A proposed stratigraphic package for filling a mid-Proterozoic rift basin under the Bellefontaine Outlier area, Ohio, and the consequences of the rift on the formation of the Outlier

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Abstract

The discovery of a mid-Proterozoic rift basin in the crystalline basement rocks under the Bellefontaine Outlier area, Ohio has had a number of consequences on our understanding of Precambrian tectonics and stratigraphy of western Ohio and the north-central North American midcontinent. In this study, a new stratigraphic package has been proposed to fill the ancient rift basin and a geological history of the area from the mid-Proterozoic to the Devonian, has been synthesized to study the consequences of this deep basement feature through time.

Three new proposed rift basin-filling volcanic and sedimentary units encode the development, maturation, and termination of the rift. A fourth proposed sedimentary unit, lying above the basin-filling sequence, documents the initial changes of the region to a massive foreland basin in front of newly developed Grenvillian thrust sheets during the late-Proterozoic. The lower contact of the Middle Run Formation has also been extended to a much greater depth overlying the fourth proposed unit and represents well-developed foreland basin sediments.

Another goal of this study considers tectonic events from the mid-Proterozoic initiation of rifting through the Devonian Acadian Orogeny, to explain the development and incomplete Paleozoic stratigraphy of the Bellefontaine Outlier. Compressive forces associated with the Grenville Orogeny may have propagated the rift-defining fault complexes up through the overlying late-Proterozoic strata and imposed significant structural weaknesses that could be exploited by the compressive forces of the Devonian Acadian Orogeny. During the Acadian, the Outlier block may have been exhumed by the reactivated faults and the Devonian Delaware Limestone and Olentangy Shale units, not present within the Outlier block, may have been syntectonically deposited in flanking basins during the exhumation.

Acknowledgements

Let me extend a sincere thanks to everyone who helped this project come to fruition. I cannot thank my advisor, Dr. Hallan C. Noltimier, enough for his crucial role in this project and his guidance, instruction, and advise for the whole of my academic career. And a thank you to Michael Fidler, whose senior thesis work modeling Precambrian basement structure truly inspired this study. To my mother, father, family, and friends, this would not have been possible without your love and support, for that I thank you.

Table of contents

Index of figures

Introduction

The Bellefontaine Outlier has long puzzled geologists. Both stratigraphic and topographical anomalies characterize the Outlier, while sparse deep-drilling in the region has provided few answers about its structural history. The Outlier block consists of Devonian shales and carbonates covered by a thin Pleistocene till layer. The immediate surrounding areas consist of Silurian shales, limestones, and dolomites to the west, and Devonian and Silurian shales, limestones, and dolomites to the east. The entire area was heavily scoured during recent glaciations leaving glacial till on the Outlier.

Geophysical evidence has suggested a long and complicated history of the area and hypotheses need to consider and incorporate this history from the mid-Proterozoic through the Paleozoic. The mid-Proterozoic extensional rift basin, the Grenville Orogenic compression inducing rift basin exhumation, anticlinal folding affecting units up through the Middle Run, and further compression/shear of the region during the Acadian Orogeny, are postulated here to have been responsible for the topographic high and partially incomplete Paleozoic stratigraphy now observed within and at the surface of the Outlier.

Numerous studies have investigated the geometry, structure, and topography of the crystalline basement rock utilizing gravity, geomagnetic, seismic, and some drill core data. These efforts have culminated in excellent controls on the depth to the crystalline basement upper surface and three dimensional models of the Proterozoic rift basin within the basement complex. This study considers and proposes a new stratigraphic sequence underlying the Middle Run Formation and overlying the crystalline basement rock beneath the Outlier. The deepest drill hole in the area penetrated only about 1.6 km below the surface and only 0.59 km into the Middle Run Formation and calculations have estimated a depth to crystalline basement at around 7.1 km. This study has proposed a stratigraphic sequence to fill this 5.5 km unknown rock package, including the extension of the lower contact of the Middle Run Formation to a depth of 5.2 km below the surface and the addition of four new sedimentary and volcanic units to fill the rift basin. As a consequence of proposing new stratigraphic units, this study has also synthesized a geological time-line to characterize and identify the depositional environment for each unit in the proposed stratigraphic sequence and to account for in situ deformation due to tectonic events during the Precambrian and Paleozoic.

Background Work

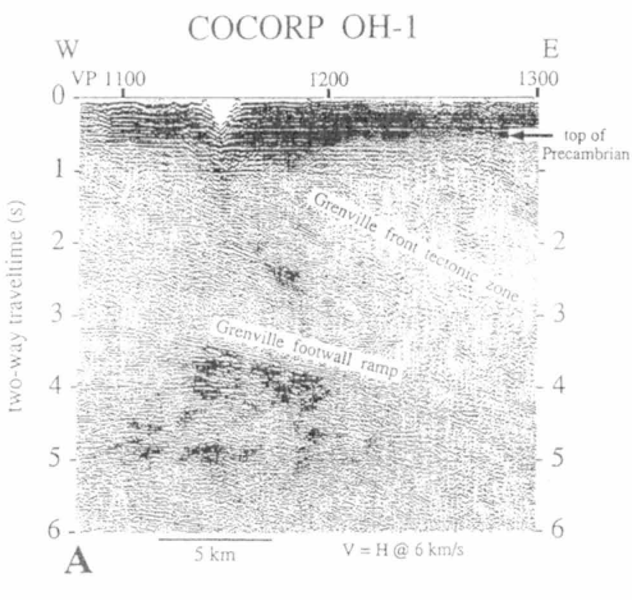
The discovery of the Precambrian Middle Run Formation (MRF) beneath the Cambrian Mount Simon Sandstone in Warren County, Ohio, has added a crucial piece of evidence to the understanding of the origins of the Bellefontaine Outlier. The penetration of this previously unknown stratigraphic unit in 1988, provided conclusive evidence for a large sedimentary Precambrian Grenville foreland basin in western Ohio that had been suggested by geophysical evidence years before. An informational circular published by the Ohio Division of Geological Survey (ODGS) in 1992 has named this deep subsurface feature the East Continent Rift Basin (ECRB). Though the MRF is sparsely drilled, the known extent of the unit extends from Putnam County, Ohio in the north, to Jessamine County, Kentucky, in the south, and to Fayette County, Indiana, in the west. Before the discovery of the MRF, all Paleozoic strata in Ohio were thought to be underlain by crystalline basement rocks of the Granite-Rhyolite Province in the west and the Grenville Province in the east (Drahovzal et al., 1992).

The Precambrian Granite-Rhyolite Province, occupying the western third of Ohio (see Fig. I), consists of unmetamorphosed rhyolitic and aphanitic volcanic and sedimentary rocks that extend from Ohio and the central interior to the southwest in the United States, with a zircon derived U-Pb age of 1480 +- 30 Ma (Lidiak et al., 1991; Hauser, 1993). The eastern two-thirds of Ohio's basement rocks consist of the Precambrian Grenville Province high-grade metamorphosed gneisses of the Grenville Orogenic belt dated around 1100 Ma (Milkereit et al, 1992). The Grenville Front, a north-south trending feature which does not crop out at the surface in Ohio, separates the

Fig. I

State of Ohio map showing tectonic province extents for the Granite-Rhyolite Province, Grenville Province, and Grenville Front (bounded by dashed lines) and location of the Bellefontaine Outlier and geophysical survey area. From Weaver (1994)

Fig. II



Segment of COCORP OH-1 line showing structure of Grenville Front tectonic zone. Taken from Hauser (1993) younger, high-magnetically susceptible, positive anomaly rocks of the Grenville Province from the older and generally less magnetic rocks of the Granite Rhyolite Province (Dean et al., 2002).

The lack of well developed foreland basins and foreland fold and thrust deformation associated with continental collisions in other areas where the Grenville Front is exposed at the surface has long puzzled geologist. The discovery of the MRF in Ohio may indicate a more traditional orogenic regional setting suggested by seismic data from the COCORP's OH-1 line (Hauser, 1993). The OH-1 line shows a complex ramp-flat thrust geometry immediately west of the Grenville Front, while the Grenville Front itself images as a wide zone of planar eastward dipping reflectors (Fig. II) (Hauser, 1993).

