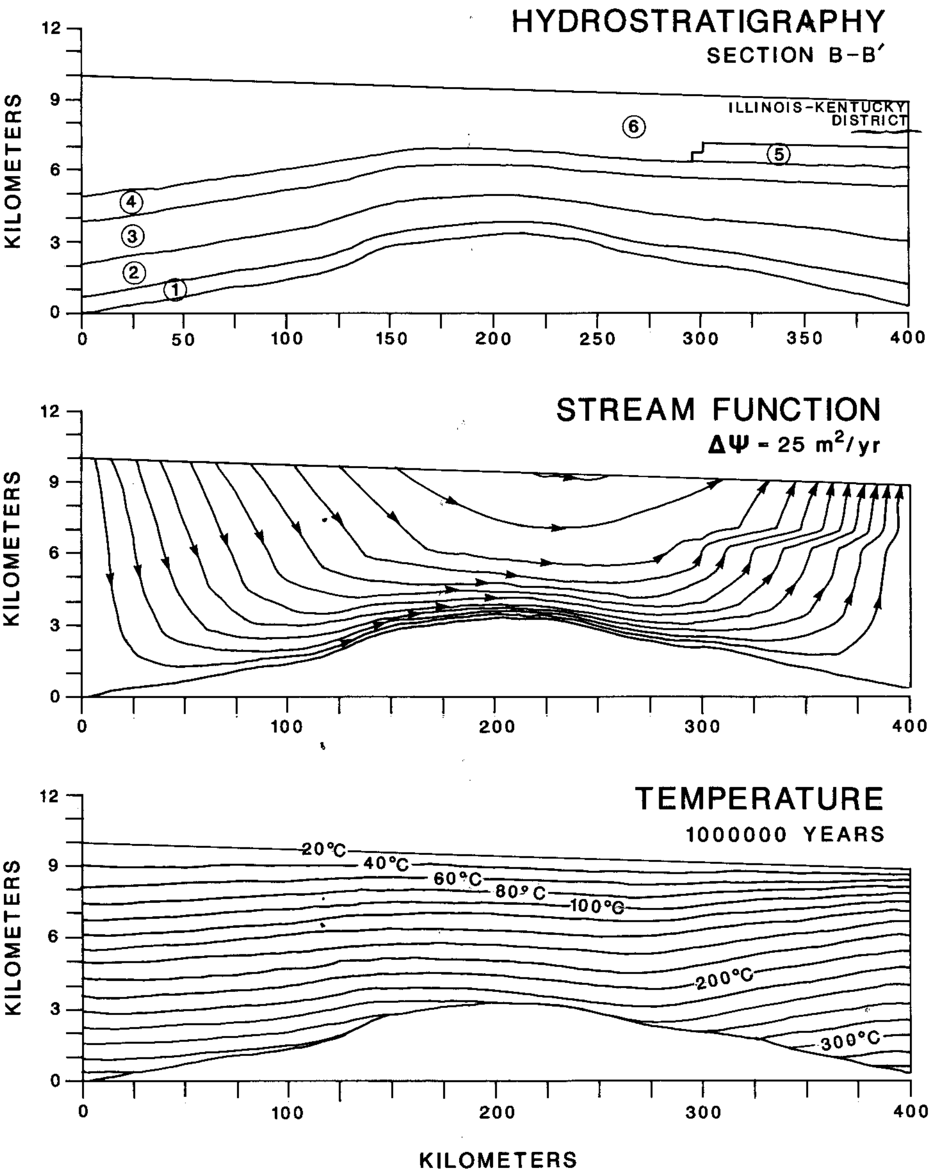

Fig. 22. Hydrogeologic model for section B–B′ along the Mississippi Valley Graben.

The numerical results are as one might expect given the hydrostratigraphic setting. Groundwater descends to depths of several kilometers in the southern half of the graben and becomes focused through the basal Cambrian arkoses as brines move up and over the basement arch at rates of about 0.8 m/yr. Deep vertical discharge is concentrated in the Cottage Grove Graben of western Kentucky and southern Illinois, a feature reflected in lead-isotope trends (Goldhaber and Church, 1989). Fluid temperatures reach 160°C in the Mississippian carbonate aquifer at a proposed depth of about 2 km in the northern end of the rift, and thermal transients suggest mineralization temperatures well above 200°C under these conditions (fig. 23). Darcy velocities here average around 0.4 m/yr.

At the southern end of the Appalachian orogen lies the Black Warrior foreland basin (fig. 1), yet another possible source region of metaliferrous brines (Rowan and Leach, 1989). Section C–C′ traverses this basin from southeast to northwest in order to reconstruct a scenario of fluid migration resulting from Late Permian uplift of the Appalachian foldbelt (fig. 12). The stratigraphy represented in the hydrogeologic model of figure 24 has been simplified from Thomas (1988); the model extends from the frontal thrust plane in the southeast, over the southern edge of the Nashville Dome, across the Mississippi Valley Graben, and terminates at a near vertical fault plane in southeast Missouri. Unit 1 represents a low permeability basement ($K_1 = 10^{-4}$) which is included in this simulation in order to capture the Mississippi Valley Graben in the numerical grid. Unit 2 includes the Cambrian-Ordovician aquifers dominated by the Knox Group ($K_2 = 200$ m/yr, $\phi_2 = 0.2$), and Units 3 and 4 contain less permeable strata of Ordovician to Mississippian age ($K_3 = 5$ m/yr, $\phi_3 = 0.15$, $K_4 = 20$ m/yr, $\phi_4 = 0.15$). Capping this passive margin sequence are low permeability shale, carbonates, and sands of post-Mississippian age. Surface elevation drops a modest 1000 m over the 600-km length of the section. Salinity is assumed to increase linearly below the 9000-m elevation level to a maximum of 20 percent equivalent weight NaCl at the deepest point in the basin. The flow region is discretized with a finite element mesh containing 25 rows and 67 columns.

The steady-state flow field and temperature map (fig. 24) illustrate a simple regional flow system, with only a minor perturbation created by the graben. Maximum Darcy flow rates of 1.6 m/yr occur in the Cambrian-Ordovician aquifer near the central part of the basin. Similar groundwater flow simulations of the section, but with no major aquifer units in the graben, produced negligible modifications of the basin hydrology. A very steep thermal gradient exists at the right margin of the section because of the abrupt vertical flow created by the boundary fault. Temperatures between 160° and 180°C are predicted in the basal aquifer unit, assuming a constant basement heat flow of 70 mW/m^2.

Eastern interior flow systems.—Regional brine migration across the eastern interior region provides yet another possible source area for ore mineralization in the Midcontinent. Deep groundwater flow would have been most strongly controlled by gravity-driven flow systems created by the closing period of the Alleghanian orogeny in Permian time (fig. 7). Uplift of the Appalachian Mountains and foreland platform would have

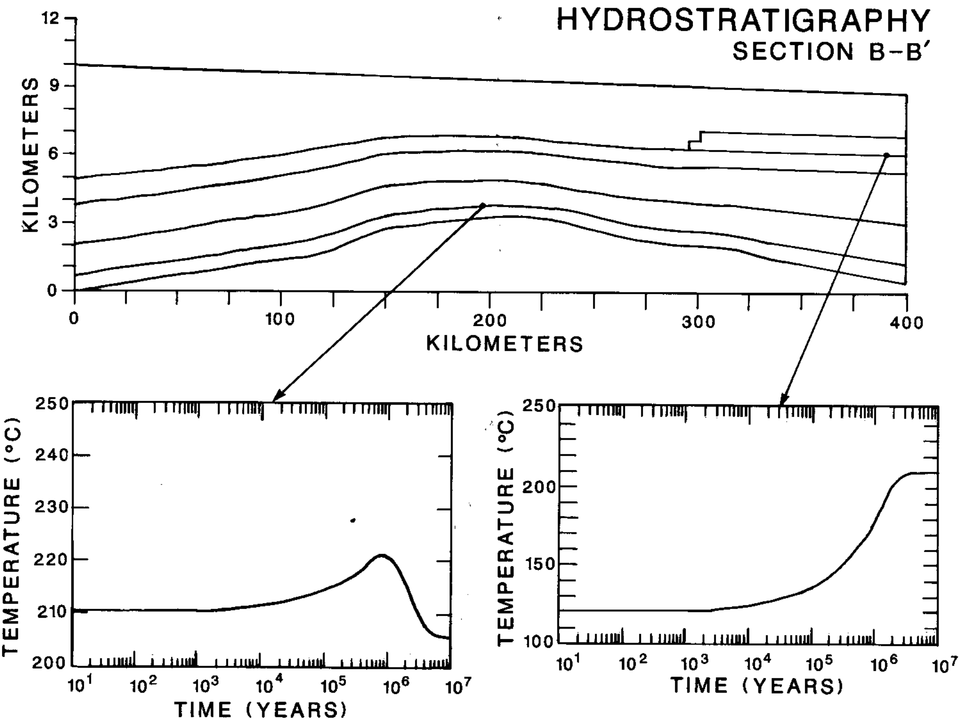

Fig. 23. Thermal history for reference points in section B–B′.

driven brines out of the Appalachian Basin, over adjacent arches and domes, across sags of the Illinois and Michigan Basins, with brine discharge focused near the edge of the sedimentary pile. The general direction of flow would have been from southeast to northwest based on present-day structural trends, but flow directions may have varied as structural deformation in the late Paleozoic was variable (Thomas, 1985).

