CARBONIFEROUS PROVENANCE TRENDS FROM CLASTIC STRATA OF THE MICHIGAN BASIN

By

Jeremy Boothroyd

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Geological Sciences

2012

ABSTRACT

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The intracratonic Michigan Basin is located between the distal margin of the Appalachian foreland, the eastern edge of the Illinois basin, and the southern boundary of the Canadian Shield. Late Paleozoic strata (Mississippian–Pennsylvanian) of the Michigan Basin are primarily coarse siliciclastic and represent the last preserved relict of fluvial-deltaic sedimentation coeval with Alleghenian orogenesis in the continental interior. Previous studies suggest that these strata were derived from source areas associated with the Appalachian orogen; however, the timing and spatial distribution of Appalachian depositional systems throughout eastern North America is the topic of ongoing debate. Summarized here are new provenance data from the Carboniferous strata of the Michigan Basin, including detrital framework modes, previously reported and newly compiled heavy mineral analyses, and the first set of U-Pb detrital zircon ages (n=431) from the Carboniferous strata in Michigan.

Provenance trends from the Early Mississippian Marshall Sandstone, and Early Pennsylvanian Parma Sandstone, Saginaw Formation, and Eaton Sandstone demonstrate variability in compositional maturity and source types, suggesting that Mississippian and Pennsylvanian units were likely derived from separate sources. Further distinctions are seen within the trends of the Pennsylvanian units, implying variation in eastern interior sediment dispersal in the Early Pennsylvanian. These fluctuations in provenance may be a result of differential exhumation from a single source area or migration of an axial river and subsequent drainage of different source areas as a result of Alleghanian orogenesis.

ACKNOWLEDGEMENTS

This Master's thesis was completed due to a combination of hard work, valuable input, and unwavering support by those around me. I am sincerely grateful for the valuable insight, guidance, and expertise provided to me by Dr. Brian Hampton and the other members of my committee. Particularly, I would like to thank Brian Hampton for providing the resources, knowledge, and an occasional push in the right direction, all of which have allowed me to develop as a geologist and scientific researcher; Dr. Michael Velbel, for his unwavering dedication to the further development of my critical thinking skills and technical understanding, as well as his constant support; and to Dr. Kazuya Fujita for his academic support and confidence. I would also like to thank George Gehrels and Mark Pecha for their lab support during the processing of our samples at the Arizona Laserchron Center.

Gratitude is extended to Michigan State University and The Michigan Basin Geological Society for financial support during this project, which has allowed me to conduct field work, analyze samples, and travel to meetings and conferences for research presentations.

Support and friendship from friends and family during this project was invaluable. I would like to thank my wife Stephanie for her patience and motivation, my parents for their understanding and support, Dan Barkley, Devon Glass, Emily Movesian, Kraig Koroleski, Cody MacDonald, and Leslie Mikesell for necessary distractions, warm and unrelated conversation, and friendship during these last two years.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 INTRODUCTION

Much of the eastern half of North America can be divided into three generally-defined tectonic provinces that include: (1) structurally-deformed Mesoproterozoic and Paleozoic components of the Grenville and Appalachian-Ouachita orogenic belts, (2) relatively undeformed Paleozoic strata of the Appalachian and Ouachita foreland basins and adjacent Neoproterozoic–Paleozoic intracratonic basins (Illinois and Michigan Basins), and (3) Archean-age rocks of the Canadian Shield and adjacent, fringing Paleoproterozoic–Neoproterozoic orogenic belts (e.g., Trans Hudson/Penokean, Central Plains, and Keweenawan) (Figure 1.1). While each of these regions has received a considerable amount of study in terms of their geologic history, the driving mechanisms responsible for the origin and evolution of many of the intracratonic basins of the eastern continental interior and their relationship with adjacent tectonic provinces are a topic of ongoing debate (Potter and Siever, 1956; Siever and Potter, 1956; Potter and Pryor, 1961; Shideler, 1969; Sleep, 1978; Sleep et al., 1980; Nunn, 1984; Quinlan and Beaumont, 1984; Tankard, 1986; Root and Onasch, 1999; Ettensohn, 2004). In the case of the Michigan Basin, subsidence and depositional history are recorded by a discontinuous stratigraphic record of mixed carbonate, evaporitic, and clastic sedimentation throughout much of the Paleozoic. In the Early Mississippian, a transition to siliciclastic dominated deposition began, which continued through the remainder of the Carboniferous. The focus of this study is on a suite of these Mississippian–Pennsylvanian, fluvial-deltaic, and nearshore marine, siliciclastic strata that are sporadically exposed throughout parts of southern Michigan and make up the uppermost parts of the Michigan Basin.

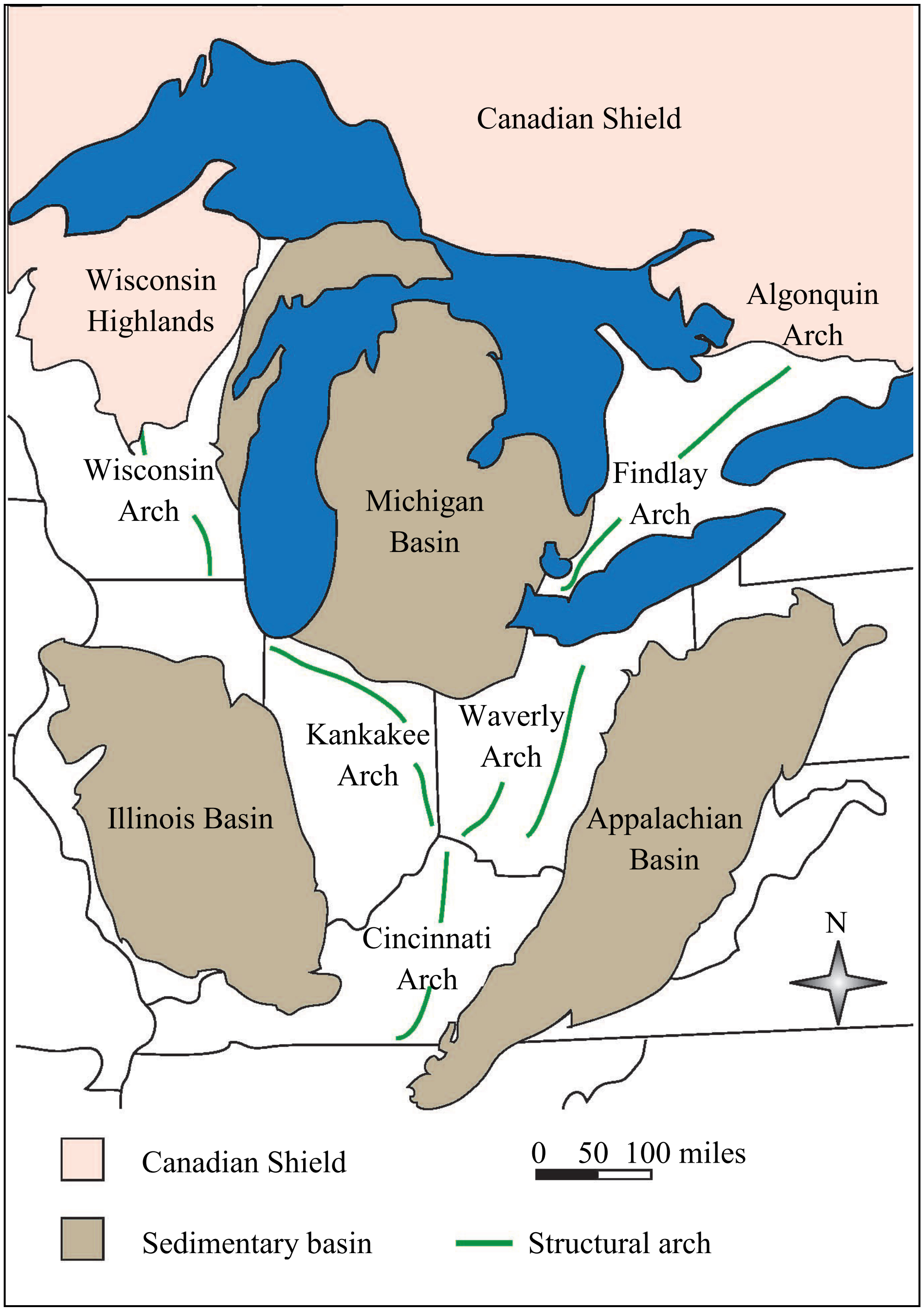

Figure 1.1: Generalized structural map showing significant North American Precambrian-Paleozoic tectonic provinces. The Michigan Basin is bordered by the Canadian Shield to north and the Appalachian foreland to the east. The Appalachian foreland basin, Illinois basin, and Michigan Basin are separated by a series of structural arches that may have once topographically isolated the basins from each other (Tankard, 1986; Faill, 1997, 1998; Ettensohn, 2004, 2008). Modified from Potter and Siever, 1956. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this thesis.

The Michigan Basin presently holds a somewhat spatially unique location in the continental interior of eastern North America in that it occupies both the southern margin of theCanadian Shield as well as the westernmost, distal margin of the Appalachian foreland (Figure 1.1). Carboniferous strata of the Michigan Basin preserve the strata that may have been influenced by mountain building (e.g., Acadian and Alleghanian orogenies) as well as eustatic sea level rise related to the Kaskaskian and Absarokan stratigraphic sequences (as well as the sub-Absaroka unconformity). Previous work to identify the regional sediment dispersal trends in the Michigan and Illinois basins has resulted in a generally-agreed upon (informally-accepted) model reflecting flow from the east-northeast during the Mississippian and shifting to a northeast to the southwest flow during the Pennsylvanian (e.g., Potter and Siever, 1956; Potter and Pryor, 1961; Shideler, 1969; Ettensohn, 2004), with the inference that sediment transport to these basins is controlled largely by Late Paleozoic erosion and exhumation in the Appalachians with possible minor flow and detrital contributions to the basin from continental interior regions. At present, however, the Michigan Basin is separated from both the Appalachian foreland and Illinois basin by a series of arches (e.g., Cincinnati, Findlay, Kankakee arches) that extend for several hundred kilometers along the margins of these basins (Figure 1.1). Entrenchment of streams through these arches (Swann, 1964; Potter and Siever, 1956) and submergent conditions (Ettensohn, 2004) did not allow complete topographic isolation of the continental interior during Mississippian-Pennsylvanian time. It is unclear exactly how tectonic activity on the eastern margin of North America has influenced nearby intercontinental features like the Michigan Basin, as well as sediment dispersal paths across eastern North America (Swann, 1963, 1964; Quinlan and Beaumont, 1984; Ingersoll, 1988; Howell and van der Pluijm, 1990, 1999).

The primary goals of this study are to address provenance by applying new sandstone modal compositions, heavy mineral meta-analysis, and new U-Pb detrital zircon geochronology data to provide a better understanding of upsection trends in provenance from Mississippian–Pennsylvanian strata of the Michigan Basin. At the largest scale, this study will provide first-order constraints on the late Paleozoic sediment dispersal history and regional paleodrainage networks that existed in easternmost Laurentia and the continental interior of eastern North America during the late-stage development of the Michigan Basin.