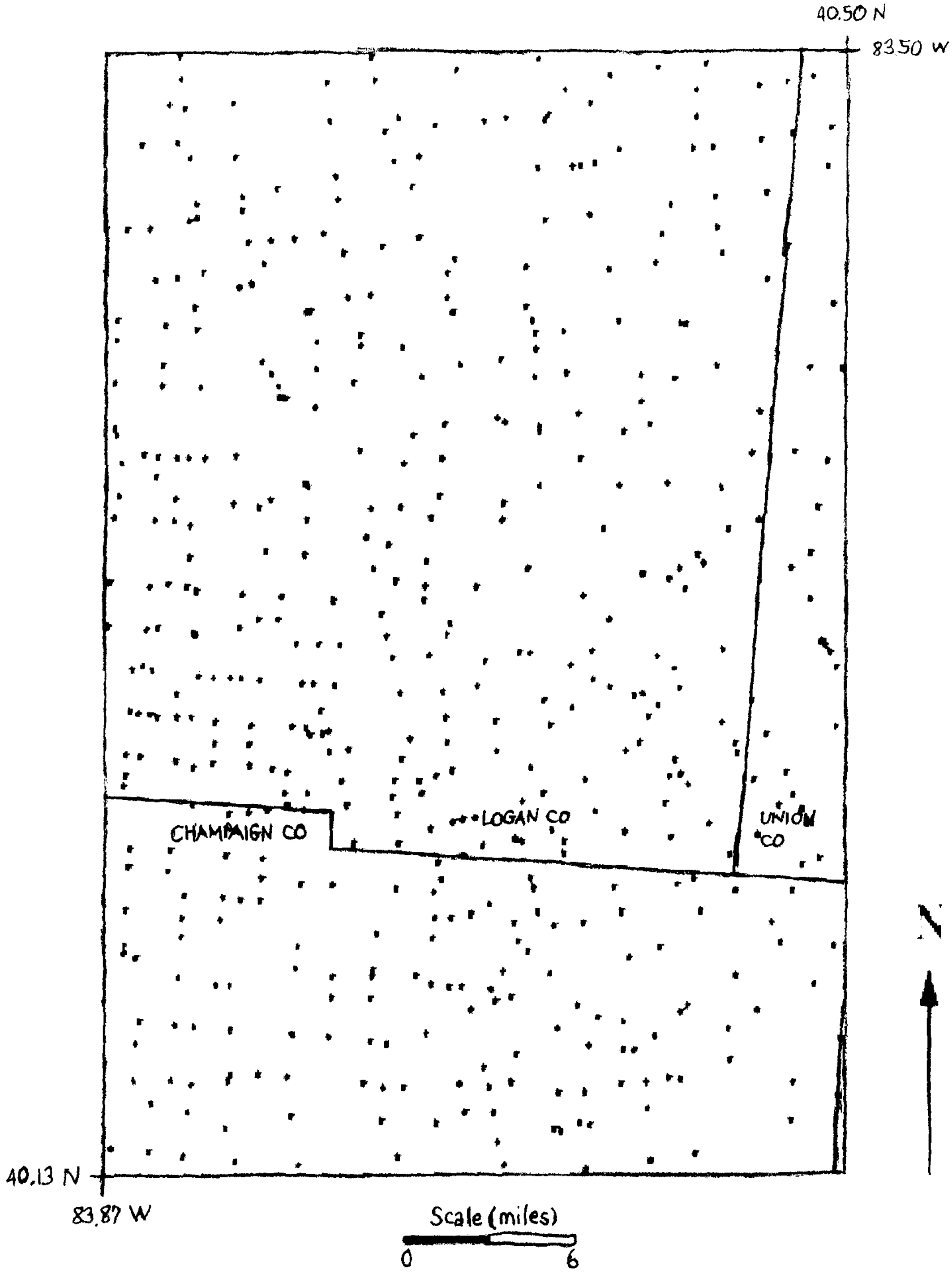
The red, lithic arenites that comprise the MRF are thickly bedded, fine- to medium grained sandstones that may contain up to ten percent siltstones and shales (Drahovzal et al., 1992). Though only 0.59 kilometers of the MRF has been penetrated, seismic profiles hint at a possible thickness of up to 8 kilometers (Drahovzal et al., 1992). A few wells penetrating the MRF in Kentucky show interbedding with minor basalts and seismic data suggests at least one substantially thick ash layer implying some degree of volcanic activity associated with the Grenville Orogeny (Drahovzal et al., 1992; Paramo, 2002).

The importance of the MRF's discovery in regards to the Bellefontaine Outlier stems from its interpretation as a foreland basin unit. If the MRF does in fact represent a clastic infill of a well developed foreland basin complete with typical foreland fold and thrust deformation as the seismic data suggests, then the Grenville Orogeny would be a crucial step in the development of the Outlier. The foreland deformation associated with the encroaching Grenvillian thrust sheets, could easily have inspired reactivation along remnant fault complexes involved in the formation of an extensional limb of the Midcontinent Rift (MCR) thought to lie in the Granite-Rhyolite Province basement beneath the Outlier. This reactivation during the Grenville Orogeny would have created structural weaknesses up through the MRF that could have been reactivated again and propagated through the Paleozoic strata during Devonian Acadian orogenic events.

Studies of the Grenville Province, Grenville Front, MCR, and Bellefontaine Outlier were reinvigorated after the discovery of the MRF. An abundance of research and paper publication followed the interpretation of the MRF as a foreland basin sequence from a number of institutions across the country. Work on the Outlier had become stagnated due to the lack of drilling data on or near the feature prior to the discovery of the MRF. Detailed surface geophysical surveys began in the early 1990's that concentrated only on the Outlier, though deep-drilling did not.

J. P. Weaver reported on his geomagnetic and gravity surveys of the area in 1994 (see Fig. III). The studies produced excellent gravity and geomagnetic anomaly data which he attributes to the fact that larger magnitude anomalies can only be produced by deep-seated features originating in the basement that extend upward into the thinner Paleozoic bedrock. The thin Paleozoic strata alone are of insufficient density and magnetic susceptibility to produce the observed anomalies. Weaver identified a narrow, long negative gravity and magnetic anomaly trending northeast from Champaign to Logan County, the northwest toward Indian Lake and Auglaize County, which he attributes to basement ramp-thrust faulting associated with the Grenville Orogeny and

Fig. III



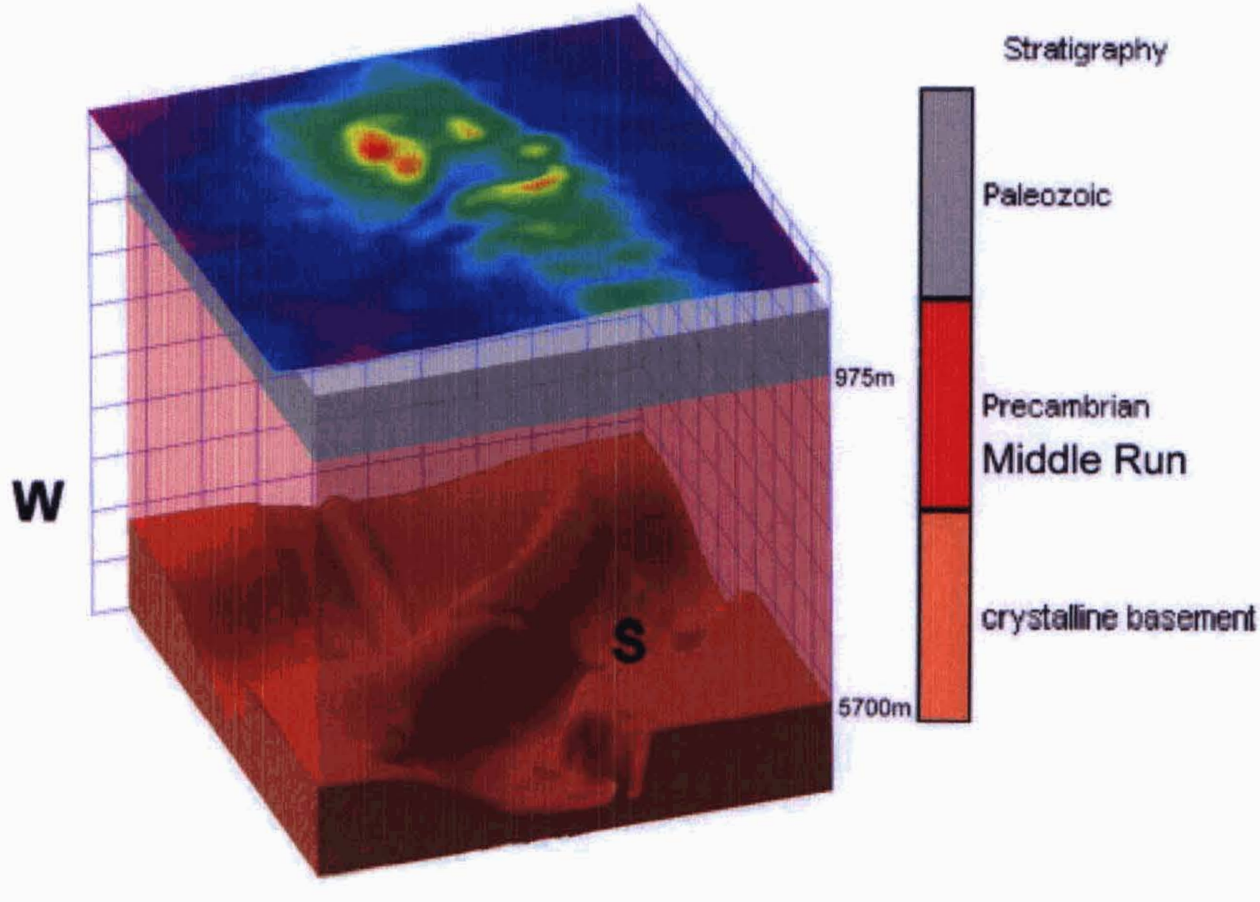
510 geomagnetic and gravity field station locations used in Weaver's survey covering areas of Champaign, Logan, and Union counties. From Weaver (1994)

later activated during the Acadian and/or the Taconic Orogeny of the Devonian. Weaver also reported a large geomagnetic positive anomaly in the southeast of the survey area that has the rough geometry of an intrusive pluton, which may have been emplaced during a rifting event before or during the earliest stages of the Grenville Orogeny. Weaver also cites the presence of paired belts of magnetic and gravity highs and lows as evidence that Paleozoic strata, since their deposition, have undergone significant tectonism in a block-faulting scenario accompanied by extensive plutonism. Since the report of his findings, Weaver's data sets have come to be further analyzed in several other studies.