Section F–F′ (fig. 12) considers one hydrogeologic profile extending from the edge of the Appalachian thrust front in West Virginia to the Old Lead Belt in southeast Missouri. This section represents a flow-path scenario where the structural relief was greatest from northeast to west, perhaps because structural uplift was faster or earlier in the northern than in the southern Appalachians. Figure 25 illustrates a generalized hydrostratigraphy: Unit 1 represents a small block of faulted basement ($K_1 = 10^{-6}$ m/yr, $\phi_1 = 0.05$), Unit 2 is the Lamotte/Mt. Simon Sandstone aquifer ($K_2 = 100$ m/yr, $\phi_2 = 0.25$); Unit 3 contains less permeable Upper Cambrian shale (Eau Claire) and carbonates ($K_3 = 5$ m/yr, $\phi_3 = 0.1$). Units 4 and 5 represent aquifers in the Lower Ordovician Knox Group ($K_4 = 50$ m/yr, $\phi_4 = 0.2$, $K_5 = 20$ m/yr, $\phi_5 = 0.15$), Unit 6

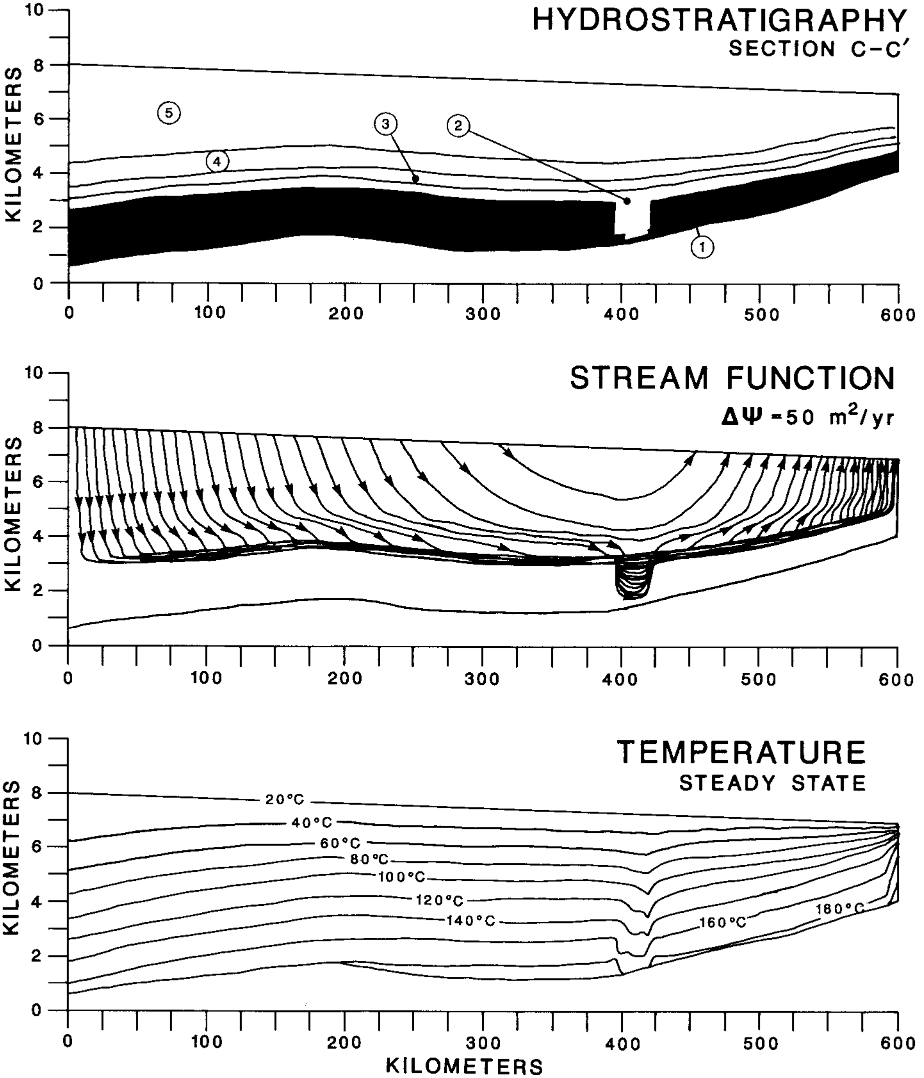

Fig. 24. Hydrogeologic model for section C–C′ across the Black Warrior Basin.

contains a permeable Mississippian aquifer (K_6 = 30 m/yr, ϕ_6 = 0.10), and Unit 7 includes the remaining sequence of Pennsylvania-Permian clastics shed off the uplifted Appalachians (K_7 = 10 m/yr, ϕ_7 = 0.15), after the Alleghanian orogeny. Groundwater salinity is assumed to increase linearly below the 7900 m elevation level to a maximum of 40 percent equivalent weight NaCl at the deepest point in the basin. The

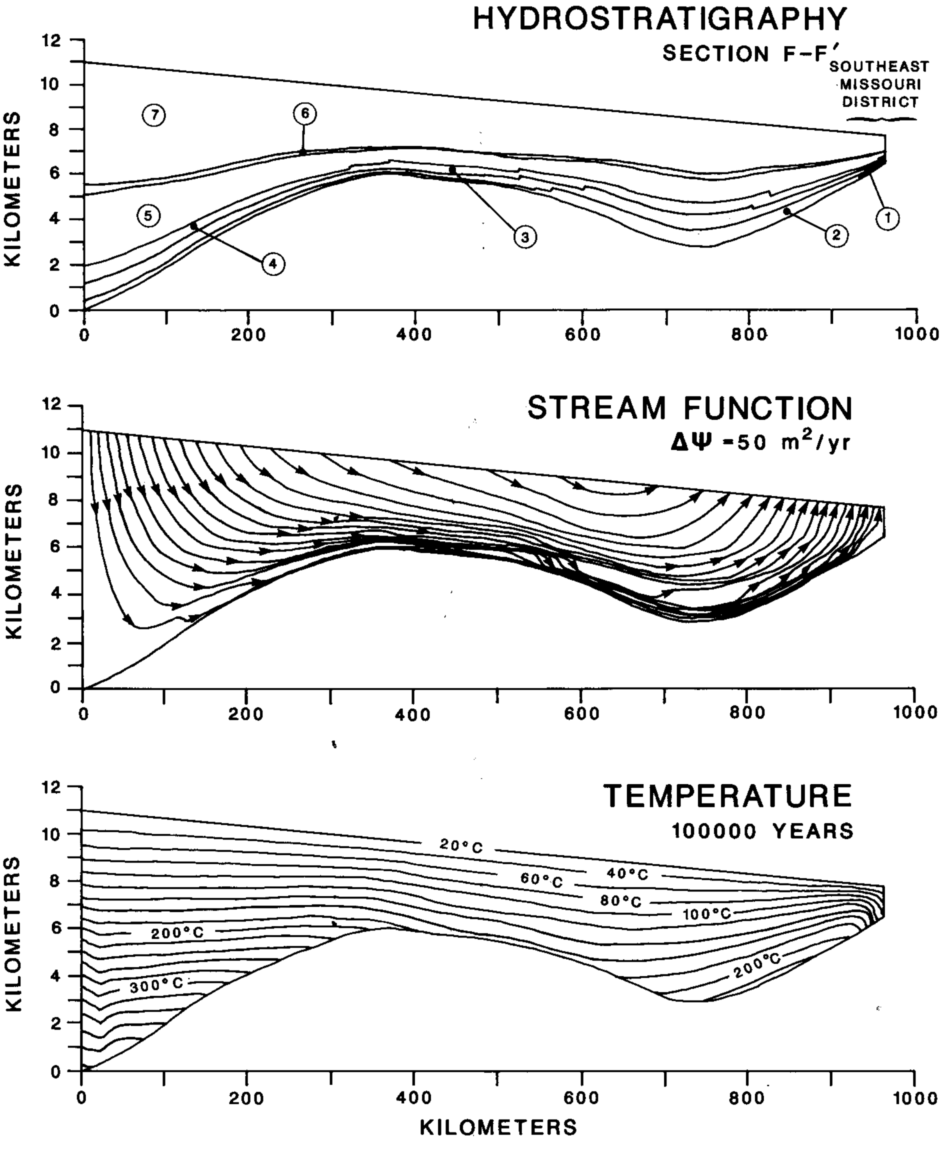

Fig. 25. Hydrogeologic model for section F–F′ across the Eastern Interior.

flow region is discretized with a finite element mesh containing 22 rows and 55 columns.

Once again a transient numerical model was constructed, with the instantaneous uplift and subsequent gravity-driven flow relaxing to a steady state in about 10^3 yrs. The steady-state representation of the flow field is shown in figure 25, along with the temperature field 100,000 yrs after uplift. Groundwater descends to depths of several kilometers in the Appalachian foreland. Maximum groundwater flow rates of 1.7 m/yr occur in the basal Cambrian aquifer, on the downstream side of the Cincinnati Arch near x = 500 km. Mostly lateral or downward flow occurs in the Appalachian Basin and Cincinnati Arch, whereas deep brines move across the Illinois Basin to discharge along its western margin on the Ozark Dome. A pronounced geothermal anomaly is created at the western edge of the model section because of the intense amount of vertical brine flow forced upward by the rapid rise in basement elevation (St. Genievieve Fault System). Although basement heat flow assigned to the model base is only 70 mW/m^2, surface heat flow is about three times the basement flux in the Old Lead Belt of southeast Missouri because of deep brine discharge. Time-temperature history at two points in the Knox Group Aquifer (fig. 26) shows that fluid temperature rises to a maximum of a 184°C near the apex of the Cincinnati Arch (Jessamine Dome) after 400,000 yrs but cools to 167°C near steady state. An even larger rise in temperature takes place at the western edge of the Illinois Basin, where maximum temperatures of 195°C occur at a depth of only 1800 m. The steady-state temperature of 170°C appears 1 Ma

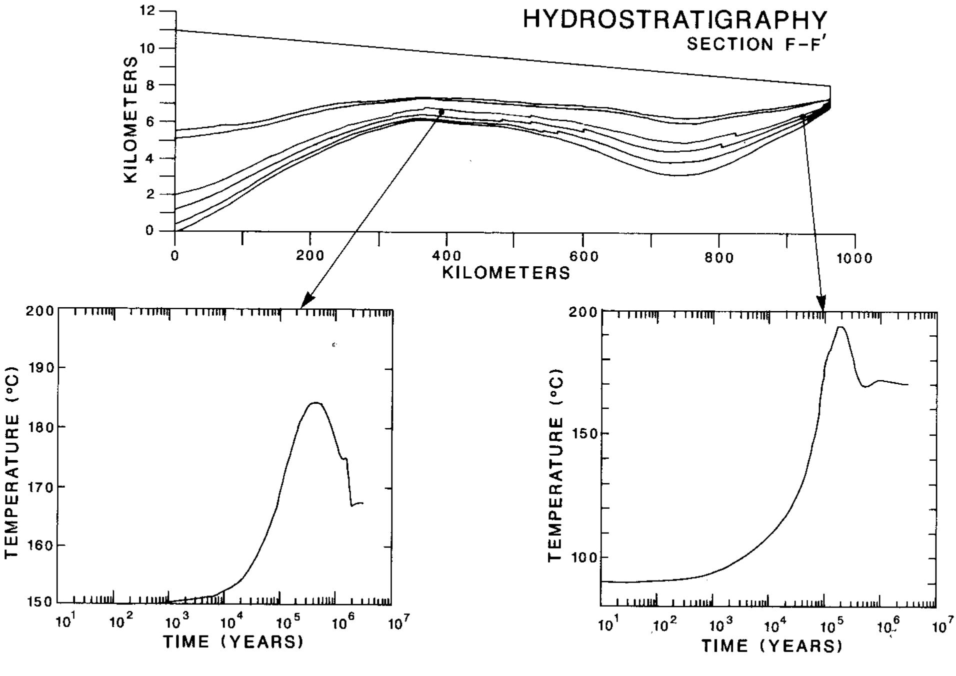

Fig. 26. Thermal history for reference points in section F – F′.

after initiation of the regional groundwater flow. Fluid inclusion temperatures in southeast Missouri ores are considerably lower (120°C) than those predicted in this numerical simulation, but cooler temperatures are predicted for other simulations where a lower basement heat flux is assigned or where a lower regional permeability is used.