1.2 GEOLOGIC BACKGROUND

Early in the Mississippian, the Laurentian continent had wandered to equatorial latitudes and was in a period of post Acadian quiescence (Figure 1.2) (Ziegler et al., 1979; Rast and Skehan, 1984; Scotese, 2002; Blakely, 2011). In Laurentia, post-Acadian sedimentation continued encroaching on the less affected interior areas adjacent to the margin (Tankard, 1986; Root and Onasch, 1990, 1999; Faill, 1997(a),(b); Ettensohn, 2004). The initiation of Alleghanian orogenesis occurred in the Late Mississippian as the Iapetus Ocean was closed and the Laurentia – Gondwana collision ensued (Figure 1.3). Deformation is thought to have extended into the eastern continental interior affecting the Great Lakes region, including the Illinois basin, axial river systems draining into the continental interior, and structural arch systems previously uplifted during the early stages of Appalachian orogenesis (Swann, 1963, 1964; Tankard, 1986; Root and Onasch, 1990, 1999; Faill, 1997(a), (b), 1998).

Mississippian strata within the Michigan Basin are thought to represent siliclastic sedimentation during periods of tectonic quiescence and orogenesis (initial stages of the

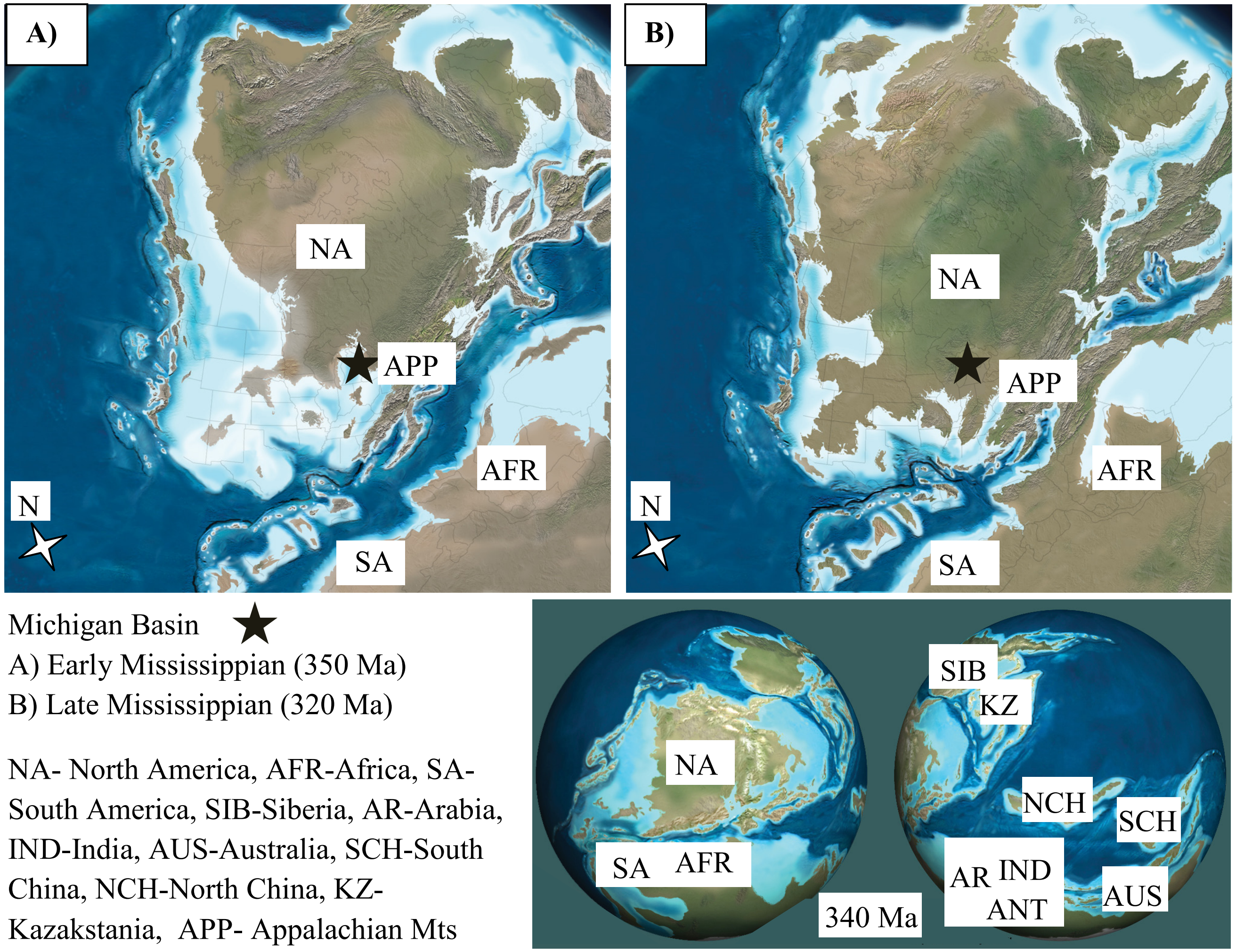

Figure 1.2: Mississippian paleogeography of the Laurentian continent. The Michigan Basin is located at the brown star. **A)** Early Mississippian: Regions uplifted during the Acadian are shedding sediment which is transported to the west-southwest. **B)** Late Mississippian: Alleghanian orogenesis begins as Laurentia and Gondwana collide. Deformation to the north shifts drainage patterns to a more southwesterly trend. Modified from Blakey, 2011.

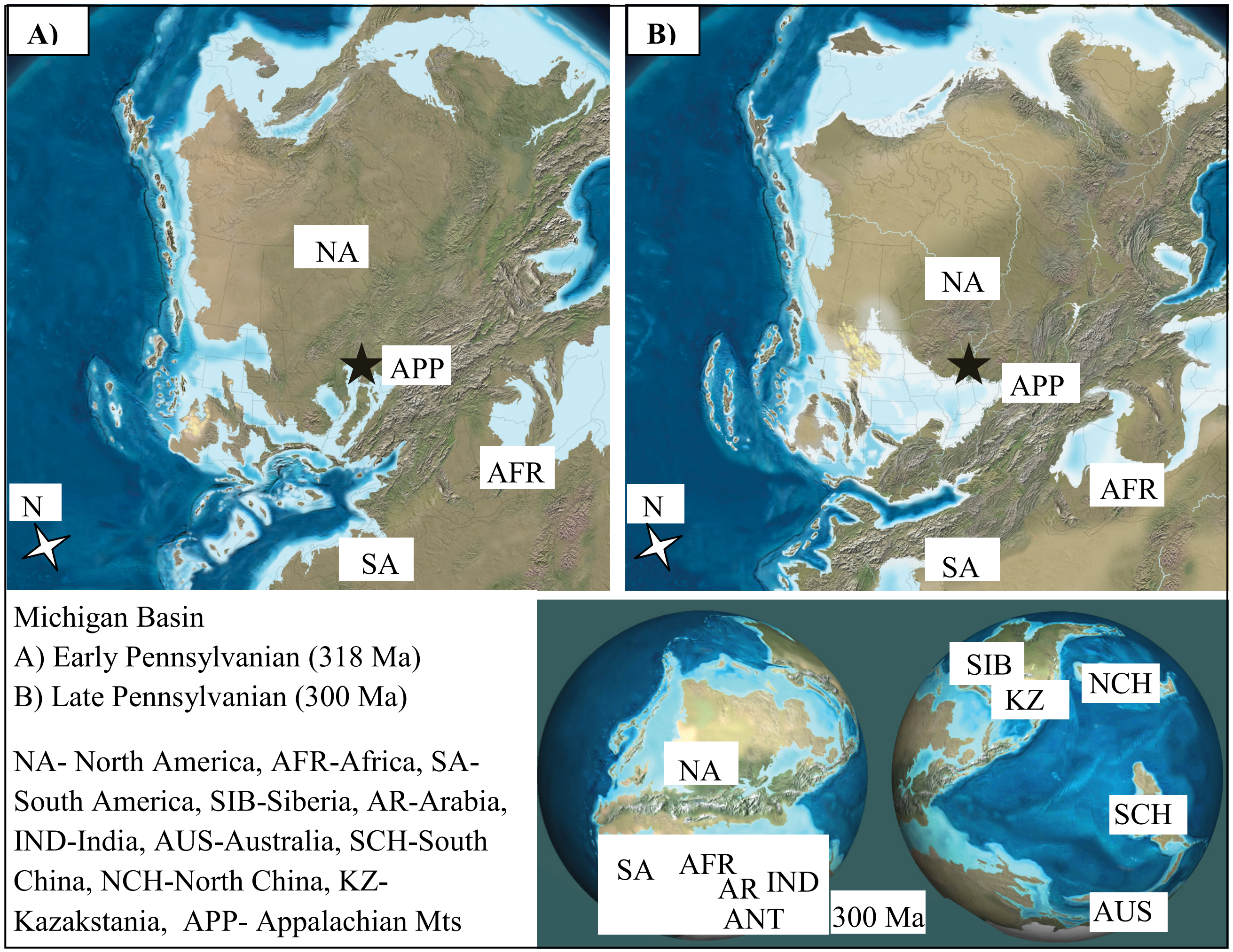

Figure 1.3: Pennsylvanian paleogeography of Laurentian continent. **A)** Early Pennsylvanian: Alleghanian orogenesis initiates and deformation is seen in the continental interior as arches uplift and drainage patterns are altered. **B)** Late Early Pennsylvanian: As the latter stages of mountain building occur uplift is further developed throughout the continental interior. Modified from Blakely, 2011.

Alleghenian orogeny) (figure 1.2 and 1.3). The Acadian orogeny (Devonian) precedes the influx of siliciclastic detritus from the east-northeast into the Michigan Basin, as well as the Illinois basin, by approximately 30 million years. Late Mississippian and Pennsylvanian strata are coeval with the Alleghenian orogeny (~320 -250 Ma) (Potter and Pryor, 1961; Park et al., 2010) (Figure 1.4). The Late Mississippian transition to coarse siliciclastic dominated stratigraphy is one of the first occurrences of coarse clastic dominated formations in the Michigan Basin since the Ordovician (Stearns, 1933; Monnett, 1948; Potter and Pryor, 1961; Westjohn and Weaver, 1998; Catacosinos et al., 2001). Similar clastic lithofacies are present in the Illinois and Appalachian basins and are Kaskaskia-Absaroka equivalents as well suggesting a connection between the basins (Potter and Siever, 1956; Potter and Pryor, 1961). At present these basins are geographically bounded by a series of structural arches and are thought to have topographically isolated the basin in the late Paleozoic (Quinlan and Beaumont, 1984; Tankard, 1986; Faill, 1997, 1998; Root and Onasch, 1999; Scotese, 2002; Blakely, 2011) but may have also been episodically submergent allowing inter-basin communication (Ettensohn, 2004) (Figure 1.1 and 1.3).