Christian Steck (1997) used Weaver's gravity anomaly data set of the Bellefontaine Outlier to identify new basement faults and to better define and illuminate previously recognized basement features. Steck's work centered on Complete Bouger Residual Anomalies calculated by Weaver (1994), from which he constructed a number of profiles perpendicular to the trend of the gravity and subsequently perpendicular to the proposed trend of the fault complexes. Steck analyzed these profiles for changes in the direction of curvature, also known as inflection points, and interpreted the steepest gradient segment along the profile to be the location of the fault responsible for the curvature. Testing his hypothesis against COCORP OH-1 data, Steck found a good correlation and perhaps a more precise fault locating technique than that utilized in Drahovzal et al. (1992). Using the Thin Slab Approximation and an equation relating gravity, density, and upper and lower depths across the faults, Steck was able to approximate their throw. Using the methods described, the prominent north-south trending gravity anomaly was interpreted to be a large graben block with a lateral backwards “S” shape (Steck, 1997). The faults identified by Drahovzal et al. (1992) were also confirmed and slightly relocated and two new faults previously unidentified were recognized.

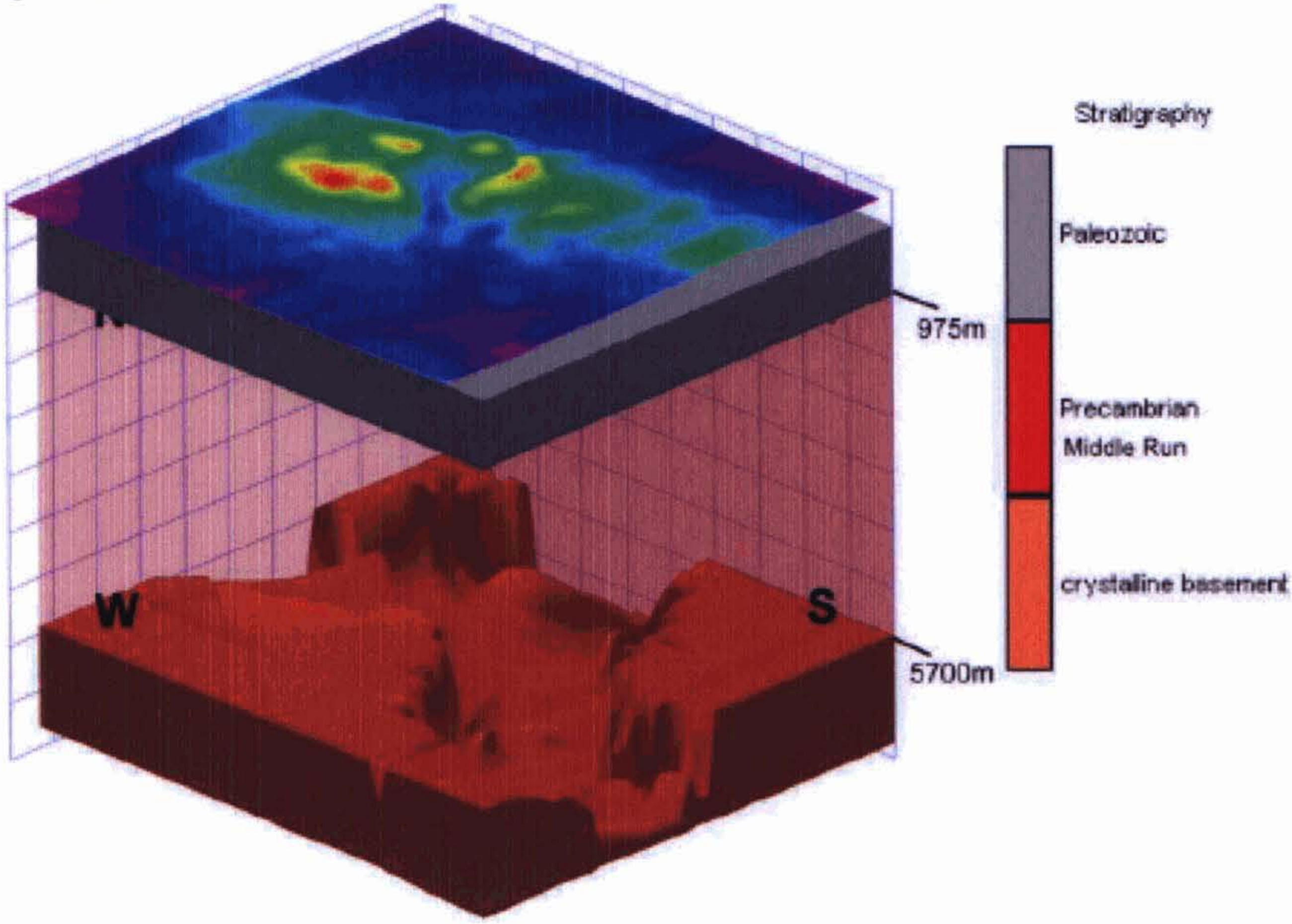
Michael Fidler (2003) reanalyzed the Weaver data using new digital computational methods to identify statistically derived points of anomalously high field gradients to give short spatial differences in the topography of the basement surface. Fidler’s calculations concerning vertical fault displacement were solely based upon lateral surface and gravity gradients with no reliance upon first-order approximations. By calculating the field gradient at each point of Weaver’s data, Fidler was able to statistically generate many short cross-sections that culminated in three-dimensional models of the basement structure and topography of the entire survey area for both the gravity and magnetic data sets. Fidler’s models have been adopted by this study as a realistic approximation of the basement setting. These models have served as the assumptions for calculating the lateral extent, down-drop of the rift valley, and volume of clastic infill used in the discussion of the rift basin (see Fig. IV A and B).

Fig. IV A



Three dimensional model of crystalline basement under the Bellefontaine Outlier based upon geomagnetic anomaly data set; also showing surface topography. Taken from Fidler (2003).

Fig. IV B



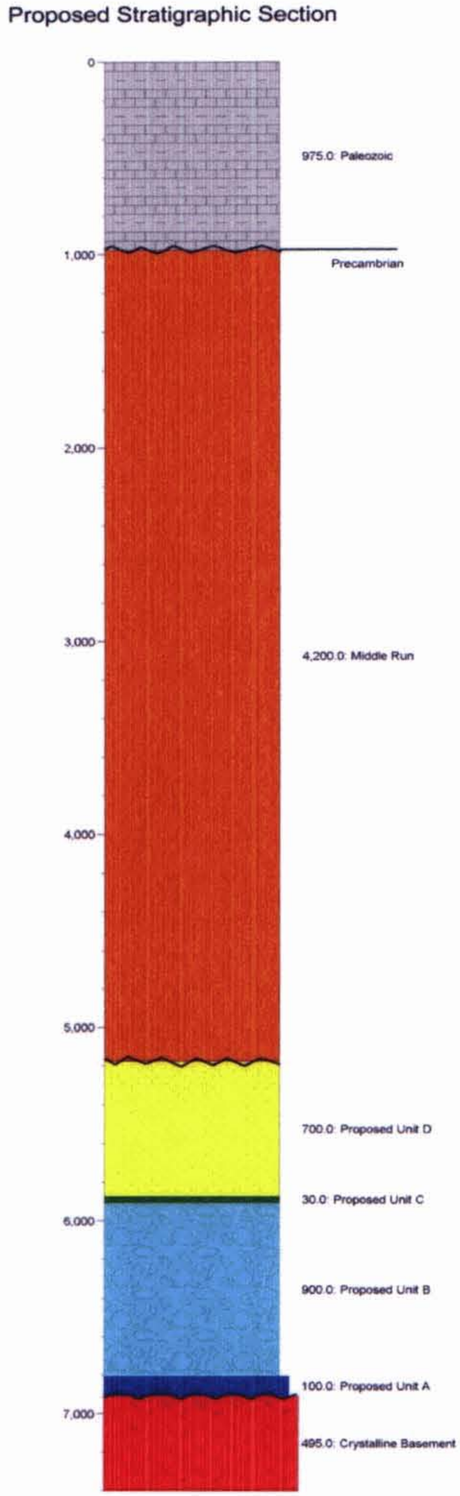
Three dimensional model of crystalline basement under the Bellefontaine Outlier based upon gravity anomaly data set; also showing surface topography. Taken from Fidler (2003).