The second simulation model in the eastern interior region also considers flow from east to west (E–E′, fig. 12) across the Appalachian and Illinois Basins, but now we have considered a scenario where the region of greatest topographic relief has shifted much farther south. Section E–E′ (fig. 27) is somewhat shorter in length, and the sedimentary sequence is not as thick as in the previous simulation. The cross section begins near the frontal thrust of the Appalachians in Virginia, straddles the Kentucky-Tennessee border over the Cincinnati Arch, and extends for about 100 km west of the Ozark Dome in southeast Missouri. The flow region is discretized with a finite element mesh containing 20 rows and 57 columns. Groundwater salinity is assumed to increase linearly below the 4600 m elevation level to a maximum of 20 percent equivalent weight NaCl at the deepest point in the basin. Unit 1 is the Lamotte/Mt. Simon Sandstone (K_1 = 50 m/yr, ϕ_1 = 0.2) which laterally is replaced by hydrostratigraphic Unit 2 over the Nashville Dome and adjacent Appalachian Basin (K_2 = 5 m/yr, ϕ_2 = 0.10). A basal Cambrian clastic sequence is also represented by Unit 1 in the easternmost part of the model, in the foreland in front of the thrust belt. The only regional aquifer characterized in the section is Unit 3, the dolostones and limestones of the karstic Knox Group (Eau Claire and Bonneterre equivalents). For Unit 3, K_3 = 200 m/yr, ϕ_3 = 0.20. Ordovician-Silurian shale and carbonates cover the Knox Group (K_4 = 1 m/yr, ϕ_4 = 0.10). Mississippian shale caps the shelf sequence as Unit 5 in the model (K_5 = 2 m/yr, ϕ_5 = 0.15). Unit 6 represents undifferentiated clastics of the Pennsylvania-Permian sequence with a nonlinear topographic profile (K_6 = 5 m/yr, ϕ_6 = 0.10). The St. Francois Mountains in southeast Missouri are barely submerged by about 200 m of Permian sediments. Lateral continuity of the Knox Group (Ozark Aquifer) and Mt. Simon/Lamotte Sandstone allow for a significant degree of flow focusing as brines are driven downward and across the Nashville Dome. Upward seepage of deep fluids appears to be prevalent all across the Illinois Basin, although most of the flow is driven laterally through the Cambrian-Ordovician aquifers and forced to discharge near the western margin of the Illinois Basin/Mississippi Valley Graben. A relatively small volume of brine migrates over the St. Francois high, where the Lamotte and Bonneterre beds provide a continuity in the flow path (fig. 27). Maximum flow rates of 3 m/yr are predicted in the Knox Group aquifer, while minimum flow rates of mm/yr occur in the deepest Cambrian shale.

Geothermal gradients are similar to the last simulation case, as forced advection of heat in southeast Missouri creates a three-fold increase in surface heat flow above the ambient basement heat flux of 70 mW/m^2. The lateral thermal gradient in the Knox paleoaquifer reaches a

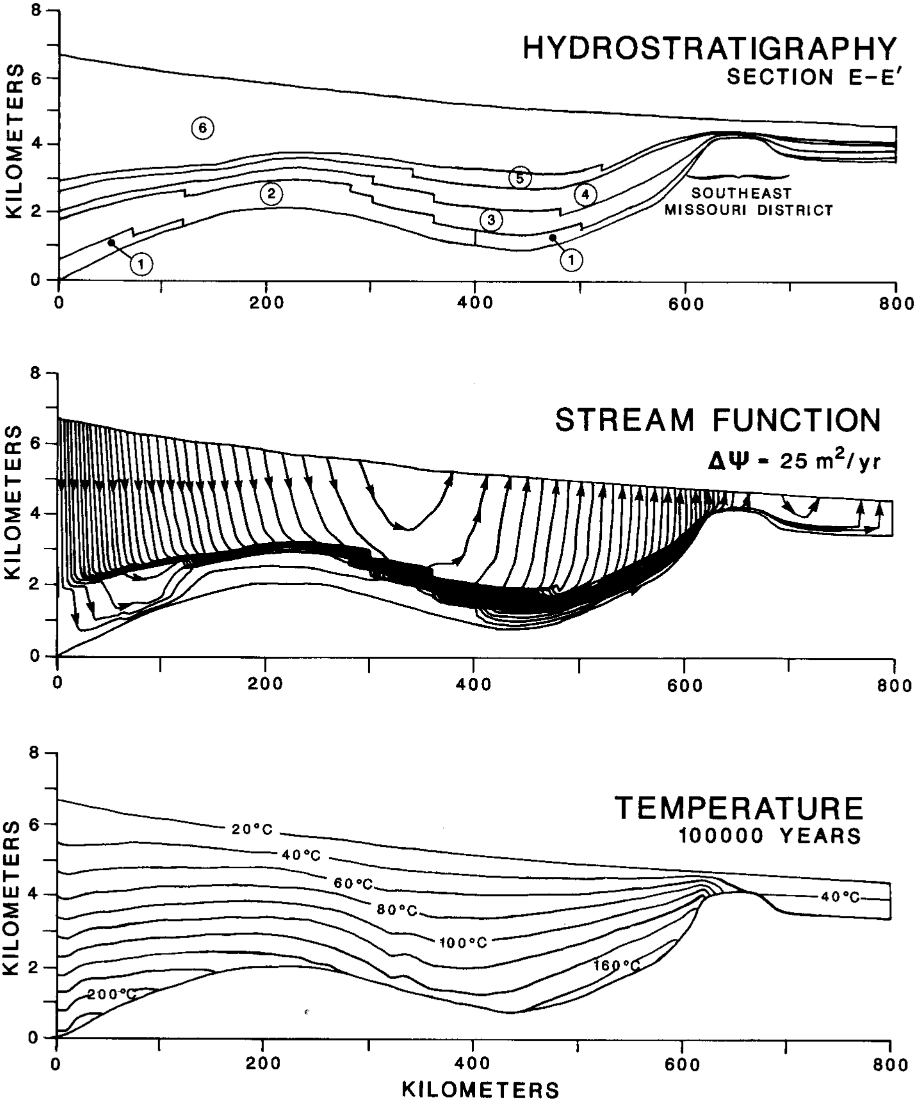

Fig. 27. Hydrogeologic model for section E–E′ across northern Tennessee.

maximum of 3.2×10^{-3}°C/m near the western margin of the Illinois Basin (near x = 600 km, fig. 27). Temperatures in the Knox Group aquifer hover around 100°C after 100,000 yrs of flow (fig. 27), except much warmer conditions persist in the western portion of the modeled section. Transient thermal histories of fluid passing through the Knox

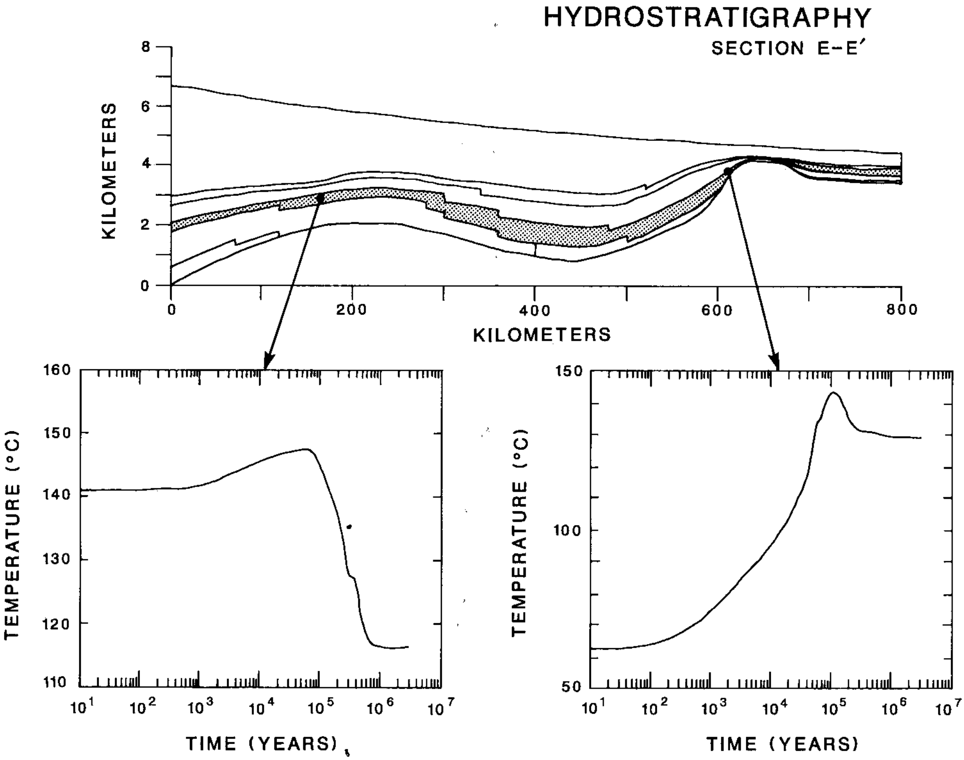

Fig. 28. Thermal history for reference points in section E–E′.

Group are displayed in figure 28. On the Nashville Dome, temperature rises to a maximum of 148°C after 100,000 yrs but later levels off to a cooler value of 115°C at the steady-state because of the deep recharge from shallower strata. On the Ozark Dome in southeast Missouri, temperature rises dramatically to a maximum at 143°C, and it levels off to a steady 129°C. Both sets of predicted temperatures for the late Permian are compatible with fluid-inclusion data from ore mineralization in Central Tennessee (100°–140°C) and southeast Missouri (90°-120°C).

As mountain building and uplift progressed farther south in the late Paleozoic, regional patterns of brine migration would have shifted as new topographic gradients were established on the craton. We believe these flow gradients shifted toward the northwest after the final phases of uplift associated with the Alleghanian orogeny. Section D–D′ represents one such possible flow path extending from the frontal thrust of the Appalachians in southeastern Tennessee, across the Cincinnati Arch and Illinois Basin, and ending on the Wisconsin Arch (fig. 29). This version of the hydrogeologic profile excludes the deepest portion of the Mississippi

Valley Graben (Wabash Graben) in southeastern Illinois-Indiana, so that a large part of the numerical grid would not have to be extended into the crystalline basement in order to characterize the rift. Version 1 along this section included the Wabash Graben but showed negligible fluid circulation in the deepest portion because of the absence of major aquifers there.