STRATIGRAPHIC OVERVIEW

Cambrian to Early Mississippian sedimentary rocks in the Michigan Basin consist of generally marine shale and carbonate strata. A marked transition to siliciclastic-dominated sedimentation occurs during the Early Mississippian and is interpreted as a result of the closing events of the Acadian orogeny (Stearns, 1933; Monnett, 1948; Swann, 1963, 1964; Ells, 1979; Catacosinos et al., 2001) (Figure 1.4 & 1.5). Occurrences of siliciclastic strata continue upsection in the basin through much of the Pennsylvanian (Catacosinos et al., 2001). Mississippian strata within the Michigan Basin show a transitional period from marine shale and

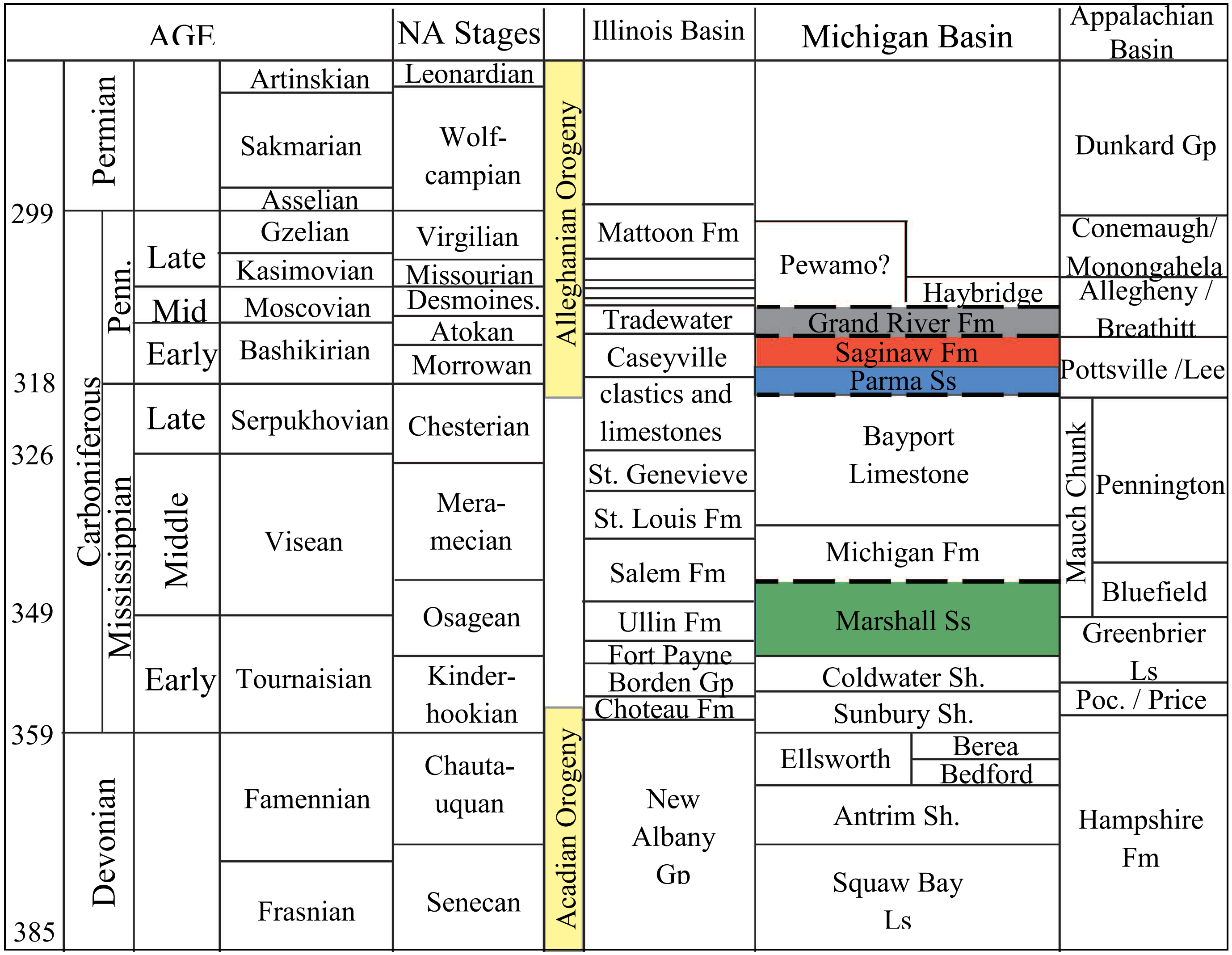

Figure 1.4: Generalized stratigraphic column across the Michigan Basin, Illinois basin, and Appalachian foreland basin (Miller and Garner, 1953, 1955; Driscoll, 1965, 1969; Landing and Wardlaw, 1981; Johnson et al. 1985; Diecchio 1986; Fichter 1986; Hatcher 1987, 2005; Johnson 1987; Harrel et al., 1991 Ettensohn 1994; Aleinikoff et al. 1995; Catacosinos et al., 2001; Eriksson et al., 2004; Swezy, 2009. Unconformities are dashed lines and are only included for the Michigan Basin.

carbonates to siliciclastic sedimentation. Early Mississippian marine shale is interbedded with fine sandstone and together is interpreted to reflect marine sedimentation in depositional systems that were characterized by low energy environments (Monnett, 1948). The remainder of the Carboniferous section contains primarily sandstones, occasionally interbedded with anhydrites, limestone, shale, and even coal in particular strata.

Marshall Sandstone

The Marshall Sandstone is one of the first sandstone dominated units in the Carboniferous. Though much of the formation contains a meager fossil record, certain units contain a diverse macrofauna and flora placing the Marshall in the Osagean period of the Early Mississippian (Miller and Garner, 1953, 1955; Driscoll, 1965, 1969; Harrel et al., 1991). Recent palynology also defines the Marshall as Osagean (Richardson, 2006) Typically, this early Mississippian unit is 60-120 meters of fine-medium grained sandstone, interbedded with red beds, dolomite, siltstone, shale, and occasional limestone (figure 1.6 &1.7) (Stearns, 1933; Monnett, 1948; Ells, 1979; Westjohn and Weaver, 1998). Fossil assemblages and sedimentological characteristics typically define the environment of deposition as marine (Stearns, 1933; Monnett, 1948; Harrell et al., 1991), with a fluvial component (Potter and Pryor, 1961). Cross-bedding measurements from the Marshall indicate a northeast to southwest sediment dispersal pattern during the deposition of the Marshall, indicating Appalachian origin (Potter and Pryor, 1961). Studies from the Appalachian region indicate southeast to northwest paleoflow potentially reaching the Michigan Basin during this time as well (Pelletier, 1958; Kittredge and Malcuit, 1958; Brezinski, 1999; Ettensohn, 2004; Matchen and Kamer, 2006). Though sediment dispersal suggests NE-SW transportation, distinctions between the eastern and

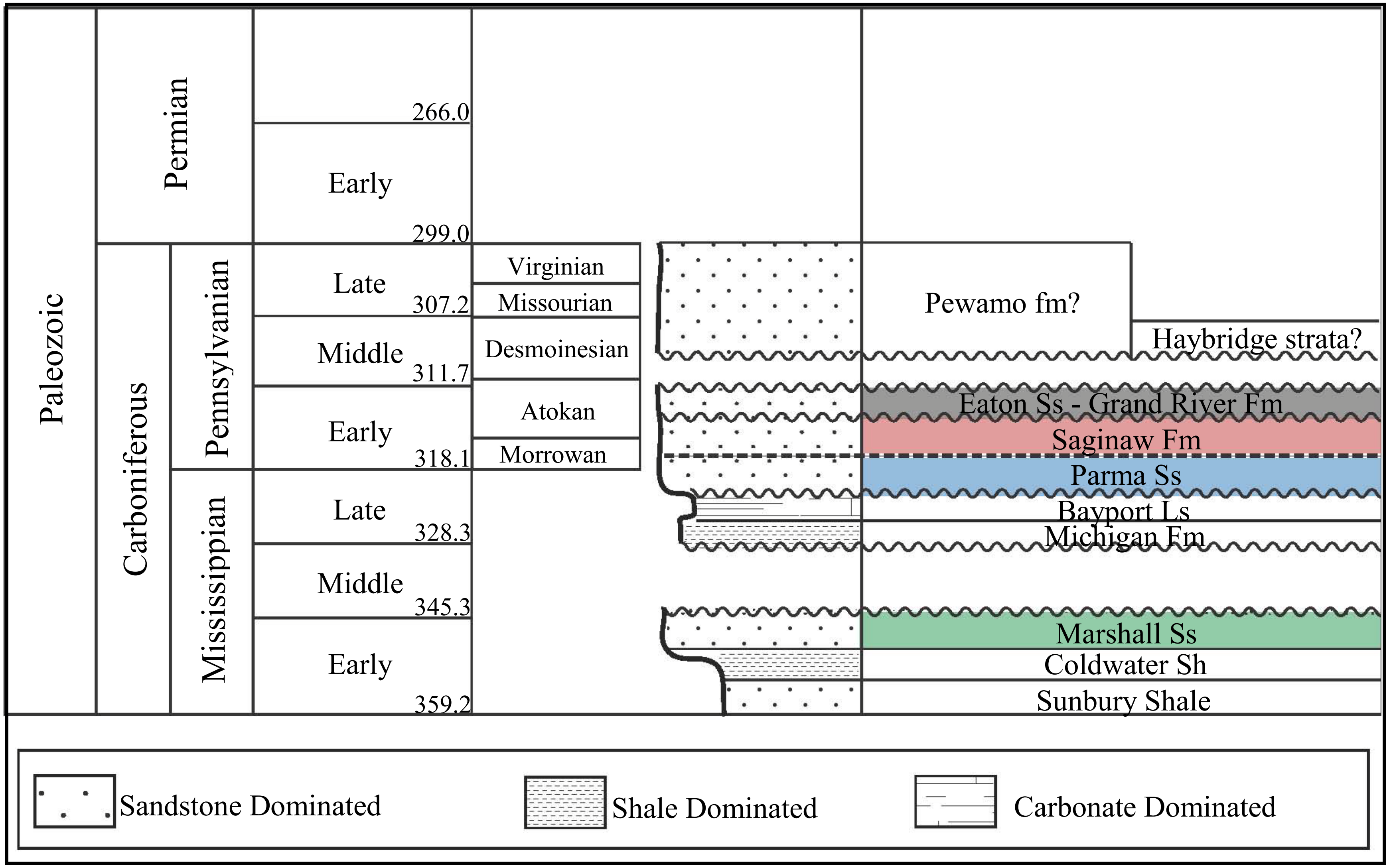

Figure 1.5: Mississippian and Pennsylvanian coarse siliciclastic dominated strata of the Michigan Basin. Colors denote the Marshall Sandstone, Parma Sandstone, Saginaw Formation, and Eaton Sandstone of the Grand River formation as the focus of this study. Colors are used consistently on all stratigraphic columns and ternary plots. Unconformities are denoted by wavy lines. Modified from Catacosinos et al., 2000.

western Marshall Sandstone units are made based heavy mineral assemblages, which suggest more local sources to the west and north (Stearns, 1933; Monnett, 1948).

The unit is typically divided by a five meter thick shale-siltstone sequence creating two members: The Lower Marshall Sandstone and the Napoleon (Upper) Member. Both are laterally extensive sandstones with diverse heavy mineral suites. Zircon, tourmaline, and garnet are most common while less persistent minerals (Pettijohn, 1941) like actinolite, epidote, and hornblende are also present in varying abundances and weathered states (Stearns 1933; Monnett, 1948). The unit overlying the Napoleon member is spatially variable; in places it may be a continuous section including the Michigan Formation, overlain by the Late Mississippian Bayport limestone, and Early Pennsylvanian Parma Sandstone, while other places may see unconformable relations and have the Parma Sandstone directly overlying the Marshall. These unconformable surfaces are thought to represent the continent scale sub-Absaroka unconformity which ends the Kaskaskia sequence (Sloss, 1963) and Mississippian section (Westjohn and Weaver, 1998; Catacosinos et al., 2001).