Discussion of Outlier Region from the Middle Proterozoic through the Devonian

The formational hypothesis for the Bellefontaine Outlier presented in this study, considers a number of tectonic and geologic events beginning in the Middle Proterozoic, continuing through the Devonian, culminating in what is now observed at the surface. Preferential erosion due to numerous glaciations has most certainly played some role in establishing Campbell Hill as the topographic high of Ohio, but the complex, deep-rooted basement structure has had a much greater influence in the formation of the Outlier. Our understanding of this basement structure is handicapped by the lack of any sufficiently deep drill holes in the area. Only eleven wells are currently know to have penetrated the MRF across western Ohio. The deepest reports merely a penetration of 0.59 km into the MRF. Seismic data suggests that the MRF may reach a total thickness of up to 8 km and have an expansive lateral extent (Drahovzal et al., 1992). Geophysical investigations remain our best modern tool for investigating the MRF and the underlying stratigraphy and basement structure of the region.

The identification and modeling of a possible extensional limb of the MCR at some depth below the MRF based upon gravity and geomagnetic anomaly data, inspired the proposal of a new stratigraphic sequence (see Fig. V) which considers the infilling of the ancient rift basin before deposition of Grenville foreland basin sediments (Fidler, 2003; Noltimier et al., 2004). These three-dimensional models of the rift basin and new sub-MRF stratigraphic scheme are incorporated into the discussion of the Bellefontaine Outlier through its development and maturation starting in the Middle Proterozoic.

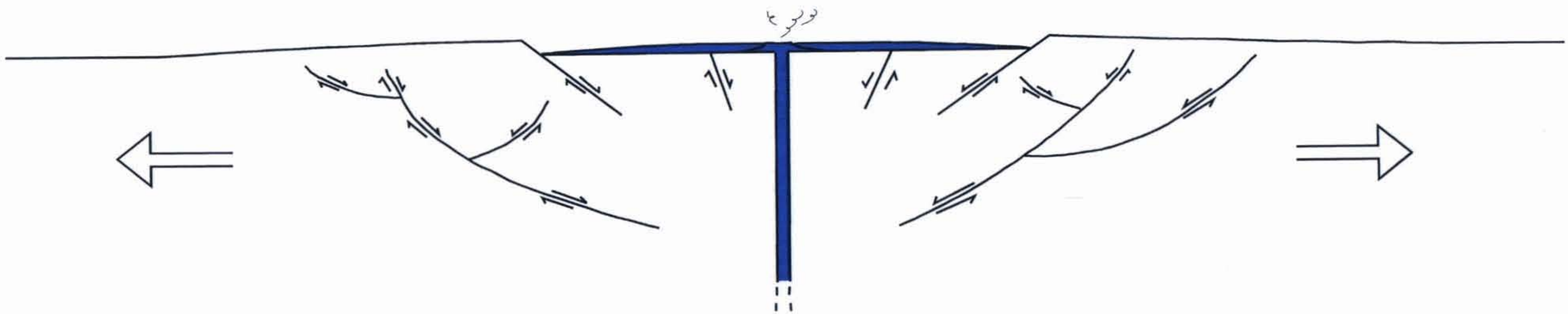
Fig. V



Proposed Stratigraphic column for Bellefontaine Outlier. Taken from Noltimier et al. (2004)

The Bellefontaine Outlier region experienced an initial regional thermally-induced doming predating any lateral extension beginning in the Middle Proterozoic (see Fig. 1). The crust thinned either due to forces associated with a rising mantle plume or from purely tensional forces associated with mantle convection. In either scenario, the relatively thinner crust of the immediate area would ride higher atop the mantle because of both isostatic considerations and lower density contrasts spurred by the massive influx of heat from the upwelling mantle. Eventually, when tensional stress magnitude exceeded rock modulus of compressibility, the crust responded with brittle extensional deformation accomplished through normal faulting. A broken linear fissure would have formed and provided a conduit for upwelling magma to reach the surface. This linear fissure would become the spreading axis of the basin, where layered extruded volcanics were symmetrically deposited about it and led to the formation of Proposed Unit A (PU-A, represented by dark blue unit in Fig.1 with arrows representing relative direction of stresses). These volcanic packages would have assumed in cross-section, a lens-like geometry, with the thickest portion at the axis and thinning gradually to the margins of the basin. The extrusion of these volcanics was episodic, with voluminous extrusion of basalts, andesites, minor rhyolites, and ash beds interrupted by periods of weathering and deposition of poorly worked conglomerates composed of clasts derived from these volcanic packages. The Portage Lake Volcanic Series (PLV) which has been compared to early stage rift filling rocks of East Africa and Iceland, lies near the base of the Keweenawan Rift in the Lake Superior region and may be an approximate analogue unit (Bornhorst et al., 1994). The PLV is a massive, thickly-bedded, layered basalt and subordinate rhyolite unit, with 5% of total rock volume occupied by sediment, the

Fig. 1



Initial rifting of basement complex circa 1.1-1.2 Ga
Accompanied by flood basalts and volcanism with tensional faulting

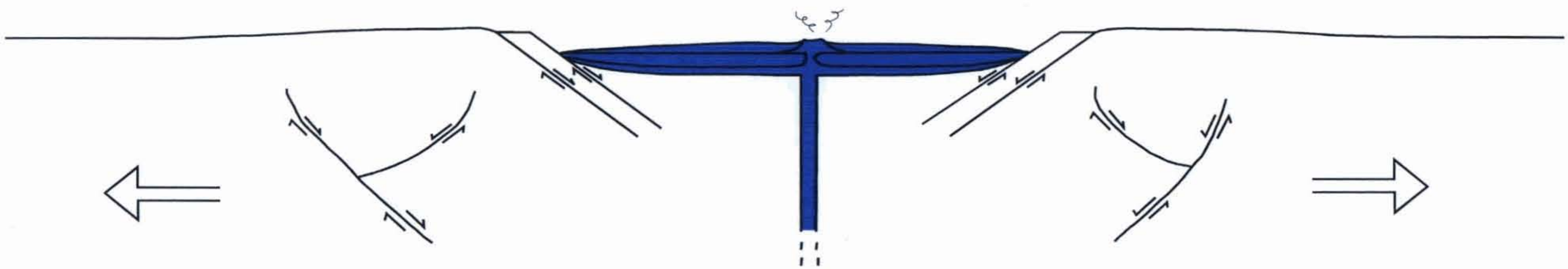
percentage of which increases in abundance near the top (Bornhorst et al., 1994). Initially, the extrusive events would have provided a large enough volume of material to keep up with the down warping of the basin flanks as major normal fault complexes formed and matured symmetrically about the basin axis.

Near the end of deposition of PU-A (see Fig. 2), conglomerates become the dominant rock type with minor inclusions of extrusive volcanics. Though less and less magma reached the surface during the latter interval of deposition of PU-A, magmatism increasingly took the form of intrusive dikes that rose and penetrated into the lower portions of PU-A. As the basin flanks continued to down warp throughout this time interval, deformation and downwarping caused the inversion of the PU-A volcanic lens from a convex-upward to concave-upward geometry.

The most massive rock body, Proposed Unit B (PU-B, represented by light blue in Fig. 3), that fills the rift basin was deposited during the subsequent time interval. During its early stages of deposition, the rift was still actively spreading, including normal displacement along rift defining fault planes and major pulses of volcanic activity depositing substantial thicknesses of layered ash and lavas.

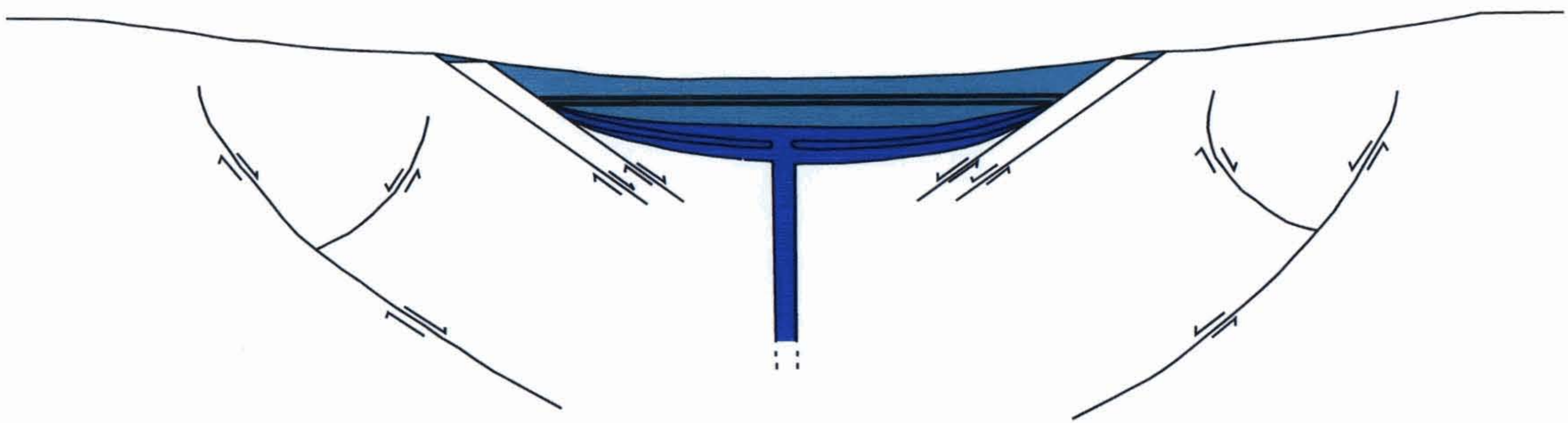
The lower facies of PU-B is certainly characterized by a conglomerate or arkosic rock body with angular to subangular clasts ranging from sand to boulder size. The majority of the clasts were derived from freshly exposed tilted fault blocks made up of Granite-Rhyolite Province crystalline basement rocks, and a lesser, but substantial, minority of clasts were derived from intrabasinal layered extrusive basalts and tuffs. The Copper Harbor Conglomerate Formation (CHC), syntectonically deposited during Keweenawan rifting during the Proterozoic, may represent an approximate analogue unit.