Figure 29 represents a second version of section D–D′ in which greater numerical detail is given to the more permeable part of the sedimentary sequence. The flow region is discretized here with a finite element mesh containing 25 rows and 71 columns. Salinity is assumed to reach a maximum of 26 percent equivalent weight NaCl at the deepest level. Unit 1 represents the basal Mt. Simon Aquifer (K_1 = 200 m/yr, ϕ_1 = 0.25); Unit 2 contains low-permeability Upper Cambrian-Ordovician shale and carbonate (K_2 = 5 m/yr, ϕ_2 = 0.10); Unit 3 is the Ozark-Knox Group Aquifer equivalent (K_3 = 50 m/yr, ϕ_3 = 0.20); Unit 4 contains Upper Ordovician through Devonian shale and limestone (K_4 = 20 m/yr, ϕ_4 = 0.15); Unit 5 represents Mississippian sandstone and limestone (K_5 = 30 m/yr, ϕ_5 = 0.10); and Unit 6 is the Pennsylvania-Permian sequence (K_6 = 10 m/yr, ϕ_6 = 0.15). Hydraulic anisotropy (K_x/K_z) is 100:1 in all six units. Once again the steady-state flowlines (fig. 29) demonstrate the effect of the Cambrian-Ordovician aquifers in focusing lateral flow across the basin. More deep groundwater moves through the Mt. Simon (Unit 1) because the hydraulic conductivity is at least four-times that of any of the shallower hydrologic units. Maximum groundwater flow rates of about 2 m/yr occur in the Mt. Simon Aquifer along the northern basin slope in Illinois (x = 700 km). Given an assigned basement heat flux of 70 mW/m^2, fluid temperatures peak at around 158°C in the same part of the aquifer 300,000 yrs after uplift (fig. 29). Fluid inclusion-filling temperatures for ores in the Upper Mississippi District (fig. 1) largely range between 70° and 150°C, although a small sample population indicates temperatures up to 190°C. Our regional flow calculations suggest the upper temperature data may be unusual for MVT ore districts. Sangster (1989) has also pointed out the anomalous nature of this data with respect to other estimators of thermal conditions in adjacent non-mineralized strata. Much more rapid flow rates or the presence of conduit-type normal faults would help transport more heat into the regional discharge areas, thereby elevating temperatures above our predictions. Bethke (1986) enlisted the effects of faults, high lateral flow rates, and three-dimensional focusing in addition to increasing basement heat flow to 179 mW/m^2 in order to explain the higher temperatures for ore mineralization in the Upper Mississippi Valley District. The results from figures 29 and 30 suggest that special hydraulic or thermal conditions are not really needed if one considers slightly elevated heat flow within the Illinois Basin caused by earlier rifting (80-100 mW/m^2) and enlist strong hydrodynamic flows generated by uplift of the Appalachian foreland in the late Permian, rather than enlist relief due to uplift of the Pascola Arch.

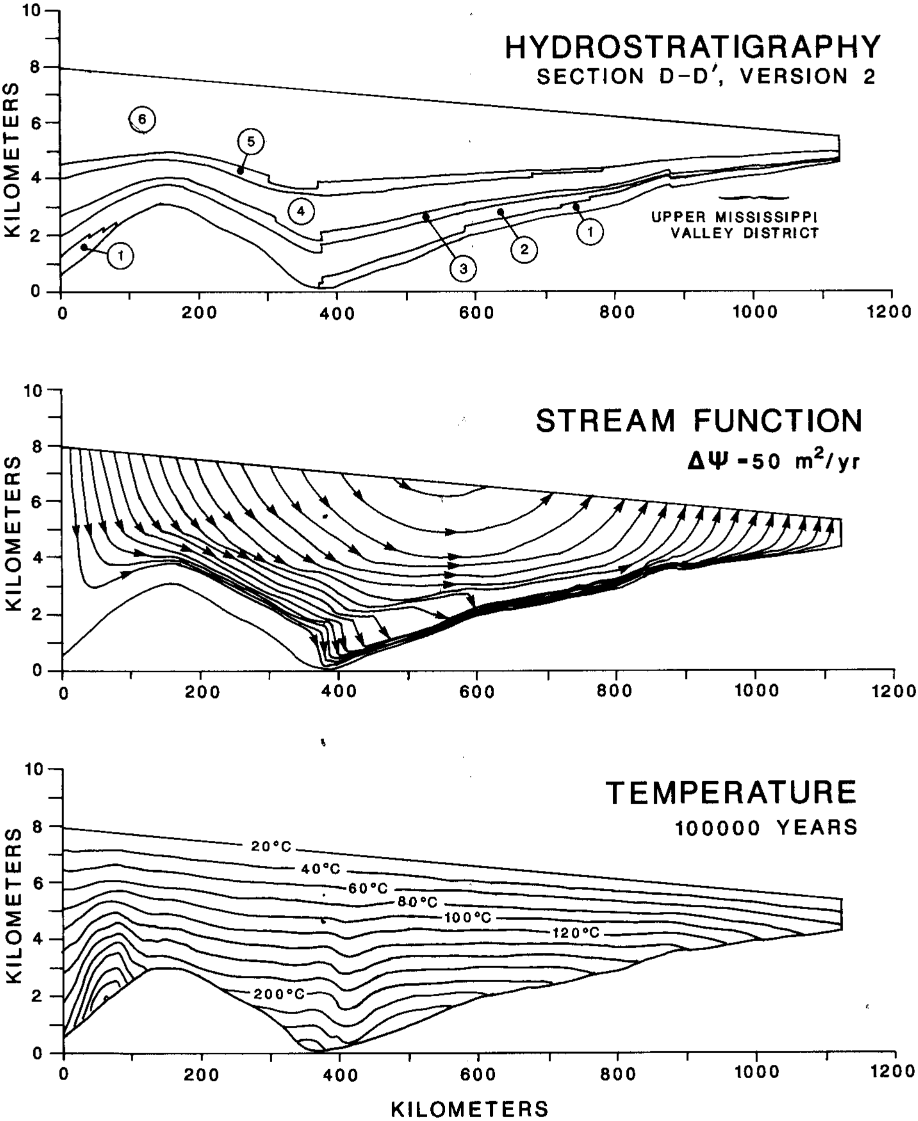

Fig. 29. Hydrogeologic model for section D–D′, version 2, across the Illinois Basin.

Western interior flow system.—Late Cretaceous to early Tertiary deformation of the Cordillera created the frontal thrusts of the Rocky Mountains, and eventual uplift of the Denver Basin foreland allowed for the development of gravity-driven flow from west to east across the Midcontinent. A subdued relict of this giant groundwater system can still be

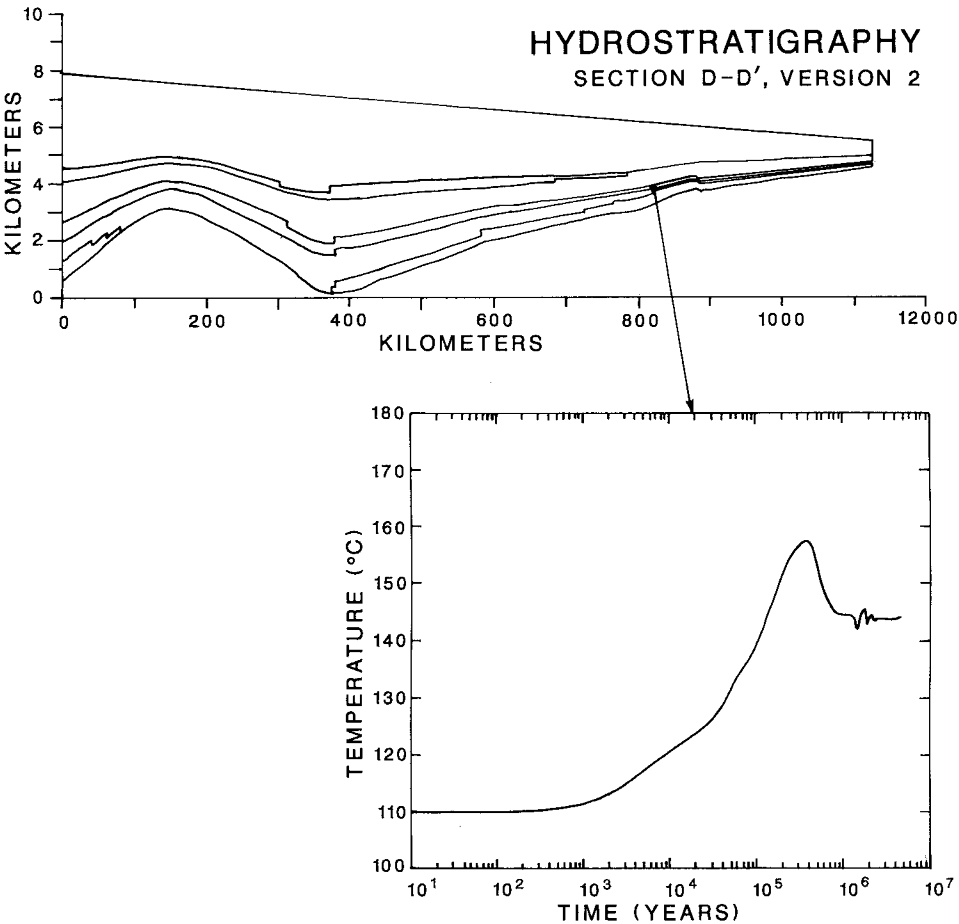

Fig. 30. Thermal history for reference points in section D–D′, version 2.

mapped in the Denver Basin and adjacent regions (Belitz and Bredehoeft, 1988). We have considered a Late Tertiary flow system as one possible scenario for stratabound ore mineralization. Section G–G′ (fig. 12) extends for about 1500 km across the Midcontinent, traversing the Denver and Salina-Forest City Basins and intervening uplifts and arches. The hydrostratigraphy along this profile has been subdivided into three simple units (fig. 31). The flow region is discretized with a finite element mesh containing 22 element rows and 85 columns. Unit 1 represents a basal Cambrian carbonate aquifer (St. Francois) assumed to maintain continuity across the Midcontinent (K_1 = 200 m/yr, ϕ_1 = 0.20). This assumption may fail in other parts of Kansas where basement highs interrupt this stratigraphy. The second major aquifer in the profile is

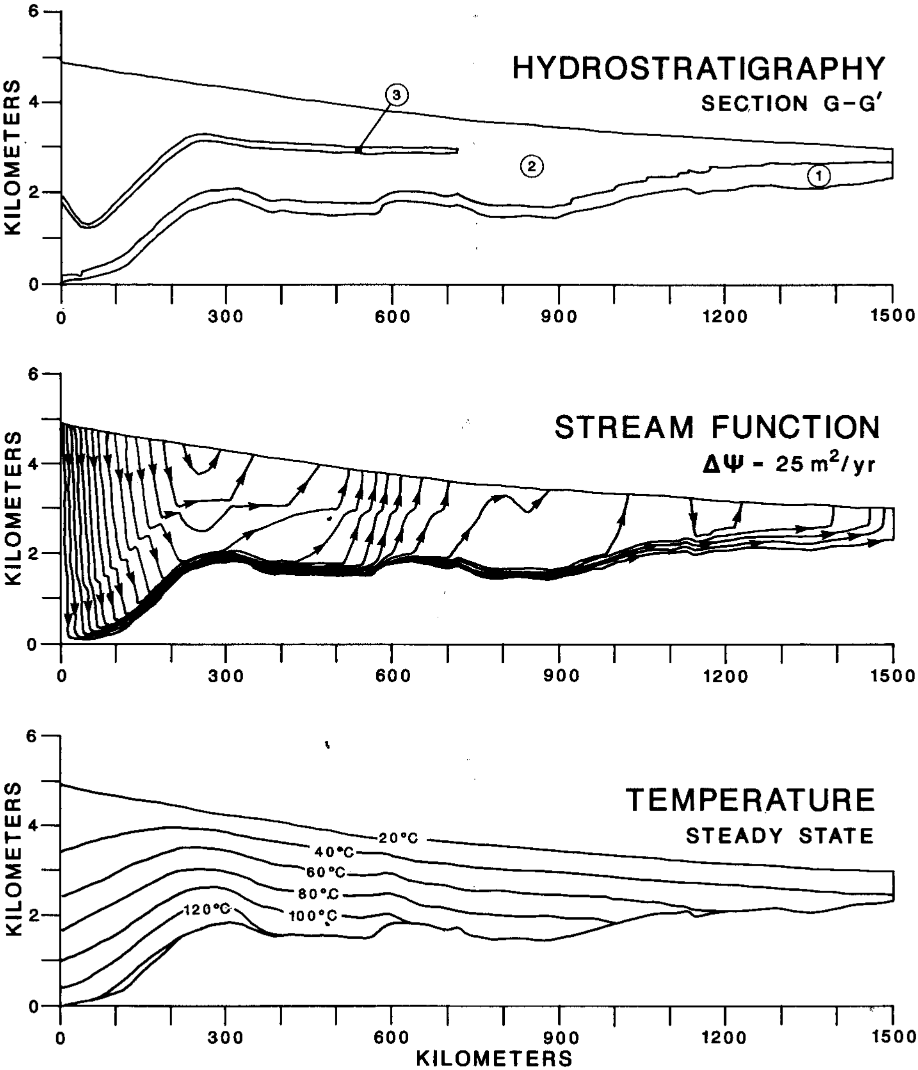

Fig. 31. Hydrogeologic model for section G−G′ across the Western Interior.