Parma Sandstone

Overlying the sub-Absaroka unconformity (Sloss, 1963) is a laterally discontinuous quartz arenite informally referred to as the Parma Sandstone. The unit is described as 0-60 meters of white sandstone containing primarily quartz, with muscovite, zircon, and tourmaline as heavy minerals (Figure 1.8) (Kelly, 1936; Cohee et al. 1951, Westjohn and Weaver, 1998; Catacosinos et al., 2001). Several thin black shale units are present in the section. Currently, the Parma is interpreted as a separate unit representing the earliest Pennsylvanian (Morrowan) deposits in the Michigan Basin and possibly including Late Mississippian (Meramecian) age deposits as well (Kelly, 1936, Potter and Siever, 1956; Siever and Potter, 1956; Wanless and Shideler, 1975; Vugrinovich, 1984; Westjohn and Weaver, 1998). Cross bedding within the unit reveals northeast to southwest sediment dispersal patterns (Kelly, 1936; Potter and Siever, 1956) that is consistent with the rest of the Early Pennsylvanian section (Shideler, 1969). Deposition of the compositionally mature sediment is thought to have occurred as part of littoral or shallow marine shelf or near shore marine environment based on compositional maturity (Shideler, 1969). Little else has been studied in terms of the geological nature of the Parma.

Saginaw Formation

The Saginaw Formation is a series of cyclically deposited carbonate, siltstone, coal, and sandstone, generally interpreted as an Early Pennsylvanian (Figure 1.9) (Kelly, 1933, 1936; Wanless and Shideler, 1975) marginal marine to fluvial-deltaic environment with components of high energy lowlands and local littoral sheets (Shideler, 1969; Velbel and Brandt, 1989). More specifically, the Saginaw is well constrained as Atokan based on conodont species present in the Saginaw's Verne Limestone member (Landing and Wardlaw, 1981). Sediment dispersal in the Saginaw is consistently interpreted as northeast to southwest by sediment isopachs (Shideler, 1969; Fisher, 1988) and cross-bedding measurements (Potter and Pryor, 1961). Thickness of the Saginaw is generally thought to be 120 meters but may extend to 163 meters (Kelly, 1936; Milstein, 1987).

Grand River Formation – Eaton Sandstone

Unconformably overlying the Saginaw Formation is the Grand River Group. The Eaton Sandstone member of the Grand River group sits at the top of the Pennsylvanian section but which epoch is belongs to is poorly understood. The Eaton has long been placed into the Late

Early Pennsylvanian age based on lithologic similarities with the Conemaugh Group of the Appalachian basin (Kelly, 1936). Palynology data is interpreted as Atokan based on comparisons to stratigraphically equivalent units in Iowa, though major Atokan palynologic indicators are absent (Ravn and Fitzgerald, 1982; Ravn, personal communication, 2006). Inclusion of the Eaton into the Atokan time period would make it the same age as the Saginaw Formation, as suggested by Benison et al. (2011). The unit generally contains ~30 meters of coarse, rust-orange colored, massively bedded sandstone with muscovite, zircon, and tourmaline as the dominant heavy minerals (Figure 1.10) (Kelly, 1936). Derivation of the sediment contained in the Eaton Sandstone is less well understood. Paleocurrent data showing flow to the north (Martin, 1982) has been interpreted as a meander in a fluvial system at a high angle to normal Pennsylvanian flow (northeast – southwest) (Velbel and Brandt, 1989).

The remainder of the section in the Michigan Basin consists of laterally discontinuous red beds belonging to the Jurassic (?) Ionia formation and Pleistocene glacial deposits (Catacosinos et al., 2001). Recent debates centered on palynology place the Ionia anywhere from late Early Pennsylvanian to Cretaceous (Cross, 1998; Knapp et al., 2007; Benison et al., 2009; Dickinson et al., 2010).

1.3 RESEARCH QUESTIONS

This study aims to constrain provenance and sediment dispersal patterns within Upper Paleozoic strata in the Michigan Basin. Mississippian and Pennsylvanian coarse clastics of the Michigan Basin have been included in several provenance related studies (Potter and Siever, 1956; Siever and Potter, 1956; Potter and Pryor, 1961; Price and Velbel, 2000); however, little is know about the relationship between the units and the depositional systems they represent. The combination of detrital framework modes, heavy mineral analysis, and detrital zircon geochronology will contribute three independent data sets to help constrain the provenance data set of the Michigan Basin. Based on our current understanding of the provenance and sediment dispersal trends from the continental interior, these new contributions will provide a first order test of the following hypotheses:

1. Provenance trends from Mississippian-Pennsylvanian clastic strata of the Michigan Basin are relatively similar and reflect sediment contributions from one primary source area (possibly the Appalachian orogen) throughout the Carboniferous. Modal composition for this hypothesis would likely show recycled orogen components while detrital zircon ages would typically correlate with Precambrian-Mississippian orogenic events (Granite/ Rhyolite, Grenville, Taconic/Acadian/Alleghanian) and could potentially include minor amounts of continental sediment of the Superior province that was included in Precambrian events. These trends would be consistent across all units.
2. Provenance trends from Mississippian strata are compositionally distinct from Pennsylvanian strata and may reflect at least one change in detrital contribution and sediment dispersal patterns during the Carboniferous. Alteration of sediment dispersal systems due to Alleghanian uplift would be reflected in modal composition as recycled orogenic sources as well as a larger continental block component. Detrital zircons ages from Eastern Laurentia should reflect Mesoproterozoic-Mississippian while sediment from the Canadian Shield and associated provinces would have Archean-Paleoproterozoic ages.

3. Provenance trends from each individual Mississippian-Pennsylvanian stratigraphic unit are compositionally distinct from each other and may reflect one or more changes in detrital contributions and ever-evolving sediment dispersal patterns throughout the Carboniferous. Episodic uplift throughout the Pennsylvanian created differential inputs of Appalachian sediment to the interior region creating what recurring trends in the data set. Data trends coeval with uplift are expected to reflect the provenance of uplifted Appalachian strata, while relaxation phases of the orogeny are expected to allow increased input from local sources.

1.4 GENERAL METHODS

This study employs sandstone modal composition, heavy mineral analysis, and U-Pb detrital zircon geochronology to make distinctions between Mississippian and Pennsylvanian sandstones in the Michigan Basin. Standard petrographic thin sections were created from 52 fine-coarse grained sandstone samples that were collected from exposed outcrop of the Marshall Sandstone, Parma Sandstone, Saginaw Formation, and Eaton Sandstone. Thin sections were stained for potassium and calcium feldspar and point-counted using a modified Gazzi-Dickinson method (Dickinson, 1970; Ingersolll et al., 1984). Modal compositions were determined by identifying 400 grains per thin section. Point count parameters are seen in Table 2.1 and raw data is included in Appendix A. Recalculated QFL percentages are presented in Table 2.2 and are based on procedures outlined by Ingersolll et al. (1984) and Dickinson (1985).

Heavy mineral analysis of the Mississppian and Pennsylvanian strata in this study was done by compiling previously reported mineral occurences. The list of minerals is that of Pettijohn (1941) which is ranked by persistence. Common environments of formation are given for further interpretation of initial source rock types. Mineral assemblages containing primarily high persistence minerals are classified as compositionally mature, having undergone significant attrition of minerals. Mineral assemblages containing minerals with a range of persistance were typically classified as compositionally immature. Maturity in the heavy mineral suite is not necessarily reflected in the other data sets.

U-Pb detrital zircon geochronology was done using traditional methods of crushing and grinding, followed by density separation using a Wilfley table, heavy liquids, and a Frantz magnetic separator. Processing resulted in a final sample composed entirely of zircon grains. Most or all of the zircons present (10's – 100's) were mounted into a 1" epoxy mount with fragments of Paleozoic (~419 Ma) zircons (R33) and sanded down to a depth of ~20 microns. They were then polished, imaged, and cleaned prior to analysis.

U-Pb detrital zircon geochronology was completed using laser ablation inductively coupled plasma mass spetrometry (LA-ICPMS) at the Arizona Laserchron Center (Gehrels et al., 2006, 2008). This process involved ablation of a 30 micron wide, 15 micron deep, spot on a zircon grain, using a New Wave UP193HE Excimer laser (193 nm wavelength). Ablated material was carried in helium into the plasma source of a Nu HR ICPMS, equipped with a flight tube wide enough to simultaneously measure U, Th, and Pb isotopes. Measurements were taken with Faraday detectors in static mode using 3e11 ohm resistors for ^{238}U, ^{232}Th, ^{208}Pb-^{206}Pb, and a discrete dynode ion counter for ^{204}Pb. Yield ions are typically ~0.8 mv per ppm. Analyses consist of a 12 second integration on peaks with the laser off (to determine background), 15 one second integrations with the laser firing, and a 30 second delay to remove remaining sample from the equipment and prepare for the next sample.

Error in each analysis occurs in determining $^{206}Pb/^{238}U$ and $^{206}Pb/^{204}Pb$, typically resulting in ~1-2% error of the $^{206}Pb/^{238}U$ age (at 2σ). Errors in the measurement of $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{204}Pb$ result in ~1-2% uncertainty (at 2σ) in grains ages over 1.0 Ga, and increase proportionally with decreasing age, due to to the low intensity of the ^{207}Pb signal. It is typical for this shift in precison to occur at the 1.0 Ga age for $^{206}Pb/^{238}U$ and $^{206}Pb/^{207}Pb$ analyses.

Correction of Pb is done by using the measured ^{204}Pb and assuming initial Pb composition per Stacey and Kramers (1975) using uncertainties of 1.0 for $^{206}Pb/^{204}Pb$ and 0.3 for $^{207}Pb/^{204}Pb$. ^{204}Hg does not affect the analysis due to its inclusion in the background measurements prior to ablation (effectively subtracting ^{204}Hg and ^{204}Pb) and low concentrations in argon gas (background ^{204}Hg = ~300 CPS).

Inter-element fractionation of Pb/U is generally ~5%, while apparent fractionation of Pb isotopes is typically <0.2%. Mid-sample measures of a standard zircon (known age of 419.3 ±.4 Ma (2σ error) were taken after every 5 experimental measurements, and used to correct for these fractionations. Uncertainty is ~1-2% (2σ) for both $^{206}Pb/^{238}U$ and $^{206}Pb/^{207}Pb$ ages. Concentrations for U and Th are calibrated relative to the standard R-33 samples.

Raw analytical data are reported in Appendix D, with uncertainties at the 1σ level, including only measurement errors. Discordant analyses (30% by comparison of $^{206}Pb/^{238}U$ and $^{206}Pb/^{207}Pb$ ages) are not considered. Resultant interpretations of age are shown in relative probability plots (Ludwig, 2008) in Chapter 4. Normal distribution of age and uncertainty is depicted in these plots as a single curve.

Sample Locations

Limited outcrop exposure is available in the Carboniferous strata of the Michigan Basin, however; several field locations have been identified for study within the lower peninsula (Figure 1.6).

MIB-062510-01 (N 44° 01’ 59” ,W 83° 00’ 07” W): Access to Clancy and Son’s quarry was granted per the owner and provided us with Marshall Sandstone. This quarry is in Port Austin and exposes Lower Marshall Sandstone along the southern wall.