Fig. 2



Basaltic intrusion and extrusion, abundant flows and volcanism, faulting continues with further development and maturation of rift-graben system

Fig. 3



Termination of active extension and rifting, tectonically stable period dominated by depostion of thick sequence of sediments shed from tilted fault blocks and intrabasinal sources

The CHC crops out along the southern shore of Lake Superior and is described to be as a massive, poorly-stratified conglomerate with minor interbedded arkosic sandstones, and a few moderately thick, layered, basic lava layers (Meshref et al., 1970). Volcanism was still very active though the pulses of extrusion were not enough to keep up with the downwarping of the basin, interpreted by the presence of these massive conglomerate packages.

The middle facies of PU-B is likely dominated by massive cross-bedded sandstones probably recording a large braided river system. The middle facies in analogue units of the Keweenawan Peninsula and elsewhere along the Midcontinent Rift, suggests an arid climate of deposition due to the presence of gypsum moulds and carbonate-filled cracks (Elmore, 1983).

Near the later stages of the deposition of PU-B, active extension slowed and eventually terminated where only subsidence due to sediment loading still persisted in the rift basin. The upper most member of PU-B probably documents the beginning stage and maturation of a large and complex hydrological drainage system that would operate in the basin until the Grenville Orogeny many years later.

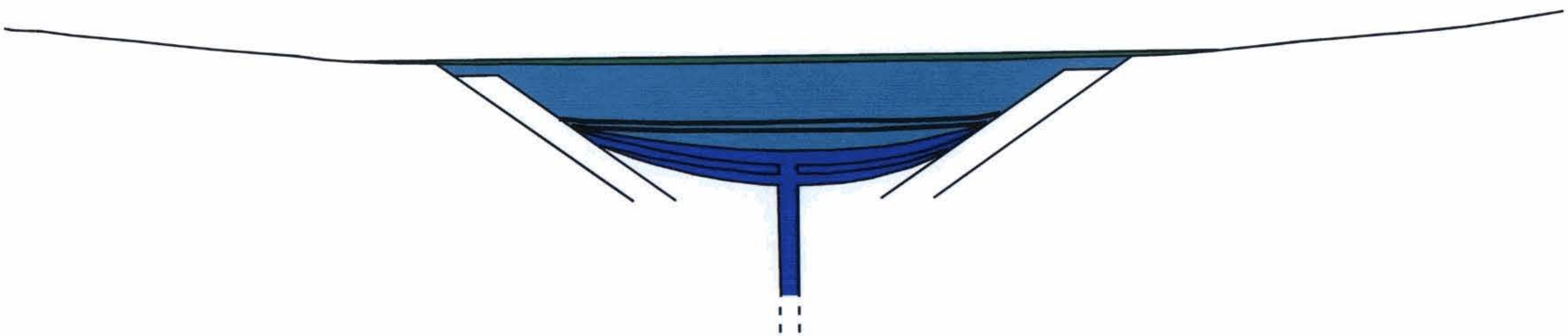
The upper facies of PU-B probably fines upward and may represent the deltacic deposits of a large, young, but still immature, lake in which Proposed Unit C (PU-C) would have been deposited. A very distinct lithological break (though conformable) above the CHC, observed in the Keweenawan region, may indicate a rapid maturation of the fluvial drainage system to a large lacustrine environment and may be applicable to the Outlier region at this time (Meshref et al., 1970). Lacustrine stromatolites have been observed in the upper most portions of PU-B's analogue units along the MCR and strengthen the argument for the continued development of a large, freshwater lake through the end of deposition of PU-B and PU-C (Elmore, 1983).

After termination of extensional rifting (see Fig. 4), the region achieved a tectonically stable setting with all local vertical movements of the crust due to subsidence via sediment loading. A large, extensive, and complex fluvial and drainage system continued to mature in the rift basin and the laterally surrounding areas. The new local hydrological environment was responsible for the deposition of both Proposed Unit C and D in this stable environment. The thin, organic rich Proposed Unit C (PU-C) is a fine-grained shale/siltstone package within which facie changes probably vary from a deeper lacustrine to a tidal mudflat environment. Analogue formations in portions of the Midcontinent Rift starting in the Upper Peninsula of Michigan continuing down into Kansas, have preserved mud crack and ripple mark sedimentary structures similarly suggesting a low energy, shallow water environment (Imbus et al., 1988).

These analogue formations also exhibit a significant hydrocarbon source rock potential which may also apply to PU-C (Imbus et al., 1988).

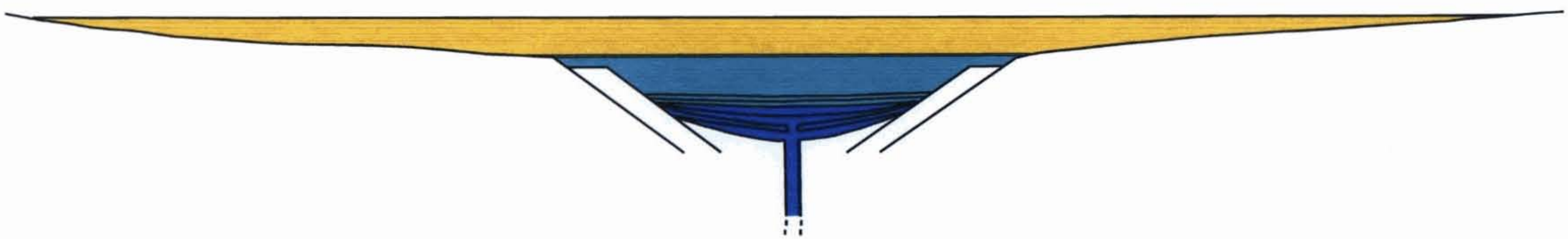
PU-C coarsens upward to a gradational contact with Proposed Unit D (PU-D) above (see Fig. 5). This well sorted, fine- to medium-grained sandstone, which becomes arkosic in its uppermost portion, probably represents the fairly massive deltaic deposits of a high energy, well developed fluvial system which we have proposed to be operating in the basin at this time. The Freda Sandstone Formation of the Keweenawan Trough, may serve as an approximate analogue unit. This exposed unit has been described as a fine- to medium-grained, well-sorted red to grey arkose with minor inclusions of greenish micaceous shale and siltstones (Meshref et al., 1970).

Fig. 4



Stable period, dominated by deposition of fine-grained, organic-rich, shallow marine facies sediment packages

Fig. 5



Stable period, marked by facies change to thick coarser-grained sandstones which may have been derived from the newly exposed Grenville thrust sheets still at some distance away (eastward in modern geographic coordinates)

By the end of the deposition of PU-D some substantial though non-dominate portion of the sediments being deposited in the basin may have been derived and transported the long distance from newly exposed Grenville thrust sheets in their infancy, still at quite a distance away in the modern east direction. The upper contact of PU-D with the Middle Run Formation (MRF) directly above is most likely gradational. Analogue units lying elsewhere along the Midcontinent Rift have varying conformable and unconformable upper contacts. The differentiation between PU-D and the MRF could probably be described through some arbitrary proportion of clasts derived from some distant provenance (i.e. Grenville thrust sheets) versus locally derived sources (i.e. intrabasinal tilted fault blocks or rocks just outside of the basin).

Tremendous sedimentation rates in the region would have matured the rift-basin to a well developed (in both structure and geometry) foreland basin in front of westward advancing Grenville thrust sheets (see Fig. 6). Thrust sheet encroachment velocity and uplift rates of mountains inspired by the Grenville Orogeny were at their peak during this period. Initially extensive strike-slip faulting may have occurred before the propagation of reverse-faults, which gradually matured to wrench faulting, then finally to traditional reverse faulting by the time the Grenville Orogeny was at its peak. The foreland basin strata are dominated by the Middle Run Formation (MRF). This massively bedded red to gray, fine- to medium-grained sandstone with minor inclusions of red siltstones, shales, and conglomerates encodes the later maturation and eventual termination of the Grenville Orogeny (Drahovzal et al., 1992).