designated as Unit 3 ($K_3 = 50$ m/yr, $\phi_3 = 0.20$) which represents Cretaceous age sands of considerable lateral extent (for example, Dakota Aquifer). Less permeable strata from the Cambrian through Eocene have been lumped as Unit 2 undifferentiated, with $K_2 = 5$ m/yr, $\phi_2 = 0.15$. The hydraulic anisotropy K_x/K_z is 100:1 for each hydrostratigraphic unit. Salinity increases with depth to a maximum value of 20 percent equivalent weight NaCl at the deepest point in the section.

Continental-scale brine migration was possible across the Eocene-Pliocene section of North America, but the flow system was probably too weak to play any important role in ore formation around the Ozark Dome. In figure 31, a steady-state simulation shows that the Denver Basin acted as a huge recharge area, but most of the deep flow system is forced to discharge over the basement highs and arches of central Kansas. Some of the deepest brines flow through the basal aquifer all the way to the ancestral Mississippi. Maximum flow rates of 1.3 m/yr occur in the Cambrian aquifer over the central Kansas uplift, yet this flow decreases to less than 0.1 m/yr in the same unit in eastern Missouri. As the rates of groundwater flow are relatively modest and the distance of transport so large, a mostly conductive thermal regime appears in the eastern half of the hydrogeologic section. It is apparent, therefore, that this scenario for gravity-driven flow affords little opprotunity for forming large MVT ore mineralization over the Ozark Dome at elevated subsurface temperatures. The lack of major lead-zinc ore districts around the rims of the Salina-Forest City Basins corroborates the numerical prediction of low mass transfer rates through the Cambrian-Ordovician strata, at least for this Cenozoic flow system. Trace occurrences of sphalerite pervade the stratigraphic cover in eastern Kansas and western and central Missouri, but this mineralization apparently was deposited at temperatures between 66° and 118°C (Leach, 1979; Coveney, Goebel, and Ragan, 1987), temperatures more typical of MVT ore formation associated with late Paleozoic flow systems as described earlier. Ores in central Missouri also are most likely associated with Permian tectonism as suggested by paleomagnetic ages (Symons and Sangster, 1991).

IV. Effects of Compaction-Driven Flow

The gravity-driven flow systems described above appear to represent the primary hydrologic process for ore mineralization in the Midcontinent, yet groundwater or brine transport was also important during other periods in the tectonic evolution of the Appalachian and Ouachita orogens. Figure 8 conceptualizes the hydrologic picture of an evolving foreland basin and platform. Thermally-driven free convection was probably active in the thicker sandstone and carbonate aquifers of the rifted continental margin, but these flow systems would be unable to transport metal-bearing brines laterally across hundreds of kilometers (Garven, 1989, fig. 23). The early to middle Paleozoic frame depicts a period of subsidence and rapid sedimentation along the rifted margin of the continent when sediment compaction would have driven pore fluids toward the edge of the platform because of overpressuring in the foreland sag. By the Pennsylvanian and Permian, thrust sheets had advanced toward the craton such that tectonic compression and thrust-induced squeezing induced further groundwater migration by compaction. We shall analyze both scenarios for compaction-driven flow through the application of two different numerical calculations, with one application to compaction in the Arkoma Basin and the other to thrusting in the Appalachians.

Arkoma Basin subsidence.—As much as 10 km of turbidite sediments were deposited in the foreland of the Arkoma Basin during the Mississippian and Pennsylvanian (Thomas, 1985). The thickest portion of this clastic sequence is the Atoka Formation (over 5 km thick) which is thought to have been deposited over a 5 Ma time period (Houseknecht, 1986). Much of the Atokan strata records the obduction of the Ouachita accretionary wedge onto the southern margin of North America. The development of a frontal thrust belt (Ouachita Mountains) resulted in the deposition of over 2 km of shallow marine, deltaic, and coal-bearing sediments (Desmoinesian age) that conformably blanket the Atoka.

The compaction-induced flow history of the far-eastern part of the Arkoma Basin was studied with a different finite-element model. Person and Garven (1992) describe in detail the numerical formulation of this model, which is similar in design to the models of Bethke (1985) and Harrison and Summa (1991). The numerical code solves a transient, head-based flow equation similar to eq (4) for a basin profile continuously changing as a result of subsidence (fig. 32). A thermal convection-conduction equation similar to (5) is also solved at each time step in order to map temperature patterns and maturation of organic matter in the subsiding basin. Although the hydraulic head and pore pressure field are two-dimensional, deformation of the porous media is assumed to occur in only the vertical coordinate such that sedimentation keeps up with basement subsidence. Fluid flow is generated by reduction of pore space due to sediment compaction, and overpressures may develop in basin aquifers when the rate of deposition for low-permeability sediments is rapid enough to exceed the ability of the sediment to expel fluid produced by porosity loss.

Our basin profile considers a simplified hydrostratigraphic model with only three layers along section A–A′ (fig. 12). The two basal layers comprise the entire Cambrian through Mississippian passive margin or shelf sequence whose combined thickness reaches a maximum of about 2 km at the southern rifted margin. Unit 1 contains sandstones and carbonates of the Cambrian-Ordovician aquifer sequence ($K_1 = 200$ m/yr) which is the most permeable layer in the model. Unit 2 represents less permeable mudstones and carbonates ($K_2 = 20$ m/yr) of the upper part of the shelf sequence (Ordovician-Mississippian). The porosity and permeability of the two basal layers are assumed to remain unchanged with time. Unit 3 represents undifferentiated Pennsylvanian turbidite sediments of the Atoka Formation which are candidates for overpressuring as they are rapidly confined during burial ($K_3 = 2$ m/yr). Permeability is also time invariant for this unit. Porosity-depth correlations were used in the calculation to predict transient flow as a function of basin compaction (Bethke, 1986). We assumed a surface porosity of 0.55 and an exponent of 5.5×10^{-4} in the porosity-decay equation for Unit 3. Vertical permeability is assigned to be 100 times smaller than the respective horizontal

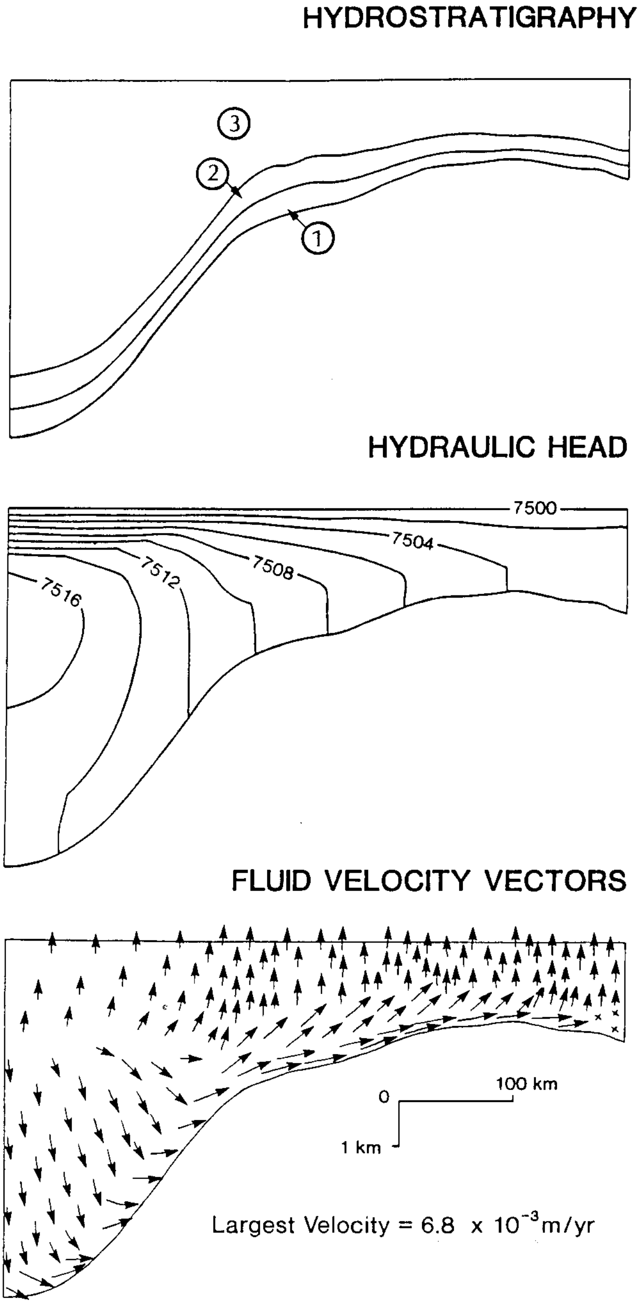

Fig. 32. Compaction simulation of Pennsylvanian sedimentation in the Arkoma Basin.

permeability in each unit. Sixty columns of finite elements were used to discretize the basin fill along the horizontal, while over two dozen element rows were used along the vertical domain. Hydrostatic pressures are assumed to exist everywhere in the shelf-sequence prior to the onset of numerical subsidence. Hydraulic divides are chosen for the southern margin (left boundary) and northern margin (right boundary). A crystalline basement provides another no-flow boundary at the base of the model, while the upper surface of the grid represents an arbitrary surface of constant hydraulic head. Fluid density and viscosity are dependent on temperature, but no corrections are made for salinity gradients.