MIB-062510-02 (N 44° 02’ 36”, W 82° 52’ 43”) Ten miles to the east in Grindstone City, a road outcrop exists along M-25 between the two outlets of Lakeshore drive. The presence of bedrock is discernable due to a hill sitting in the middle of an agriculture expanse. The strata exposed here are Lower Marshall Sandstone as well.

MIB-070810-01 (N 42° 17’ 25”, W 84° 24’ 09”): An outcrop along exit 139 on I-94 in Jackson, provided coarse grained sandstone from the Parma Sandstone.

MIB-072510-01 (N 42° 45’ 45”, W 84° 45’ 50”): This was collected from Fitzgerald Park in Eaton County from an outcrop of interbedded fine grained sandstone, siltstone, and coal.

MIB-072010-01 (N 42° 46’ 02”, W 84° 45’ 57”): This was a sample of medium grained sandstone, collected from Lincoln Brick Park in Eaton County.

Samples used for modal composition thin sections were taken from these outcrops as well, typically including 6-10 samples per area spanning the vertical and horizontal extent of the outcrop. Further thin section samples were taken by Michael Velbel as part of a previous study.

Samples from the Marshall Sandstone, Parma Sandstone, and Saginaw Formation come from quarries in Owosso,MI and outcrops near Kalamazoo, MI.

1.5 SUMMARY

The provenance of Carboniferous coarse clastics of the Michigan Basin is generally accepted as having been derived from the northeast, possibly an Appalachian source, based on sediment dispersal patterns and paleocurrent trends from much of the Pennsylvanian strata of the Michigan and Illinois basins (Kelly, 1936; Potter and Siever, 1956; Potter and Pryor, 1961; Shideler, 1969) while others have suggested local sources (Wisconsin Highlands, Huronian Rocks of the southern Canadian Shield, Grenville around the basin; (Stearns, 1933; Monnett, 1948) based on mineral suite correlations. Understanding of when, or if, these potential source areas contributed to sedimentation in the Michigan Basin remains poorly understood. Geographically, structural deformation of eastern North America during the Alleghanian potentially complicates sediment dispersal from the Appalachians across the region. While the structural and topographic Michigan Basin lies between Precambrian provinces of the Canadian Shield and Grenville, and adjacent to the Appalachian foreland, it may be that not all of these sources were contributing detritus throughout the Carboniferous. This project aims to investigate compositional patterns and grain ages trends within the Michigan Basin's Carboniferous coarse clastic strata using detrital framework modes, heavy mineral analysis, and U-Pb detrital zircon geochronology. Detrital framework modes and heavy mineral analysis will help to constrain source rock type, while detrital zircon ages will provide a first order constraint on initial magmatic provinces. Modal composition data sets for the Illinois basin and Appalachian basin have been compiled and will be analyzed to correlate temporal variations in provenance across the basins of the continental interior of eastern North America.

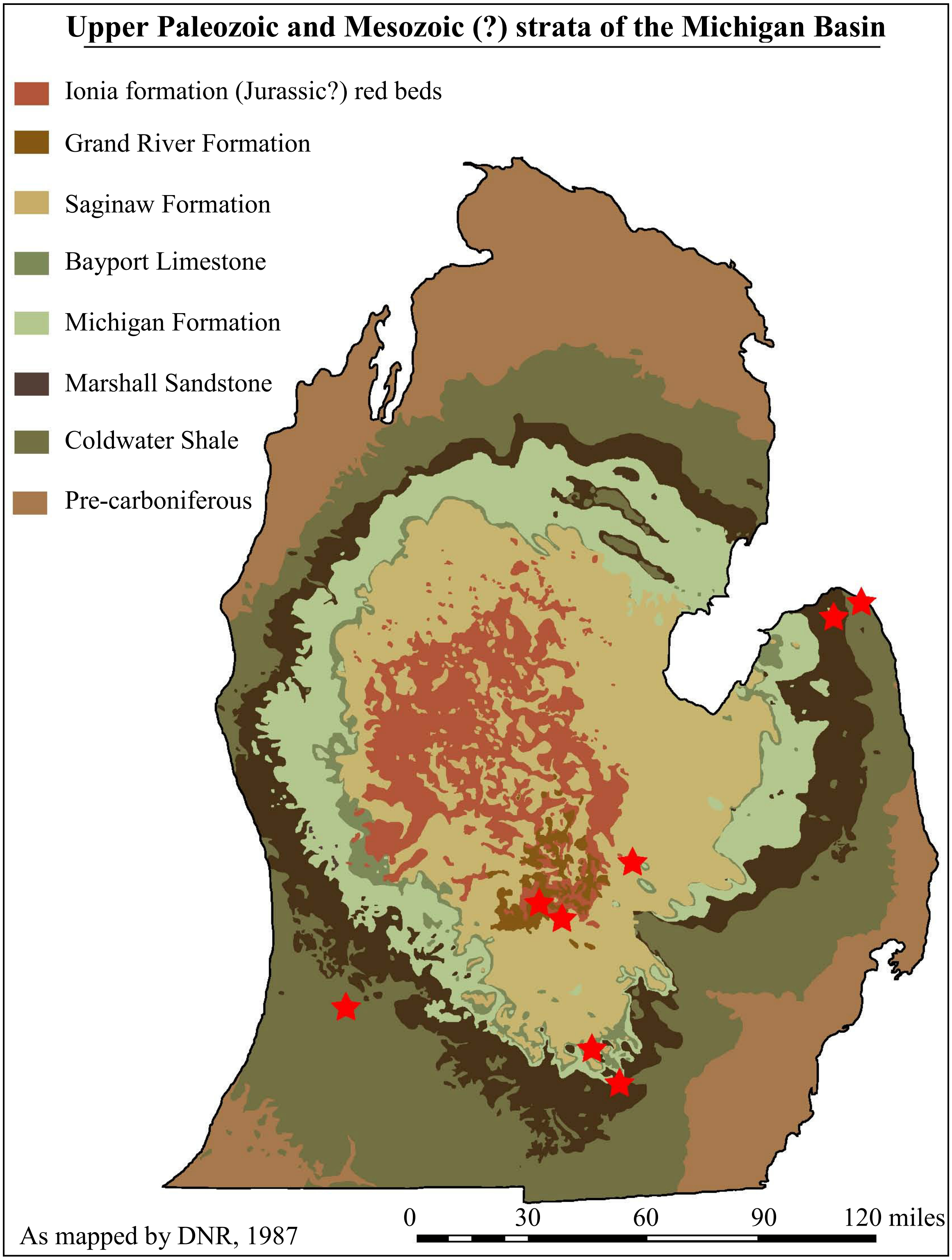

Figure 1.6: Carboniferous geological map of the Michigan Basin. Red stars denote field locations. Small, limited outcrop exposures of Parma Sandstone and Marshall Sandstone are present in areas that are not necessarily shown here, or are covered by location markers. After Milstein, MDNR, 1987.

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CHAPTER 2: DETRITAL FRAMEWORK MODES OF UPPER PALEOZOIC STRATA FROM THE MICHIGAN BASIN: IMPLICATIONS FOR PROVENANCE IN EASTERN NORTH AMERICA

2.1 INTRODUCTION

The occurrence of sedimentary basins is often associated with fundamental tectonic events at plate margins, such as subduction, collision, and even divergence in a rift setting (Dickinson, 1974; Dickinson, 1976; Ingersoll, 1988). These settings are generally well studied and well understood. Basins within the interior of continents are more difficult to explain (Dickinson, 1974; Dickinson, 1976; Middleton, 1980; Lambeck, 1983; Ingersoll, 1988; Baird et al., 1995; Kaminski and Jaupart, 2000). In North America, the subsidence of intracratonic basins such as the Michigan and Illinois basins has been suggested to be driven by thermal activity. The Michigan Basin is thought to have been further affected, by Early-Mid Paleozoic tectonic activity on the eastern margin of North America which caused tilting of adjacent regions demonstrating the reach of structural influence into the interior continent (Howell and van der Pluijm, 1990, 1999). The extent of structural deformation (Quinlan and Beaumont, 1984; Tankard, 1986; Howell and van der Pluijm, 1990; Faill, 1997 (a),(b),1998; Howell and Van der Pluijm, 1999; Root and Onasch, 1999); sedimentation (Thomas, 1988; Ettensohn, 2004), and sediment dispersal patterns (Potter and Siever, 1956; Potter and Pryor, 1961; Shideler, 1969; Graham et al., 1975; Thomas, 1988) are generally well understood along the active margin of North America, and yet, how these processes influence the distal portions of the adjoining continental interior remain unresolved. Understanding how sedimentation and sediment dispersal are affected is crucial to determining the sediment dispersal history of the Mississippian-Pennsylvanian strata in the Michigan Basin.

One of the more enigmatic of these intracratonic basins is the structural, and previously topographic, Michigan Basin (Figure 2.1). Many hypotheses have been presented, including a variety of thermal contraction models (Haxby et al., 1976; Sleep and Sloss, 1980; Cercone, 1984; Nunn and Sleep, 1984; Hamdani et al., 1991) and suggestions for tectonic influence from Appalachian orogenic events (Howell and van der Pluijm, 1990; Howell and van der Pluijm, 1999; Root and Onasch, 1999). Additional structural features in the region include the Waverly arch, Cincinnati arch complex, and the Kankakee arch which surround the southern half of the basin (Figure 2.1). The Waverly arch and Cincinnati arch are thought to be expressions of Taconic and Alleghanian forebulges, while the perpendicular Kankakee arch is attributed to subsidence in the Michigan Basin (Tankard, 1986; Faill, 1997; 1998; Root and Onasch, 1999). The basin is first expressed in Ordovician strata and is interpreted as having undergone initial subsidence during the Ordovician (Nunn et al., 1984). Generally, the Paleozoic strata in the basin are shallow marine deposits which continue until the Upper Paleozoic, when coarse clastic dominated formations are prevalent. Previous studies in the Late Paleozoic Michigan Basin have primarily focused on lithologic characterization and sedimentology, including biostratigraphic relationships (Kelly, 1933, 1936; Stearns, 1933, Hale, 1941 Monnett, 1948; Siever and Potter, 1956; Velbel and Brandt, 1989; Westjohn and Weaver, 1998; Price and Velbel, 2000; Benison and Knapp, 2011) while provenance and geochronology of the clastic stratigraphy remain poorly constrained (Potter and Siever, 1956; Potter and Pryor, 1961, Shideler, 1969). Potential similarities between proximal sources for Carboniferous coarse clastics of the Illinois, Michigan, and Appalachian basins, and the remainder of the eastern continental interior will shed light on sediment dispersal patterns and how eastern margin tectonics may have influenced them.