In the cored samples available, which reached only into the uppermost unit of the MRF, an observable fining-upward depositional sequence is observed and may represent

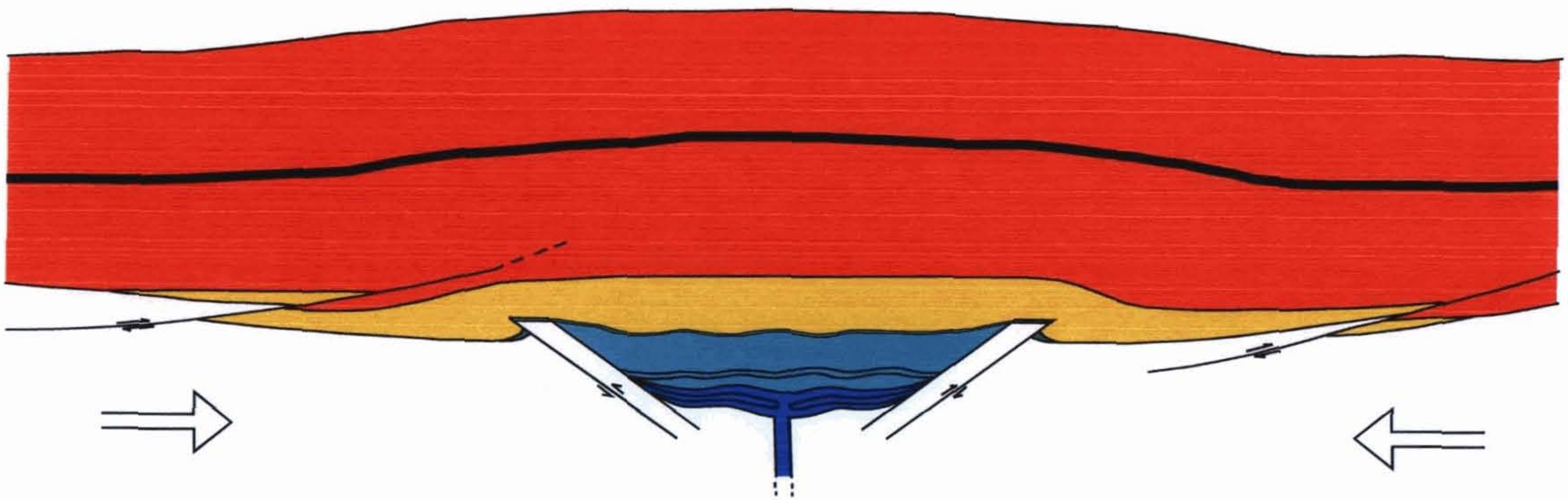
Fig. 6

Early stages of deposition of Middle Run Formation in the early, actively subsiding Grenville foreland basin, including extensive volcanic ash horizons the period in which the area was returning to a tectonically stable setting. Some rock fragments contained in these samples have been correlated with both the Granite-Rhyolite Province (GRP) crystalline basement and from overthrusted, Grenville basement thrust sheets. Other volcanic rock fragments, not associated with the GRP and Grenville, are also included in the sample. The provenance of the fragments may lie outside the basin at sites of massive volcanic activity associated with the Grenville Orogeny to the east, but microseismic evidence suggests that there may be minor occurrences of layered volcanics deeper within the MRF that may have been the source for these fragments. This microseismic data has also identified thick volcanic ash horizons most likely due to massive eruption events to the east during the Grenville Orogeny (Paramo, 2002).

Further encroachment of Grenvillian thrust sheets (see Fig. 7) and sediment loading in the foreland basin, caused continued subsidence in the foreland basin until the end of deposition of the MRF. Simultaneously, compressive forces conducted westward aided in the initiation and propagation of shallow angle thick-skinned reverse faults, originating in the middle basement up through the bottom of the MRF (Dean et al., 2002). Reactivation along the rift-defining fault planes caused an upward extrusion of the rift basin, with the result being the uplift of the graben fault block relative to the surrounding basement rock with a displacement substantial enough to disturb the strata overlying the area. A regional, gentle anticlinal dome structure developed in the MRF, Proposed Unit D, and Proposed Unit C Formations and was further exaggerated by tectonic events during the Paleozoic.

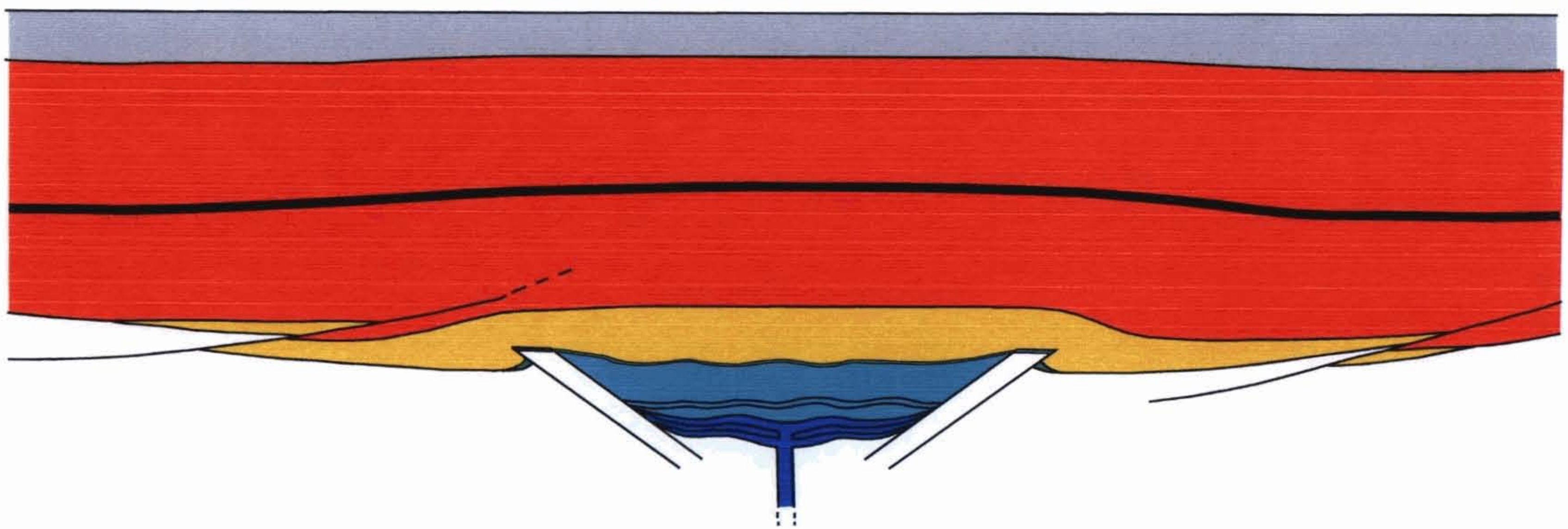
As the Grenville Orogeny finally slowed and terminated, deposition rates of the MRF fell as the region affected by the stresses relaxed. Shortly after the geologic

Fig. 7



Reactivation of rift-defining faults coupled with propogation of low angle reverse faults due to compressional stresses associated with the Grenville Orogeny circa 700 Ma

Fig. 8



Stable period characterized by deposition of Paleozoic marine and lacustrine carbonate and clastic sediment sequences environment had reached a degree of stability, a sea-level drop, perhaps due to Gondwanaland influences or an isostatic exhumation of most of the eastern continent, exposed and subjected the MRF to active erosion. Petrological studies of the MRF have alluded to a complex and interesting history of cementation dating before the deposition of any Paleozoic strata and may have been due to expelled fluids and brines driven off by the Grenville Orogeny (Drahovzal et al., 1992). An unconformity encodes the exposure of the foreland basin at the end of the Precambrian and earliest Cambrian and provides the upper bound for the MRF.

Deposition of marine and lacustrine carbonate and clastic sedimentary units characterize the pre-Acadian Paleozoic geology in the outlier area (see Fig. 8). From the beginning of the Paleozoic through the early Devonian, the Bellefontaine Outlier region was tectonically stable and conducive to massive sedimentary deposition.