Significant overpressures develop in the thickest part of the Arkoma Basin (fig. 32) as expected because of the rapid rate of subsidence with infilling of low-permeability muds. Over 5 km of Pennsylvanian sediments are laid down during the simulation. Deep groundwater moves away from the overpressured region in all directions, with some focusing provided by the basal Cambrian-Ordovician aquifers. Excess hydraulic gradients computed by the model were nowhere greater than 6.5 m/km. The maximum rate of groundwater flow is on the order of 5×10^{-3} m/yr in the basal aquifer. Vertical seepage rates of 10^{-6} m/yr or less characterize the bulk of the low permeability Pennsylvanian section. Heat transport is dominated by conduction in this compacting basin because the quantity of heat advected by groundwater flow is too small to perturb the conductive temperature field. The isotherms from this simulation are not displayed here as the temperature map is simply conductive in nature. Similar results were documented by Bethke (1985, 1986) and Bethke and Marshak (1990) for adjacent basins. The average rate of subsidence along the section line chosen in our calculation is 1×10^{-3} m/yr which likely represents a maximum (Sloss, 1988, fig. 5). Lowering the permeability would increase the amount of overpressuring predicted in the basin, but flow rates would be invariant to these changes because fluid velocities are only affected by the rate of subsidence or the assumed porosity-depth relation.

Appalachian-Ouachita thrusting.—Overpressures could also have been generated in the sedimentary piles of the Appalachian and Ouachita orogens as lateral and vertical forces loaded the continental margin during thrusting (fig. 33). Oliver (1986) envisioned deep expulsion of basinal brines out of the compressed orogens with migration toward the continental interior and mixing with gravity-driven groundwaters in the foreland platform. Ge and Garven (1992) modeled the effects of both lateral and vertical compaction in driving deep groundwater out of the Arkoma Basin onto the Ozark Dome. For a single phase of orogenic compression, their model predicted maximum flow rate perturbations of about 0.2 m/yr above ambient conditions in the Cambrian-Ordovician aquifers on the flank of the Ozarks. The overpressures and perturbed flow generated by lateral compression appear to dissipate after a few hundred years for a single event. Their calculations for metal require-

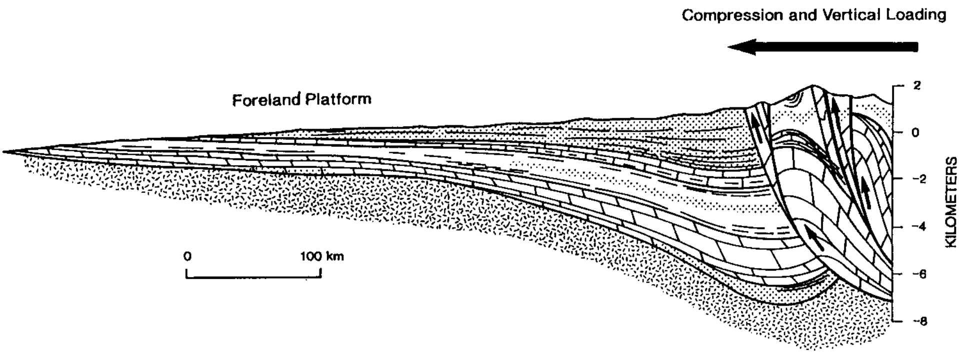

Fig. 33. Tectonic compression in a foreland basin (after Ge and Garven, 1987).

ments in Southeast Missouri indicated severe mass balance limitations based on the volume of brine expelled by simple compression in the Ouachita orogen.

More detailed hydrogeologic modeling of thrust-induced flow can be developed to account for actual mechanical displacements along thrust planes in addition to sediment compaction of adjacent thrust sheets. Figure 34 shows one example of the structural style resulting from the Alleghanian orogeny. As is characteristic of the Appalachian deformation style, thick Cambrian-Ordovician sandstone and carbonate shelf sequences ramp up from a décollement near the base of the Paleozoic

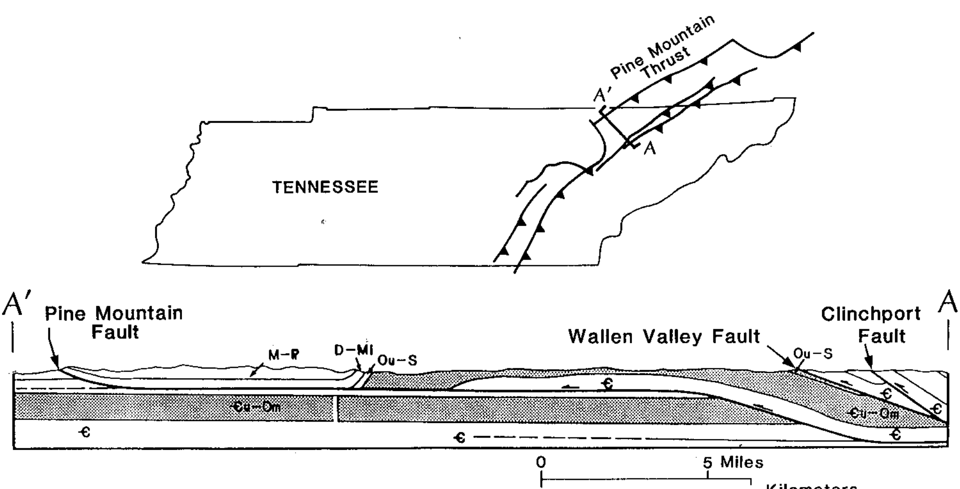

Fig. 34. Pine Mountain Thrust, Tennessee (after Kilsdonk and Wiltschko, 1988).

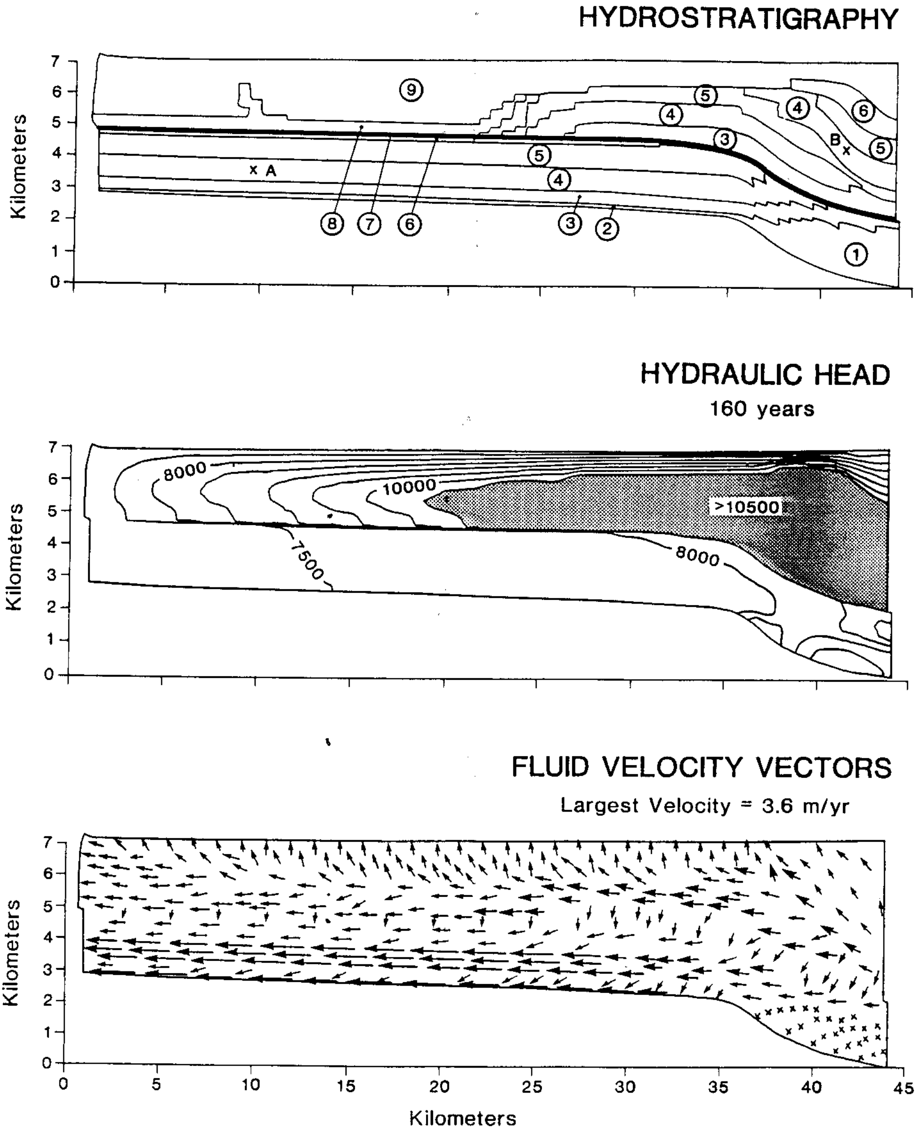

Fig. 35. Pine Mountain thrusting simulation.

which is at a relatively shallow depth (Thomas, 1985). The Pine Mountain Thrust exhibits about 17 km of offset at its southwestern end, and the youngest deformed rock is Pennsylvanian in age (Kilsdonk and Wiltschko, 1988). Nine hydrostratigraphic units are used in figure 35 to represent

TABLE 1

Model parameters for the Pine Mountain Thrust simulation

Hydrostratigraphic unit	Hydraulic conductivity K_x(m/yr)	Porosity (fraction) ϕ	Young's modulus $E(Pa)$	Rock density ρ(kg/m^3)
9. Pennsylvanian shale	0.10	0.25	2×10^{10}	2400
8. Devonian-Mississipian limestone	1	0.20	4×10^{10}	2400
7. Thrust fault gorge	0.01	0.10	4×10^{10}	2500
6. Silurian shale and limestone	2	0.10	4×10^{10}	2500
5. Upper Cambrian limestone	5	0.10	4×10^{10}	2500
4. Ordovician dolostone (Knox)	50	0.20	4×10^{10}	2500
3. Cambrian-Ordovician shale	1	0.10	2×10^{10}	2500
2. Cambrian sandstone	100	0.30	6×10^{10}	2500
1. Precambrian basement	0.01	0.02	7×10^{10}	2600

the structure and lithology of the modeled section (table 1). The flow region is discretized with a finite element mesh containing 20 rows and 67 columns. Cambrian sandstone (Unit 2) and Ordovician carbonates (Unit 4) are the most permeable strata in the section, while the Pine Mountain fault zone gouge (Unit 7) is assumed to have a relatively low permeability of 3×10^{-18} m^2. The vertical hydraulic conductivity is assumed to be ten times smaller than the horizontal value in each hydrostratigraphic unit. A finite element mesh containing 67 columns and 20 rows of simple quadrilaterals provides the spatial discretization needed for solving the fully-coupled groundwater flow and poro-elastic strain equations. Discussion of the theoretical aspects of modeling groundwater flow during deformation of a thrust belt is beyond the scope of this article, as the details are given by Ge (ms) and Ge and Garven (1992). Suffice it to say that sets of differential equations for fluid flow and strain must be solved simultaneously as external stresses are applied to boundaries of the model domain. The presence of a thrust surface décollement requires the introduction of special slip-element theory to accommodate large displacements along this surface. Poro-elasticity properties for the thrust zone and other rock units are also given in table 1. The thrust fault plane is assumed to support a cohesive strength of 1×10^8 Pa and an internal friction angle of 28°. Thrusting is initiated by instantaneously applying a tectonic force of 8×10^8 Pa on the right-side boundary of the numerical grid, but only for the strata above the décollement. The lateral force assigned for the section below the thrust plane is only 1×10^7 Pa. A Poisson ratio of 0.3 is assumed for each unit in the model, and a specific storage coefficient of 1.6×10^{-6} m^{-1} was computed from the assigned mechanical properties. A porosity-depth decay factor of 2.0×10^{-8} was also assigned to each layer. Large deformation occurs along the thrust fault in response to the suddenly imposed tectonic stress, but the magnitude of strain varies with position because of internal deformation and slip propagation. Under this condition, deformation rates and magnitudes differ for strata below, above, and near the thrust (fig. 36).