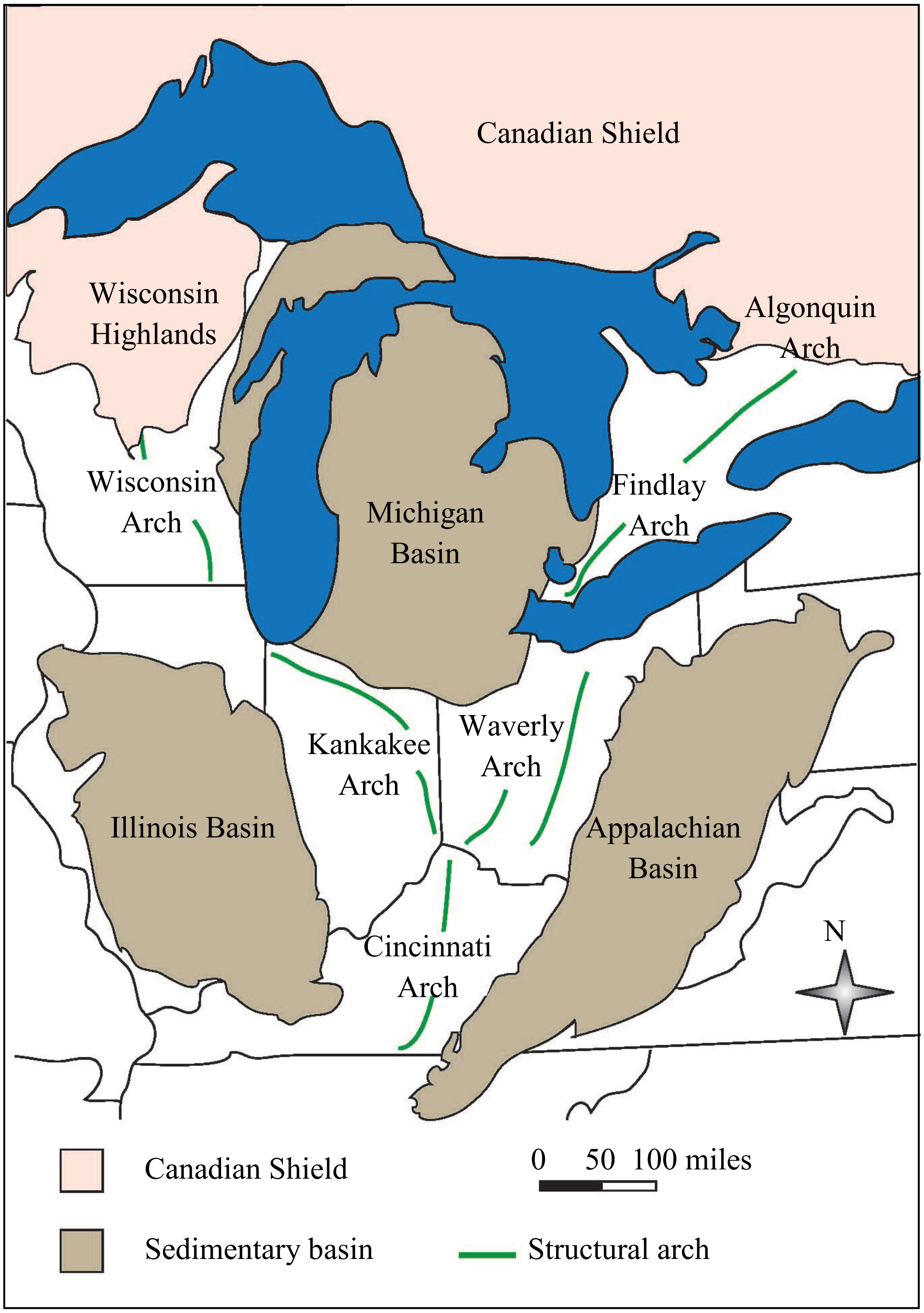

Figure 2.1: Generalized structural map showing significant North American Precambrian-Paleozoic tectonic provinces and orogenic belts. The Michigan Basin is bordered by the Canadian Shield to north and the Appalachian foreland to the east. The Appalachian foreland basin, Illinois basin, and Michigan Basin are separated by a series of structural arches that may have once topographically isolated the basins from each other (Tankard, 1986; Faill, 1997, 1998). Modified from Potter and Siever, 1956.

This study focuses on new analyses of detrital framework modes of Upper Paleozoic (Mississippian-Pennsylvanian) sandstones of the Michigan Basin and interprets provenance, as well as relationships between structural features of the eastern interior and active eastern margin. Comparisons are also made to modal composition trends from previously reported Appalachian and Illinois data.

Previous interpretations of sediment dispersal direction suggest primary proximal sources to the northeast and a secondary source to west for the Michigan Basin's Carboniferous strata (Kelly, 1936; 1948; Potter and Siever, 1956; Siever and Potter, 1956; Potter and Pryor, 1961; Shideler, 1969; Velbel and Brandt, 1989), with minor contributions from nearby sources like the Wisconsin dome and granite-gneiss belts of the Canadian Shield (Stearns, 1933; Monnett, 1948; Wanless, 1955; Potter and Siever, 1956; Siever and Potter, 1956; Potter and Pryor, 1961). The southeastern Canadian Shield is also thought to have been under a Mid-Late Paleozoic sedimentary cover derived from Appalachian orogenesis in the Late Paleozoic (Siever and Potter, 1956), providing an initial Appalachian source of recycled sediment as an alternative to first cycle Canadian Shield and Grenville sources (Siever and Potter, 1956; Sloss, 1988). Though Appalachian sources are typically inferred as the primary source for much of the Carboniferous strata in the Michigan Basin (Potter and Siever, 1956; Siever and Potter, 1956; Potter and Pryor, 1961; Shideler, 1969) a number of other sources from the west to northeast, both local and distant, have also been suggested (Stearns, 1933; Kelly, 1936; Monnett, 1948; Archer and Greb, 1995) and cannot be discounted based on existing data sets.

2.2 GEOLOGICAL OVERVIEW OF THE MICHIGAN BASIN

In the Early Mississippian, the North American continent continued its occupation of tropical, equatorial latitudes (Scotese, 2002; Blakely, 2011). Suturing of the Iapetus Ocean had been completed while the continual closure of the Rheic Ocean to the south occurred as Gondwana moved north toward the Laurentian continent (present day North America) (Figure 2.2). Widespread sedimentation associated with the culmination of Acadian orogenesis extended as far west as the Illinois basin and north into present day Ontario, Canada (Ettensohn, 2004; Blakely, 2011). Mississippian carbonates in the Appalachian, Michigan, and Illinois basins suggest a brief transgression of the epicontinental sea between orogenic events (Catacosinos, 2001; Swezey, 2002, 2009). Initiation of the Alleghany orogeny followed in the Late Mississippian. Continuation of Alleghanian orogenesis (Figure 2.3) and the onset of Ouachitan orogenesis (~300 Ma) on the southern margin of North America tilted the continent to the southwest as a result of crustal loading (Potter and Siever, 1956; Siever and Potter, 1956; Ettensohn, 2004). Orogenesis in these systems peaked in the Pennsylvanian, directly resulting in increased sedimentation into the Appalachian foreland and the continental interior (Thomas, 1988; Thomas et al., 2004; Ettensohn, 2004). Tropical coal swamps thrived in the equatorial climate resulting in massive coal deposits (Moore, 1929; Ziegler et al., 1979).

The Cincinnati-Waverly-Findlay arch system (south and east), the Wisconsin arch (west), Wisconsin Highlands (northwest), and the Kankakee arch (southwest) surround the basin, geographically isolating it from the Illinois basin and Appalachian foreland basin (Figure 2.1). These arches are generally assumed to be part of forebulges associated with Grenville and Taconic collision events (Faill, 1997a; Root and Onasch, 1999). Reactivation of these arches, resulting in topographical isolation from east to west sediment transport, may have been possible

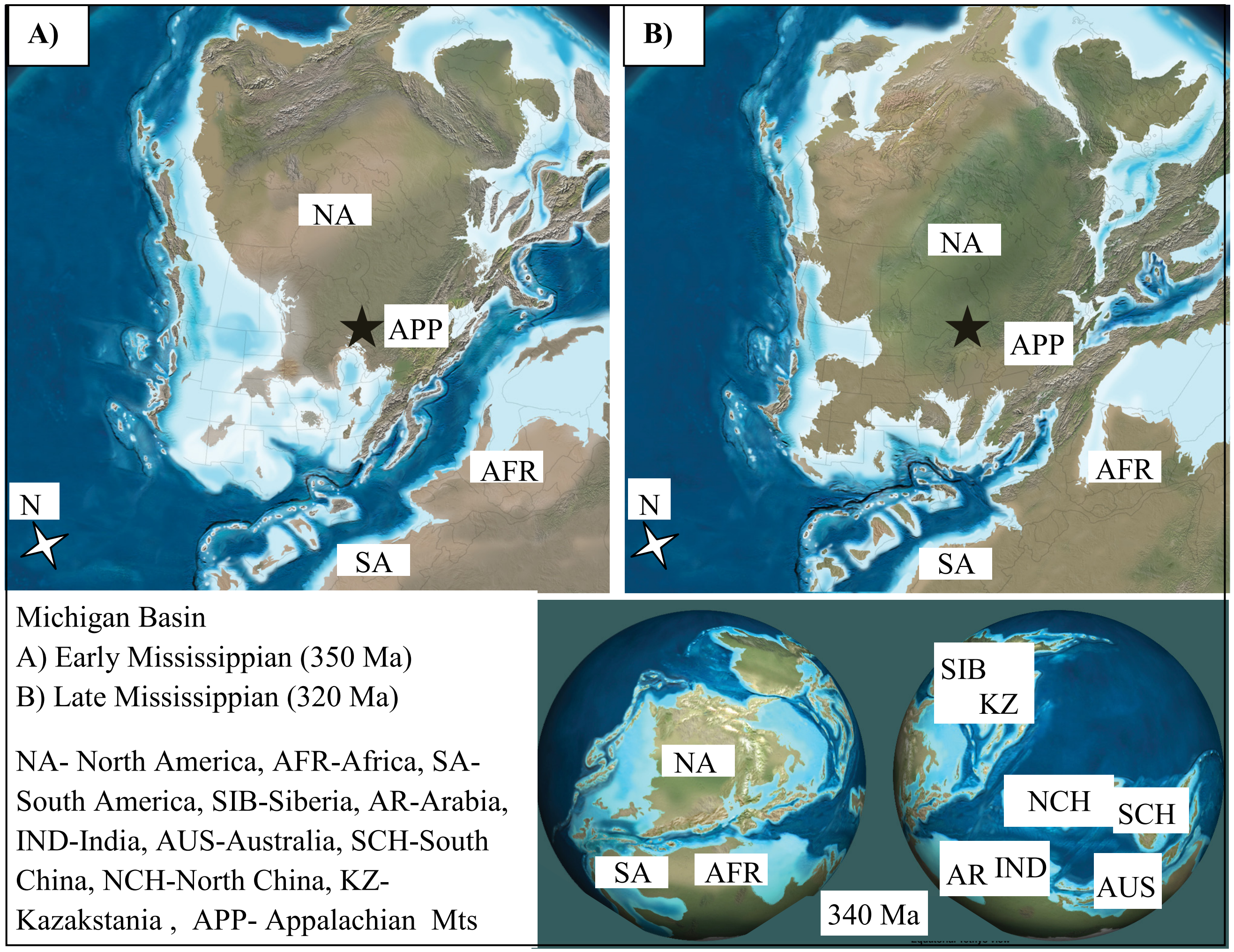

Figure 2.2: Paleogeography of the Mississippian with focus on the North American continent. The Michigan Basin is marked with a brown star. In the Early Mississippian the Acadian orogeny concludes and post-Acadian sedimentation begins. (A) and the onset of Alleghanian orogenesis as Africa collides with North America (B). The Michigan Basin is covered by or near the shallow epicontinental sea. Modified from Scotese, 2002; Blakely, 2011.