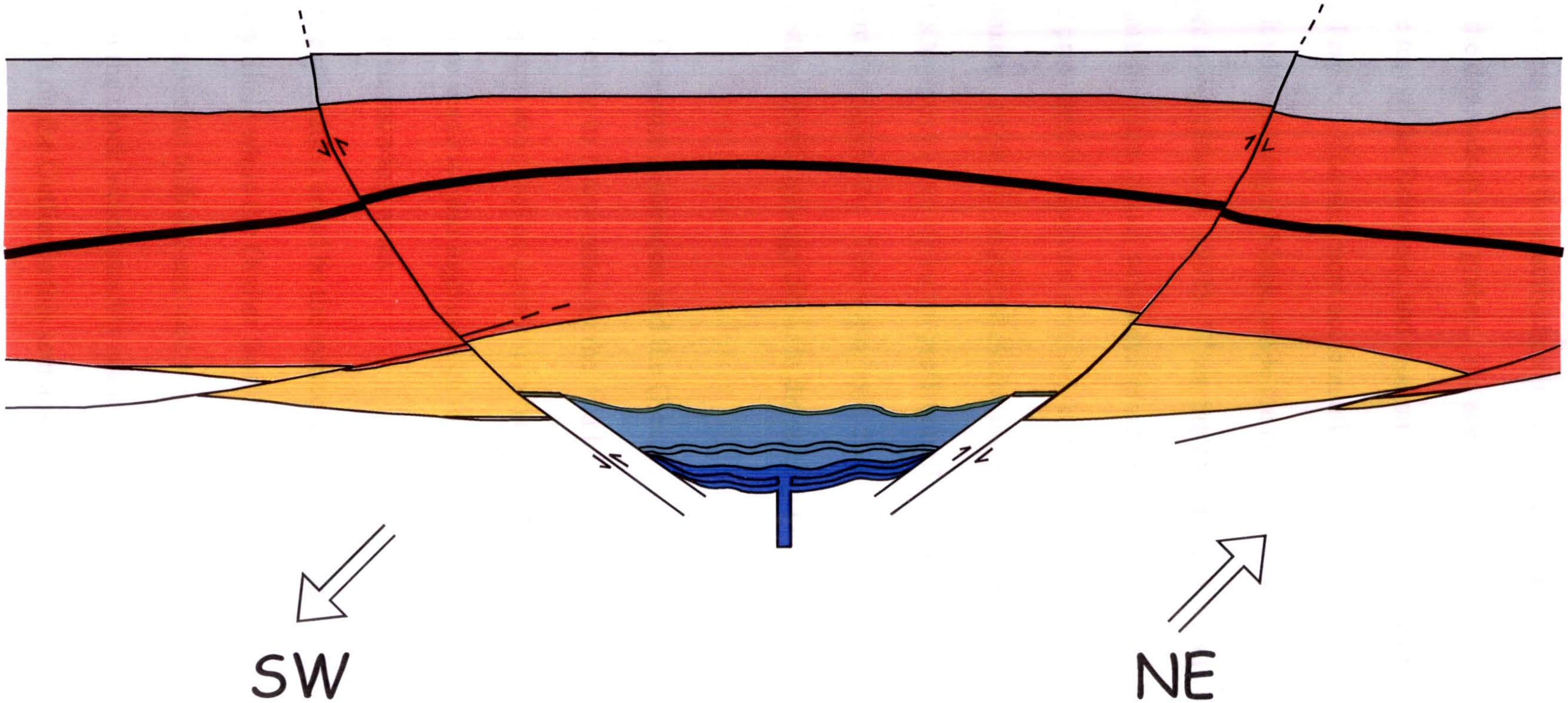
Directly overlaying the unconformity marking the top of the Middle Run Formation, lies the Cambrian Mt. Simon Sandstone Formation, a fine-grained shelf-type unit that coarsens upward to a sandy conglomerate, achieving a thickness of 120 ft in the area (Slucher et al., 1995). Above the Mt. Simon Sandstone, lies the intertongued fine-grained shale, deep water-type Rome and Eau Claire Formations, with a rough thickness of 200 ft (Slucher et al., 1995). Overlying the Eau Claire formation is the 40 ft thick Kerbel Formation, a fine- to medium coarse-grained sandstone that may record a marine to non-marine depositonal environment transition (Slucher et al., 1995). Above the Kerbel Formation lies the Knox Dolomite Formation recording a thickness of about 390 ft, bounded above by an unconformity, and is interpreted as the youngest Cambrian unit in the region (Slucher et al., 1995). The thin Wells'Creek Formation siltstones mark the beginning of the Ordovician. The microcrystalline Black River Limestone Formation conformably overlays the Wells Creek Formation and achieves a thickness of 480 ft (Slucher et al., 1995). Directly above the Black River Formation, lies the 310 ft thick Trenton Limestone Formation which becomes increasingly fossiliferous near the upper boundary with the Undifferentiated Cincinnatian Series (UCS) (Slucher et al., 1995). The UCS is dominated by green shales interlayered with limestones achieving a thickness of 634 ft in the outlier region (Slucher et al., 1995). The youngest Ordovician unit, the thin 28 ft thick Whitewater Formation, directly overlays the UCS and is dominated by a brown limestone with a gradational contact to a green shale that marks the lower member of the Silurian Brassfield Formation (Slucher et al., 1995). The Brassfield Formation with a local thickness of 107 ft, grades to dolomite in its uppermost member and is overlain by the 34 ft thick interbedded cherty-limestone and shale layers of the Sub-Lockport group which grades to the crystalline, vuggy Lockport Dolomite with a regional thickness of 97 ft (Slucher et al., 1995). The Brassfield Formation is overlain by a gradational contact with the Greenfield Dolomite Formation with a local thickness of 47 ft (Slucher et al., 1995). Atop the Greenfield Dolomite Formation, lies the silt and clay inclusive, Tymochetee Dolomite Formation recording a thickness of 70 ft (Slucher et al., 1995). The gray, fine-grained Salina Group conformably overlays the Tymochetee Dolomite and marks the last unit deposited during the Silurian (Slucher et al., 1995). The Columbus Limestone Formation of the Devonian, composed of crystalline dolomite with chert, silt, and fossil inclusions, has a local thickness of 87 ft (Slucher et al., 1995).

Two Devonian units, the Delaware Limestone and Olentangy Shale, are not present in the stratigraphic column of the Bellefontaine Outlier but can be found in the areas directly encompassing the Outlier area. The Delaware Limestone, a gray-brown crystalline limestone, has a local thickness of 45 feet (Slucher et al., 1995). The Olentangy Shale, greenish-gray, calcareous in part, fine-grained shale maintains a local thickness of about 50 feet near the Outlier (Slucher et al., 1995).

Compressive forces focused east to west associated with the Acadian Orogeny during the Devonian, resulted in a reactivation and propagation to the surface of old rift-defining fault complexes (see Fig. 9). The Acadian Orogeny has been shown to be associated with the collision of Laurentia (ancestral North America) with Gondwanaland (Western Africa) (Steck, 1997). This reactivation was almost certainly accompanied by some degree of lateral translation along the fault planes (NE-SW relative direction), in the typical wrench-style faulting observed in other locations affected by this Orogeny. The fault block comprised of rocks from the Precambrian to the Devonian, was subsequently exhumed and uplifted in the area that is now called the Bellefontaine Outlier. Observations at modern outcrop suggest varying displacement of at least 90 feet (about 27.5 meters), though actual uplift due to reactivation may be less when considering differential subsidence. This uplift was directly responsible for the missing Delaware Limestone and Olentangy Shale on the Outlier block but the exact timing and mechanics are still unclear. Three possible explanations can explain the absence of these two units.

One of the earliest Outlier theories to be published after the discovery of the MRF, proposed a fault-graben system influenced by deep basement rock structure. Hansen (1991) speculated that initially the Outlier was a positive topographic feature surrounded by a warm, shallow sea during the early Devonian. Hansen then suggests that

Fig. 9



Secondary reactivation of rift-defining faults and lateral wrench-faulting associated with the Acadian Orogeny, uplift of Bellefountain outlier coupled with differential subsidence due to sediment loading in both flanking basins a late or post-Devonian event caused the reactivation of ancient deep-seated fault complexes resulting in the down-drop of a graben. His scenario continues with sediment accumulation during the rest of the Paleozoic, and erosion across the whole region for both the Mesozoic and Tertiary. The sediment accumulation in the rift valley protected the Devonian strata in the down-dropped block, while the other Devonian layers outside the valley where stripped away (Hansen, 1991). When the graben bedrock was finally exposed, it's capping unit, the Ohio Shale, was much more resistant than the surrounding Silurian carbonates and protected the less resistant Devonian carbonates within the block (Hansen, 1991). Eventually, a number of glacial events during the Tertiary further illuminated the Outlier's topographical stature by preferentially eroding the country side in an effort to circumvent the highlands. This hypothesis does not clearly account for the missing Deleware Limestone and Olentangy Shale in the stratigraphy of the Oultier block.

Second, both the Delaware Limestone and the Olentangy Shale could have been deposited on the Outlier before its reactivation by the Acadian Orogeny. When the block was exhumed, weathering and erosional processes may have acted long enough to remove the two units before sea-level was high enough to facilitate deposition on the Outlier and the immediate surrounding areas.

A third plausible explanation could be the syntectonic deposition of the Delaware Limestone and Olentangy Shale while the Outlier fault block was slowly being exhumed. Flanking basins that developed on both the east and west margins of the fault block filled with sediments shed from the block which quickly accumulated. The Columbus Limestone, the capping unit on the Outlier in this scenario, was eroded and its sediments deposited in these flanking basins. This sediment contribution, as well as sediment input from sources outside the area, culminated in the deposition of the 22-45 feet thick Delaware Limestone and then the 23-45 feet thick Olentangy Shale during the exhumation interval of the Outlier.

An erosional disconformity lies between the Columbus Limestone and Ohio Shale on the Outlier, implying the third hypothesis is the most likely. In either the second or third hypothesis, the sediment loading in both flanking basins may have been substantial enough to lead to active subsidence at these margins and may have further exaggerated the observed upward displacement of the fault block.

After the compressive and/or shear forces dissipated, the region achieved a relatively stable setting through the rest of the Paleozoic. The Ohio Shale unit of the Devonian (currently exposed at the surface of the Outlier), may represent the time-slice when the Outlier and the surrounding areas of western Ohio began to again share a common history.