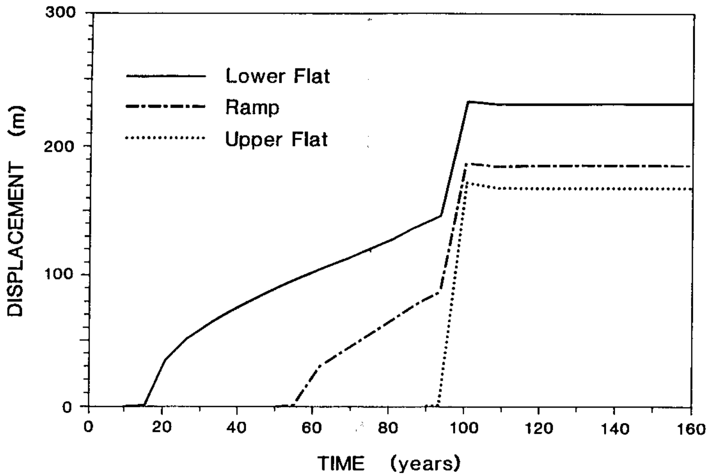

Fig. 36. Simulated displacements for a reference point on the Pine Mountain thrust.

The hydraulic system in figure 35 considers one time snapshot in the flow field, which was at steady state prior to thrusting. A gentle topographic gradient existed initially from east to west such that groundwater velocities are everywhere less than 0.03 m/yr. The upper surface of the model is the water table. No-flow boundaries are assumed for the right side and base, while the left side of the mesh toward the undeformed shelf platform is assigned a constant hydraulic head in order to allow for lateral flow away from the thrust belt. Very large overpressures develop with the onset of compression and renewed thrusting (fig. 35). As a result, hydraulic gradients are rapidly increased by orders of magnitude locally, and deep groundwater is driven away from zones of overpressuring above the thrust fault. Fluid flow is mostly lateral in the Cambrian-Ordovician aquifers and nearly vertical in adjacent aquitard strata. Very little fluid migration occurs along the thrust surface itself, because it is assumed to be of low permeability in this simulation scenario. Velocity arrows in figure 35 have been enlarged within the aquifer units in order to highlight the hydrostratigraphy. Flow rates on the order of 10 m/yr occur in the basal aquifers soon after a thrust event, although these transients appear to dissipate within 100 yrs (fig. 37). The degree of overpressuring predicted in this model may be excessive because of the relatively large stess rate applied, but the simulation provides a good estimate of the rates of episodic flows created by thrusting. Rates of loading, mechanical properties, heterogeneity, and permeability affect the general flow patterns, fluid flow rates, and strain (Ge and Garven, submitted). Multiple thrusting events over several million years would place additional hydrologic and thermal overprints on the sedimentary section.

Clearly, thrust-induced groundwater migration has important implications for aqueous mass transport and mineralization near the fold and

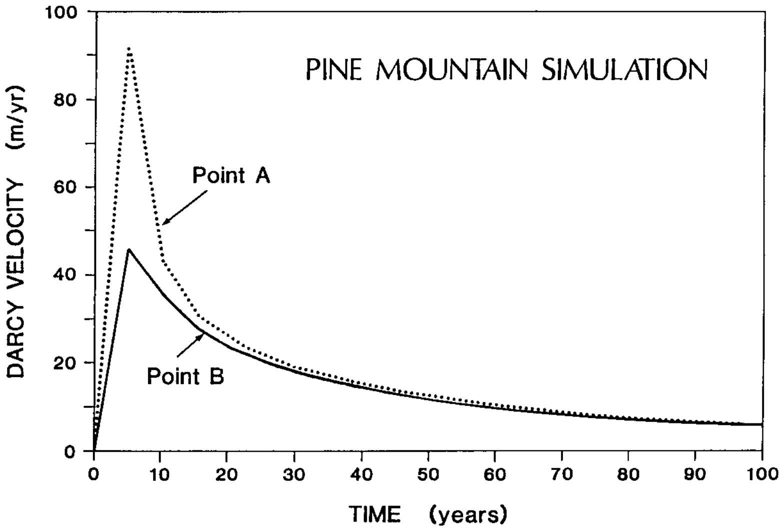

Fig. 37. Flow rates for two reference points in the Pine Mountain simulation.

thrust belt. Dorobek (1989) argued for thrust-related fluid migration as an explanation for high-temperature cements in Silurian-Devonian strata within the Valley and Ridge province of the central Appalachians. Bradbury and Woodwell (1987) proposed a variety of flow systems to explain isotopic data for the thrust belts of the Canadian Rockies and the southern Pyrenees. The calculations shown here suggest that episodic fluid migration over several tens of kilometers would be associated with thrusting and ramping, a phenomenon that has been observed for modern thrust environments within accretionary wedges (Reck, 1987; Vrolijk, Myers, and Moore, 1988). The flow volumes generated by thrusting, however, are very small and transient relative to the systems generated by topography. Under these circumstances, it seems unlikely thrusting had much influence in forming the large MVT ore districts located hundreds of kilometers from the orogenic belts (fig. 1).

Hydrogeologic modeling of heat transfer during deformation has not been considered in our calculations for the Pine Mountain Thrust. The depth of the Cambrian-Ordovician (Knox) aquifer burial (4 + km) would have been much greater near the fold and thrust belt (fig. 35) than on the foreland platform, and so mineralization temperatures would easily exceed 200°C. Basement heat flow may have been elevated to begin with because of the kinematics of overthrusting (Shi and Wang, 1987). One might expect, however, that hydrothermal anomalies also could be generated by rapid expulsion of deep brines along thin aquifers or fault zones. Heat transport calculations by Cathles (1987) and Deming, Nunn, and Evans (1990) indicate thermal perturbations as high as 50°C might be possible if flow is channeled rapidly along thin aquifers or through faults, although neither of these calculations considered the short time interval simulated for the Pine Mountain Thrust. Once the thrust belt was elevated to a subaerial mountain belt, significant fluid circulation and heat transfer could have been possible within the thrust sheet due to gravity-driven flow (Forster and Evans, 1991). Regional transport or lateral fluid migration into the foreland basin would have been restricted by stacking of thrusts (fig. 8), particularly if the décollement bottomed out near the base of the Paleozoic section.

V. Discussion of the Hydrogeologic Models

The hydrogeologic modeling conducted here sought to explore more specific and direct hydrologic evaluation of the nature of regional groundwater flow in a framework that united all the major Mississippi Valley-type ore districts of the North American Midcontinent. Scenarios of deep groundwater migration and heat transport have been postulated within a numerical modeling approach that relies on mathematical and physical principles, so we can be reasonably sure that the results are internally consistent and geologically realistic given proposed boundary conditions and representative properties for basin strata and fluids. It is important to remember, however, that the hydrogeologic models are only as representative as are the model parameters and boundary conditions chosen for the simulations. We have no direct way of knowing the actual topographic relief across the basin, the precise range in regional permeability or basement heat flow, nor the chemical variability of the brines as the regional groundwater flow systems evolved over the past 300 Ma. Some uncertainty needs to be acknowledged in any admission of the limitations of numerical calculations. Knowledge of the tectonic history helps constrain the driving forces and therefore likely hydraulic gradients, which also can be inferred from sedimentation patterns (Heller and Paola, 1989; Koltermann and Gorelick, 1992). Abundant fluid-inclusion data exist for the ore deposits, and so we have good constraints for checking the thermal calculations, at least within the uncertainty of estimates for burial depths and crustal heat flow in the Late Paleozoic. Rates of mass transport are controlled by the hydraulic conductivity and hydraulic gradient in Darcy's law, neither of which can be constrained with great precision, but the effects of hydraulic and thermal properties on fluid and heat flow have been documented in earlier studies (Garven and Freeze, 1984b; Bethke, 1986; Garven, 1986, 1989). Many of the simulations results presented above could be scaled up or down to consider simple changes in model parameters or boundary conditions. Large flow rates could be generated, for example, by increasing either the topographic gradient or regional permeability. Higher temperatures would develop along the basin margin because of this forced convection. Alternatively, higher temperatures (+10° to 25°C) could be generated if larger crustal heat flow is assigned or the assumed depth of burial adjusted by a few hundred meters. Therefore, despite the limitations inherent in any mathematical model of Earth processes, geologically realistic flow patterns and rates of heat and mass transfer are provided that allow one to make new observations and test or compare competing hypotheses (Bethke and others, 1988).

With reference to the present study, several important and unambiguous observations can be made for the genesis of MVT ore districts based on the hydrostratigraphic setting, basin-scale hydrogeologic simulations, and known tectonic history of the Midcontinent region:

1. Tectonic uplift of the Appalachian and Ouachita foldbelts and adjacent platforms during or soon after the Alleghanian orogeny sustained the topographic relief needed to drive basinal brines out of the foredeeps, across intracratonic basins, along basement grabens, and over basement arches and domes to form the largest MVT ore deposits. Earlier phases of fluid migration may have been associated with the Taconian and Acadian orogenies, but it is certain that neither the same relief nor stratigraphic burial existed in these periods for comparable hydrologic systems driven by topography. The last major phase of gravity-driven fluid migration in the Midcontinent would have been associated with the Laramide orogeny, although the flow systems generated by uplift of the Rocky Mountains were too weak in Missouri to play a significant hydrologic role in ore formation.

2. Our hydrogeologic models presumed that Cambrian-Ordovician aquifers served as the primary conduits for transporting and focusing deep groundwater and brines across the Midcontinent, while younger strata served as source beds for ore-forming components and confining units for regional flow. This setting was replicated in all the basin simulations, and it is consistent with the distribution of ores, associated mineralization, and present-day hydrogeology. In some cases, regional aquifers within Mississippian strata also allowed for extensive fluid circulation, which created favorable conditions for ore mineralization. The widespread distribution of aquifers was dictated by the sedimentation history common to the Arkoma and Appalachian foreland sequences. It would not be unreasonable to speculate that regional permeability was probably enhanced through fracturing in this foreland sequence as compressive stresses developed during the Alleghanian orogeny. Extensive fault systems were not a prerequisite for fluid migration, however, as stratigraphy provided the best framework for continuity in regional flow.