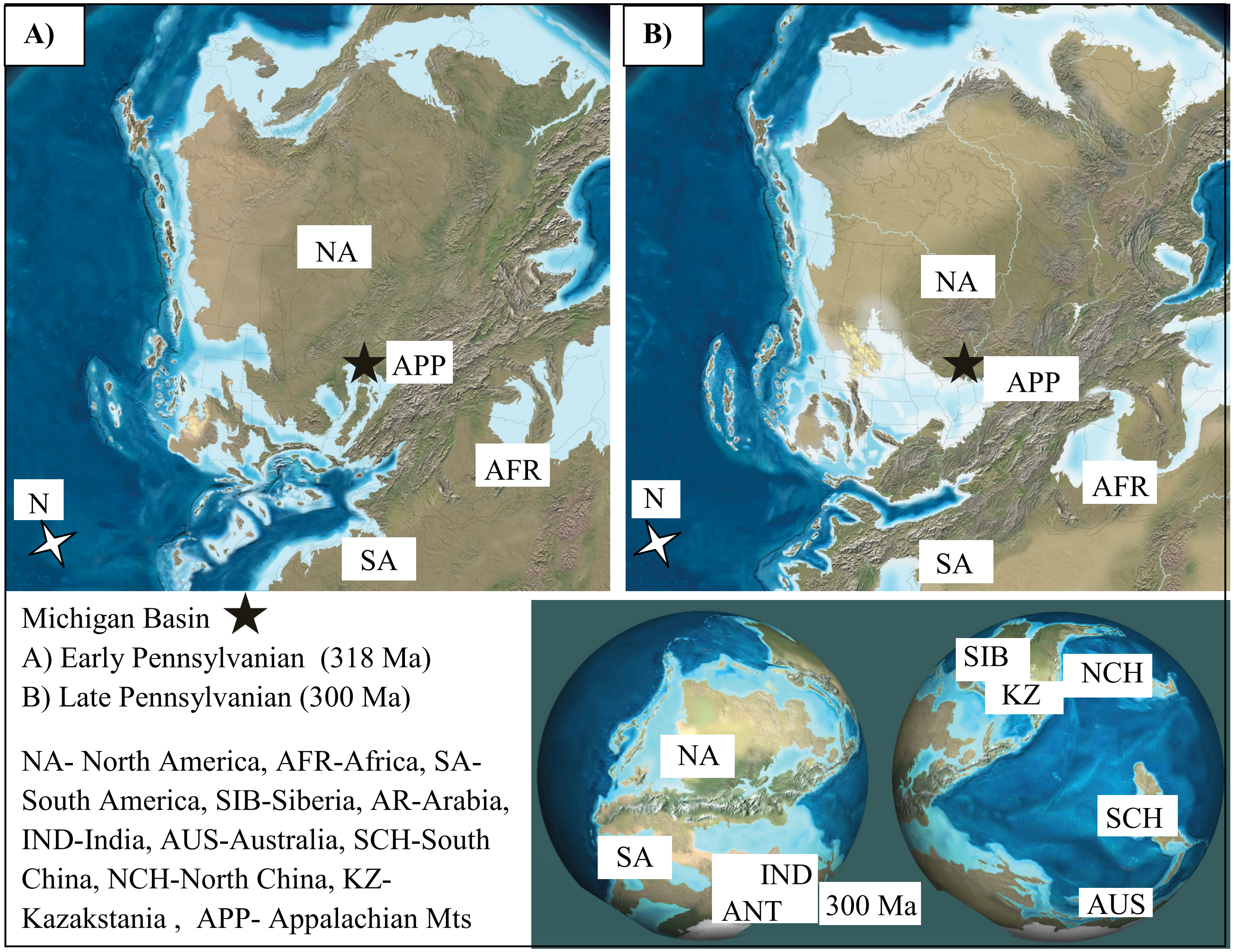

Figure 2.3: Paleogeography of the Pennsylvanian with focus on the North American continent. The Michigan Basin is marked with a brown star. In the Pennsylvanian we see the peak of Alleghanian orogenesis as Africa collides with North America Apparent forebulge uplift in the form of structural arches subtly changes the landscape of the continental interior. The Michigan Basin is covered by or near the shallow epicontinental sea. Modified from Scotese, 2002; Blakely, 2011.

if these arches were uplifted to significant relief at any time during the Carboniferous. Any isolation is thought to have been brief as correlations can be made with coal marker beds across all three basins in Pennsylvanian stratigraphy (Weller, 1930, Kelly, 1933; Swezey, 2002). Sediment dispersal patterns from the Carboniferous continental interior show sediment transport from the central and northern Appalachian Range to the southwest, eventually depositing sediment in the Michigan and Illinois basins (Stearns, 1933; Kelly, 1933; 1936; Monnett, 1948; Potter and Siever, 1956; Potter and Pryor, 1961; Shideler, 1969). This sedimentation is thought to have occurred in a fluvial-deltaic setting along the northern edge of the shallow continental sea (Kelly, 1933; Stearns, 1933; Monnett, 1948; Potter and Siever, 1956; Potter and Pryor, 1961; Shideler, 1969; Fisher, 1988). This setting has been interpreted as a regional – continental scale axial drainage system which may or may not have split into parallel drainage basins in the Late Mississippian; an event roughly coeval with reported northwestward shifts (100-200 km) in delta fronts and shorelines in the Illinois basin (Swann, 1963,1964; Archer and Greb, 1995; Robinson and Prave,1995).

2.3 STRATIGRAPHIC OVERVIEW

Early-Mid Paleozoic sedimentation in the Michigan Basin generally consists of marine shale and carbonate units with few siliciclastic inclusions (Figure 2.4). The increased abundance of siliciclastic units in the Late Devonian -Early Mississippian mark a transition in contributions to the Michigan Basin; a potential result of the conclusion of Acadian orogenesis (Stearns, 1933; Monnett, 1948; Swann, 1963, 1964; Ells, 1979; Catacosinos et al., 2001) (Figure 1.4 & 1.5). Thick sandstones are present throughout much of the Late Paleozoic strata, typically making up

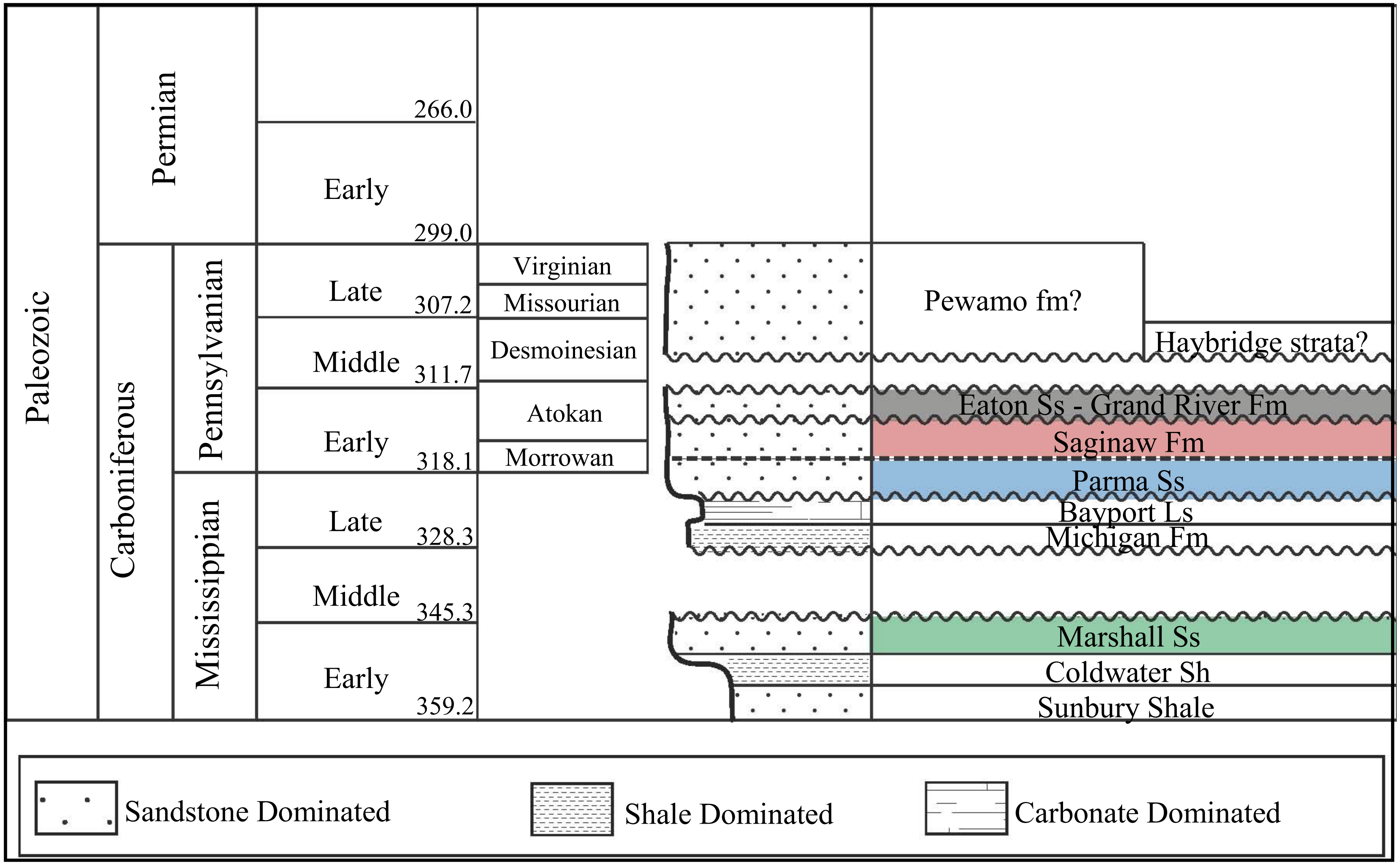

Figure 2.4: Mississippian and Pennsylvanian siliciclastic dominated strata of the Michigan Basin. Colors denote the Marshall Sandstone, Parma Sandstone, Saginaw Formation, and Eaton Sandstone of the Grand River formation as the focus of this study. Colors are used consistently on all stratigraphic columns and ternary plots. Unconformities are denoted by wavy lines. After Stearns, 1933; Kelly, 1933,1936; Monnett, 1948; Miller and Garner, 1953, 1955; Driscoll, 1965, 1969; Landing and Wardlaw, 1981; Vugrinovich, 1984; Harrel et al., 1991; Catacosinos et al., 2000.

much of each unit in the Mississippian and Pennsylvanian (Stearns, 1933; Kelly, 1936; Monnett, 1948; Cohee et al., 1951; Siever and Potter, 1956; Shideler, 1969 Fisher et al., 1988; Westjohn and Weaver, 1998; Catacosinos et al., 2001; Benison et al., 2011). The Mississippian section of interest contains the Early Mississippian Marshall Sandstone, interbedded shale, sandstone, anhydrites, and carbonates of the Michigan Formation, and the Bayport Limestone. Pennsylvanian rocks of interest to this study overlie the Mississippian strata and include fine-coarse grained sandstones from the Early Pennsylvanian Parma Sandstone, Saginaw Formation, and Eaton Sandstone.