Economic potentials within and under the Middle Run Formation in the Outlier Region

If my third hypothesis for the geological development of the Bellefontaine Outlier proves to be correct, the economic consequences deserve consideration. Though the Paleozoic strata of Ohio have been intensively studied for their hydrocarbon and economic mineral potential, the MRF and underlying rift basin may host significant, unrecognized economic prospects. Though few Proterozoic and Archean hydrocarbon source rocks have been identified globally, a few strata with a significant potential have been discovered along the MCR in Upper Michigan, Kansas, and Iowa (Dean et al., 2002), Major tectonic events may also have produced mineralization episodes affecting the MRF and subjacent stratigraphic units. Profuse copper and iron deposits in Proposed Unit A and Proposed Unit B may have originated as a consequence of initial rifting followed by the Grenville Orogeny.

Precambrian hydrocarbon source rocks may lie within the MRF and its underlying rift-filling strata in western Ohio. A 700-ft thick black carbonate sequence was penetrated just below the Mount Simon Sandstone in Clark County, Ohio and may be the best example of a source rock lying in the MRF. Though the relationship between this pre-Mount Simon carbonate and the MRF has not been completely determined, the carbonate may be an example of the kind of facies that would have facilitated organic-rich deposits during MRF deposition (Dean et al., 2002). Though source rocks may exist, the poor reservoir nature (as far as presently known) of the MRF as a whole, make the unit unattractive for exploratory drilling. Only one well in Hart County, Kentucky, has penetrated a friable sandstone interval within the MRF that has an adequate porosity and gas show (Dean et al., 2002). No wells drilled into the MRF in Ohio, have encountered sandstones with a significant porosity due to primary porosity occlusion by calcite, hematite, quartz and feldspar cements (Drahovzal et al., 1992; Shrake et al., 1990). The structure and discovery of favorable source and reservoir rocks in other areas of the Midcontinent, similar to the ECRB beneath the Outlier, preserve the possibility of a major petroleum discovery in the future. Dean and Baranoski's (2002) reprocessing of COCORP's OH-1 and OH-2 line data, led to the interpretation of a few potential hydrocarbon traps. They identified favorable traps along the inverted normal faults cutting the MRF and along the margins of the truncated anticlinal structure imposed on the MRF and underlying strata. While both favorable and unfavorable characteristics complicate the hydrocarbon prospects in the MRF, underlying rift-filling strata may lay claim to being more significant source rocks.

Proposed Unit C (PU-C) may represent the best prospect for source rock in the Bellefontaine Outlier region. The Nonesuch Shale of Upper Michigan, the Rice Formation of Kansas, and the Unit C shales of Iowa, are all thin, organic-rich, Precambrian shales found within the rift-filling stratigraphy of the MRC (Dean et al., 2002). These units have been dated to have ages around the estimated age of the PU-C contact and may serve as excellent analogues. The Nonesuch Shale is the only one of these analogues exposed at the surface, while the others are buried under the thick Midcontinent Paleozoic and Mesozoic platform sedimentary units, and Cenozoic glacial cover. While no wells drilled into the Nonesuch Shale have reported significant hydrocarbon discoveries, iron and copper mines in the area have reported significant oil seeps (Mauk et al., 1992; Imbus et al., 1988).

Two major, distinct mineralization events since the mid-Proterozoic may make the rift basin and infilling strata a prime target for iron and copper ore deposits. Tectonically induced volcanism and plutonism have repeatedly affected the Precambrian strata beneath the Outlier. Other areas of the MCR, especially in the Keweenawan region, have been shown to contain major economic iron and copper deposits. At one time, these lodes led the world in extraction and production beginning in the late 19^{th} century up until the market price of both metals was abruptly halved due to the end of World War II.

Synsedimentary mineralization during the deposition of PU-B, while the region was still subject to an extensional stress regime, may have been the more significant of the two mineralization events. As volcanism increasingly took the form of intrusive dikes during the latter stages of the deposition of PU-B, metal-rich brines were hydrothermally mobilized. This fluid percolation through PU-A may have caused alteration and iron-enrichment of the layered basalts, which may be responsible for the anomalous magnetic rift valley signature. There may have been later second- and third-stage mineralizations and the inversion of the PU-A lenses which further illuminated the geophysical signature. The base of PU-B was originally a very coarse, poorly sorted, poorly cemented, highly permeable conglomerate with a crude cross-stratification. Hydrothermal fluids could easily travel through this interval, replacing the original cementing agent and precipitating ore grade iron deposits in the ample pore space provided by the boulder to cobble sized conglomerate.

A Grenvillian-age second-stage mineralization, during the beginning stage of deposition of the MRF, may have resulted in further iron enrichment within PU-A and base of PU-B and massive copper precipitation in the top of PU-B and within PU-C. The emplacement of the large pluton identified and dated to coincide with the Grenville Orogeny by Weaver (1994), could have been the source of rich cupriferous fluids that migrated up through the rift-filling strata. Should PU-C contain organic material as postulated, these migrating fluids would have replaced available pyrite to form CU-bearing sulfides and native copper. Many authors have studied the connection between organic material and mineralization and a number of studies have specifically concentrated on native copper deposits in the Nonesuch Shale and Copper Harbor Conglomerate units filling the Keweenawan rift. These studies have concluded that organic matter can facilitate precipitation of metallic and especially copper-bearing minerals via two processes (Mauk et al., 1992). The oxidation of organic matter can be coupled to the reduction of an oxidized species where the organic matter plays a direct role in the precipitation of the ore minerals (Mauk et al., 1992). Alternatively, the reduction of a sulfate to sulfide causes the oxidation of the organic matter which can then react with a metal species where the organic matter can either play a direct or indirect role in the mineralization (Mauk et al., 1992). In the direct role scenario, the sulfide reacts with the cuprous ions to form chalcocite (Mauk et al., 1992). The indirect role involves the formation of pyrite which is later replaced to form the Cu-sulfides (Mauk et al., 1992).

Economic prospects along the Midcontinent Rift from Kansas to Upper Michigan, have continued to improve with each investigative study. The comparisons and analogues suggest that the rift basin beneath the Bellefontaine Outlier may be equally as attractive. Hydrocarbon source rocks and economic mineral deposits most certainly exist within and below the Middle Run Formation, but their abundance and extent are still poorly known. The sheer volume of Paleozoic and Middle Run strata overlying the rift basin has been a major impediment to exploration in the area. Unfortunately, many technological advancements may be necessary to capitalize on the prospects within the Proterozoic stratigraphic section of the Outlier region.

Interpretations and Conclusion

A more sophisticated stratigraphic understanding of western Ohio during the Precambrian and Paleozoic is necessary for any deep-focused study of the area. Without sufficiently deep-drill hole data, educated speculation must be made on rift-filling and Grenville foreland basin sediment and volcanic layers underlying the top of the MRF and overlying the crystalline basement in the region. Because of the rift basin's interpretation as an extensional limb of the MCR, a new stratigraphic package comprised of four major units has been proposed to fill this mid-Proterozoic rift with many analogues to strata present in other areas along the MCR. Western Ohio's very close proximity to the Grenville Front has also warranted the extension of the MRF's lower contact to a greater depth overlying the proposed package. A geological history for western Ohio and the north-central North American midcontinent has been synthesized to explain much of the reasoning involved in the new stratigraphic model presented in this study.

The oldest unit, a thick downwarped, lens shaped layered volcanic sequence, sytectonically deposited during rift basin extension, lies atop the rift crystalline floor. Directly above, a massive, coarse conglomerate perforated by minor volcanic lenses, documents the final stages and the eventual termination of active spreading. A thin, organic rich, lacustrine shale layer records a stable period of deposition and overlies the conglomerate. Directly above lies a thick, well-rounded sandstone deposited in a changing landscape during the infancy of the Grenville Orogeny, before the region's maturation into a foreland basin. The thickest unit in the column, the MRF, records massive deposition of foreland basin sediments in front of Grenville thrust sheets and represents the youngest Precambrian strata preserved under a thin package of Paleozoic sedimentary units.

Incorporated with findings from other studies of the area, the new stratigraphic model and geological history presented here may fit another piece of the complicated Precambrian and Paleozoic puzzle of western Ohio and North America. The rift basin has already been postulated to have had a direct influence in the development of the Outlier, but it may have a greater contribution to our understanding of the MCR and history of the Midcontinent. More detailed modeling of the basement rock through geophysical data in western Ohio could further constrain the extent of this limb in the region and may aid our knowledge of the age of rifting, stresses involved during the rifting, reasons for rifting termination, and its relationship with the MCR.

The transition from a failed rift basin to a Grenville foreland basin within a 400 million year time interval is also a new idea presented in this study. Since the discovery of the MRF, the ECRB has been widely accepted as a dominant structural feature west of the Grenville Front though poorly constrained in geometry and time. This geological transition has proven to be much more complicated than the early ECRB models proposed. A major Grenvillian consequence was the upward propagation of structural weaknesses that would be the mechanisms for reactivation during the Paleozoic. Rift block exhumation during the Paleozoic may extend along the whole length of this limb in Ohio, where the Bellefontaine Outlier is one of the few remaining locations to preserve evidence at the surface.

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