3. Permian groundwater flow rates of 1.0 to 5.0 m/yr were characteristic in sandstone and carbonate aquifers throughout the Arkoma, Appalachian, and Illinois Basins and adjacent arches or domes during the apex of the Alleghanian orogeny. Cross-formational flow rates were orders of magnitude smaller throughout the rest of the foreland aquitards, particularly in the deeper parts of the Mississippi Valley Graben. Some of the simulations suggested that only small amounts of basinal brines would have circulated in the crystalline basement underlying the Cambrian-Ordovician aquifers because of the large contrast in permeabil-

ity. Unless the Precambrian unconformity is deeply weathered and fractured, one could not rely on the basement as a direct source of metals. Peak groundwater discharge through the Midcontinent basins appears to have ranged between about 500 and 1000 m^3/yr per meter width, with a large percentage of this discharge focused through the Cambrian-Ordovician and Mississippian aquifers.

4. Late Pennsylvanian-Permian uplift initiated transient flows, but these likely established a maximum state in about 10^5 to 10^6 yrs. Under gravity-driven flow, groundwater descended to great depths in expansive recharge areas in front of the fold and thrust belts acquiring salinity, heat, and metals. Enormous volumes of deep brines were driven updip, but no doubt the flow system also supplemented the salt balance by dissolution of evaporites within Cambrian-Permian sediments. Ores were precipitated from brines within the basal aquifers at depths of less than 2 km, although burial depths of 3 km or more probably existed over some of the basement arches and within the basin forelands. Regional flow was driven mostly to the north across the Arkoma Basin and to the northwest across the Appalachian and Illinois Basins. Uplift of the Rocky Mountains during the Laramide orogeny would have driven brines to the east across the Kansas uplift, albeit flow rates were relatively small (cm/yr) in the far reaches of Missouri.

5. Alleghanian uplift of the Appalachians evolved such that paleo-relief probably reached a maximum first in the northeast and then migrated south, culminating with subaerial exposure of the Ouachita fold belt and Arkoma platform. Based on this tectonic interpretation, regional migration pathways are likely to have varied considerably throughout the Late Paleozoic. For example, ores along the Old Lead Belt in Missouri may reflect a discharge pathway for brines driven to the west out of the Appalachian foredeep and Illinois sag as illustrated in two of the simulation models. A similar scenario probably applied for the ore districts in Tennessee. Later uplift in the southern Appalachians drove brines northwesterly out of the Black Warrior Basin and into southeast Missouri, perhaps adding another chemical signature to ore formation in the Old Lead Belt. Mineralization in the Upper Mississippi Valley District is most likely to have originated through the migration of brines out of the Appalachian foredeep and across part of the Illinois sag as a direct result of uplift of the Appalachian Mountains rather than later by uplift of the Pascola Arch in southern Illinois (Bethke, 1986). Relief generated by the fold and thrust belts of the Appalachians, Ouachitas, and Rocky Mountains was much more considerable than relief associated with any of the intracratonic arches or domes. Uplift of the Ouachita Mountains and foreland platform resulted in the massive migration of brines to the north and in part to the northeast. Ores in the Tri-State District, Northern Arkansas, Viburnum Trend, and Central Missouri record this hydrologic system of which there is little dispute. Deep brines could have moved easily also along the axis of the Reelfoot Rift (Mississippi Valley Graben) under a gravity-drive to form the fluorite deposits in southern Illinois.

6. All the fluid flow systems probably dissipated during the latest Permian and early Mesozoic, when erosion would have finally reduced the deeper flows to rates below centimeters per year, as subregional and local groundwater systems evolved thereby erasing the prevailing north-flowing basin-wide circulation patterns (see fig. 8). It is difficult to imagine any of the regional flow patterns nearly reversing as has been inferred by some geochemical data for southeast Missouri, unless larger differential changes in relief developed. However, rapid erosional unloading could induce transient flow patterns not accounted for in the present study, and so flow reversal cannot be ruled out. Too much of the post-Paleozoic cover has been stripped away in the northeastern Midcontinent to offer any reliable prediction about Mesozoic to Cenozoic flow patterns in the eastern interior, except for the general trend for local rather than basin-wide flow. Long-distance, west-to-east migration would have been established in the Tertiary as a result of Laramide uplift, but hydraulic gradients were too small to increase basin heat flow or form ore districts in Missouri.

7. The development of gravity-driven flow systems in the Late Paleozoic perturbed the thermal state of all basins in the Midcontinent. The Cambrian-Ordovician aquifers served to focus advection of both groundwater and thermal energy. Fine grained and less porous younger strata served as a thermal blanket that helped sustain elevated temperatures as fluids were driven across the basins. Heat flows were depressed over huge recharge areas of the basins but elevated near the edges of the Arkoma, Appalachian, and Illinois Basins where warm brines discharged in regions of lower topographic relief. The numerical simulations suggest that the basins should have seen a transient thermal history with peak temperatures lagging up to 10^5 to 10^6 yrs behind the onset of the gravity-driven flow systems. Thermal transients would have provided very high temperatures for mineralization periods lasting up to 5×10^5 yrs. These transients help explain the wide range in fluid inclusion temperatures observed for the paragenetic history of mineralization (for example, see fig. 4). Periods of cooling reflected in the fluid inclusions also suggest a temporal reduction in salinity which may be indicative of salt-source exhaustion or the invasion/mixing of fresh groundwater as the basin-wide flow systems were gradually weakened by landscape erosion.

8. Thermal conditions representative of ore mineralization are replicated by all the hydrologic simulations, except for that of the Western Interior flow system. For southeast Missouri, northward regional flow generated temperatures as high as 130°C during peak transients for burial depths of about 1 km on the Ozark Dome. Flows across the Illinois and Appalachian Basins generated temperatures up to 150°C for similar burial depths. Maximum temperatures near 200°C would have been possible if basement heat flow exceeded 70 mW/m^2 or if estimates of burial depths at ore sites were increased to 2 km. Similar observations apply to other major ore districts: our modeling results appear to satisfy

fluid-inclusion temperature data throughout the region, within any reasonable level of geologic uncertainty regarding crustal heat flow and burial estimates. Despite the high geothermal gradients created by forced convection in the basins, temperature gradients across the platform margins are deceptively gradual (10^{-4}°C/m or less), except where groundwater flow encounters steep normal faults near the Reelfoot Rift. The large-scale thermal modeling conducted here provides only a crude picture of local detail, but it seems difficult to rely on brine cooling for ore deposition given the predicted gradual changes in subsurface temperatures.

9. Salinity of the ore-forming fluids would be mostly derived from brine present in the foreland sag and rifted continental margin prior to uplift, but this source would be exhausted if strong gravity-driven flow persisted for time scales longer than 10^6 yrs (Bethke, 1986; Deming and Nunn, 1991). Dissolution of Paleozoic evaporites within the Appalachian, Arkoma, Illinois Basins, and Mississippi Valley Graben would have provided another source for sustaining salinity, a scenario that exists for young foreland basins in other parts of the world. About 150 m of bedded salt would be required to sustain a salinity of 20 percent equivalent weight NaCl for 10^6 yrs of groundwater flow, if one considers a source bed on the order of 300 km wide in the recharge end of the basin. Mass balance constraints for ore-forming components such as metal and sulfur have not yet been considered for the specific deposits in the Midcontinent, although calculations made for comparable MVT deposits in other basins (Garven, 1985) suggest that mineralization periods of less than 10^6 yrs would be sufficient. This time frame is also compatible with the duration of peak temperatures sustained by transient flow. One could speculate that flow of cooler yet more saline water would evolve to warmer yet less saline groundwater as the hydrodynamic system adjusted to subaerial relief after maximum uplift. Erosion of the foreland platform would eventually lead to much cooler temperatures and mixing of brines with fresh groundwater, perhaps in the manner observed by Banner and others (1989) for present-day discharge in the Western Interior.

10. Sediment compaction in the eastern Arkoma Basin generated significant overpressures and mm/yr flow rates during the early Pennsylvanian, a simulation scenario replicated elsewhere for the western section of the Arkoma Basin (Bethke and Marshak, 1990). Flow rates, however, are too small to satisfy the thermal conditions or mass balance constraints for MVT ore formation on the Ozark Dome. Compaction-driven flow out of the Appalachian foredeep and Illinois sag is unlikely to have fared any better. However, thrust-induced compaction along the leading-edge of the Ouachita and Appalachian orogenic belts could have resulted in transient pulses of brines which could have periodically invaded nearby thrust sheets. Flow rates of m/yr were simulated with thrust-sheet loading, but the flow is too short-lived to compete with the enormous volumes of brine driven by topographic relief. Local elevation of temperature may have been possible where flow was channeled in fractures, but the volume

of flow generated by thrusting or the so-called "squeegee" effect (Oliver, 1986) would have had a negligible effect on distal platform rocks where the largest MVT ore districts formed.

CONCLUDING REMARKS

The carbonate-hosted lead–zinc–fluorite–barite ore deposits of the Midcontinent provide a superb data set for quantifying the nature of ancient groundwater flow systems at the continental scale. The ore deposits have been extensively mapped, the tectonic history of the surrounding sedimentary basins and orogenic belts are well known, and now a clearer picture has emerged through this study regarding the paleohydrogeology of ore formation at a regional scale.

The theory that topography- or gravity-driven groundwater flow is a sufficient mechanism for the genesis of major carbonate-hosted lead-zinc has been firmly established through earlier publications dealing with individual basins and ore districts. Some have argued that topography-driven flow may not be the sole mechanism involved in MVT ore formation, a point of view that may be correct for smaller ore deposits now exposed in thrust belts, but it is very difficult to rely on the major involvement of any other hydrologic mechanism when evaluating the huge ore districts situated on the distal foreland platforms. There is little need, therefore, to impose more exotic hydrologic theories of regional brine migration in formulating the evolution of stratabound ore genesis in the Midcontinent.

Numerical simulations were used to demonstrate how brine migration occurred throughout the Early Paleozoic as foreland basins and intracratonic sags subsided and later were subjected to thrusting, but this compaction-derived flow was only a harbinger of the massive flow systems to follow. Tectonic uplift of the Appalachian and Ouachita foldbelts and adjacent platforms in the Late Paleozoic provided the necessary topographic relief for driving continental-scale brine migration that resulted in MVT ore formation. Basinal brines moved up-dip and out of the Appalachian Basin to the west and northwest through regional aquifers at rates of m/yr to form ore deposits in central Tennessee, central Kentucky, southeast Missouri, and southern Wisconsin. Brines were later driven northward out of the Arkoma Basin to form ore deposits on the Ozark Dome and along the Reelfoot Rift to form deposits in southern Illinois and Kentucky. The largest flow rates were sustained for at most a few million years, and fluid velocity gradually waned as erosion caught up with uplift such that the continental-scale flow systems were too weakened and dissected by local flow to generate large ore districts. The thermal and hydrologic conditions indicated are consistent with observed fluid-inclusion data for mineralization temperatures.

A future communication will explore other factors not covered in this study, including the effects of three-dimensional flow and the implications of reactive brine flow for geochemical mass transport at the district and formation scales.

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