Marshall Sandstone (Early Mississippian)

The Marshall Sandstone is 60-120 meters of primarily fine-medium grained sandstone, interbedded with red beds, dolomite, siltstone, and shale (Stearns, 1933; Monnett, 1948; Ells, 1979; Westjohn and Weaver, 1998). Biostratigraphic and chronologic indicators are scarce in much of the Marshall, though certain sections contain a diverse macrofauna and flora of Early Mississippian affinity, specifically Osagean (Miller and Garner, 1953, 1955; Driscoll, 1965, 1969; Harrel et al., 1991). Miospores from the Marshall also indicate an Osagean age (Richardson, 2006). The presence of cephalopods and sedimentary structures typically define the environment of deposition as marine (Stearns, 1933; Monnett, 1948; Harrell et al., 1991), with a fluvial component that may be part of a deltaic feature (Potter and Pryor, 1961). Northeast to southwest sediment dispersal is inferred from cross-bedding measurements (Potter and Pryor, 1961) throughout the Marshall Sandstone, indicating a source potentially to the northeast (Appalachian?) (Potter and Pryor, 1961). Westerly (Wisconsin Highlands) and northerly sources (Huronian rocks from the Upper Peninsula of Michigan and nearby Canadian Shield, and Grenville rocks) have also been suggested based on mineral assemblages (Stearns, 1933; Monnett, 1948). Other dispersal patterns suggested are southeast to northwest sediment from the Appalachian region, potentially reaching as far as the Michigan Basin (Ettensohn, 2004). Despite these ideas, the origin of the Marshall remains unclear.

One of the interbedded shale units is generally thought to act as the dividing line between the Lower Marshall Sandstone and the Napoleon (Upper) members (Figures 2.5 & 2.6). Laterally extensive sublitharenite-litharenite sandstones make up both members and contain zircon, tourmaline, and garnet, as well as actinolite, epidote, and hornblende (Stearns 1933; Monnett, 1948). The unit overlying the Napoleon member is variable. Conformable stratigraphic relationships place the interbedded sandstones, siltstones, and anhydrites of the Michigan formation on top. In some places, unconformable surfaces may place any Late Mississippian to Early Pennsylvanian unit above the Marshall. A complete section would see the Michigan Formation directly overlying the Marshall, with the Bayport limestone atop it, and Early Pennsylvanian Parma Sandstone as the latest Mississippian strata. Large scale unconformable surfaces in the Late Mississippian strata are thought to be the sub-Absaroka unconformity which ends the Kaskaskia sequence (Fig 2.4) (Sloss, 1963) and Mississippian section (Westjohn and Weaver, 1998; Catacosinos et al., 2001). The sub-Absaroka unconformity is present across much of the region (Sloss, 1963).

Parma Sandstone (Late Mississippian – Early Pennsylvanian)

Atop the Mississippian section, is a white quartz arenite informally referred to as the Parma Sandstone (Figure 2.7). The unit is laterally discontinuous, often ranging between 0-60 meters, with several thin, black, interbedded shale units (Kelly, 1936; Westjohn and Weaver,

Figure 2.5: Thin (2-5 cm), horizontally laminated strata of the Lower Marshall Sandstone. This poorly exposed, roadside outcrop of Lower Marshall is near Grindstone City, MI on M-25, and Lakeshore Dr. A small hillside of Marshall is exposed in an area which is surrounded by subsurface Coldwater shale. Rock hammer for scale.

Figure 2.6: Napoleon Sandstone member of the Marshall Sandstone, from Jude Quarry in Napoleon, MI. More thickly bedded (.5-1.5 m) deposits are seen above, the thickest being approximately one and a half meters. It has been suggested that bedding is actually thin (Monnett, 1948) as 2-8cm slabs can be broken off (seen on pallet). Weathered surfaces of the outcrop make distinguishing this difficult.

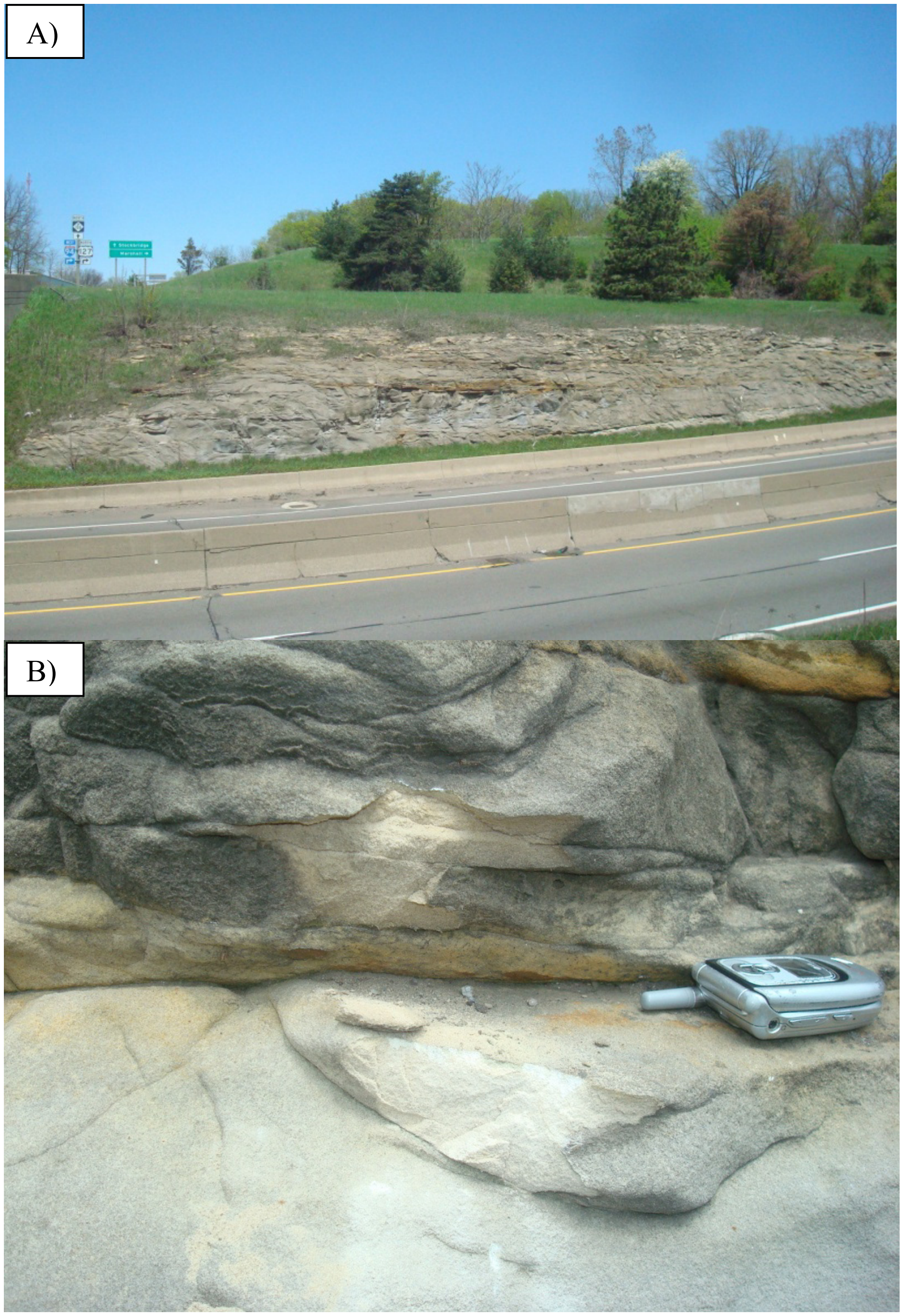

Figure 2.7 A): Parma Sandstone exposure along I-94 in Jackson, MI. Several erosional surfaces are present (as seen in bottom picture). Standard road sign for scale. **B)** The characteristic white sandstone is seen below the unconformity while a slightly more orange (iron rich) sandstone overlies it. However, both are quartz arenites. Cell phone for scale.

1998). Commonly reported heavy minerals are zircon and tourmaline (Kelly, 1930, 1936; Cohee et al. 1951; Westjohn and Weaver, 1998; Catacosinos et al., 2001). Currently, the Parma is interpreted as a separate unit representing the latest Mississippian to earliest Pennsylvanian (Morrowan) deposits in the Michigan Basin, though that is not constrained (Kelly, 1936, Potter and Siever, 1956; Siever and Potter, 1956; Wanless and Shideler, 1975; Vugrinovich, 1984; Westjohn and Weaver, 1998). Cross bedding within the unit reveals northeast to southwest sediment dispersal patterns (Kelly, 1936; Potter and Siever, 1956) that are consistent throughout the Early Pennsylvanian section (Shideler, 1969). Deposition is thought to have occurred as part of littoral or shallow marine shelf or near shore marine environment based on compositional maturity (Shideler, 1969). Little else has been studied in terms of the geological nature of the Parma.

Saginaw Formation (Early Pennsylvanian)

The Saginaw Formation is a series of interbedded carbonate, siltstone, coal, and sandstone, generally interpreted as an Early Pennsylvanian (Kelly, 1933, 1936; Wanless and Shideler, 1975) marginal marine to fluvial-deltaic environment and local littoral sheets (Figure 2.8) (Shideler, 1969; Velbel and Brandt, 1989). An Atokan age is well defined by conodont species present in the Saginaw's Verne Limestone member (Landing and Wardlaw, 1981). Sediment dispersal in the Saginaw is consistently interpreted as northeast to southwest by sediment isopachs (Shideler, 1969; Fisher, 1988) and cross-bedding measurements (Potter and Pryor, 1961). The thickness of the Saginaw is generally thought to be 120 meters but may extend to 163 meters (Kelly, 1936; Milstein, 1987).

Grand River Formation – Eaton Sandstone (Early-Late Early Pennsylvanian)

Figure 2.8 Saginaw Formation from Fitzgerald Park in Grand Ledge, MI. Sandstones are interbedded with shale, coal, and limestone suggesting cyclical variability in the environmental conditions. Coal seam is <.5 meters thick with field notebook for scale.

The Grand River Formation is at the top of the Pennsylvanian section, unconformably overlying the Saginaw Formation. A Late Early Pennsylvanian age is given to the Eaton Sandstone based on lithologic similarities with the Conemaugh Group of the Appalachian basin (Kelly, 1936). Palynology data (Venable, 2006) is interpreted as Atokan, based on comparisons to stratigraphically equivalent units in Iowa, though major Atokan palynologic indicators are absent (Ravn and Fitzgerald, 1982; Ravn, personal communication, 2006). Assignment to the Atokan would mean an age similar to that of the Saginaw Formation, as suggested by Benison et al. (2011). The Eaton is typically ~30 meters of coarse, rust-orange colored, massively bedded, sandstone with muscovite, zircon, and tourmaline as the dominant heavy minerals (Figure 2.9) (Kelly, 1936). Derivation of the sediment contained in the Eaton Sandstone is less well understood. Paleocurrent data showing flow to the north (Martin, 1982) has been interpreted as a meander in a fluvial system at a high angle to normal Pennsylvanian flow (northeast – southwest) (Velbel and Brandt, 1989). The remainder of the section in the Michigan Basin consists of laterally discontinuous red beds belonging to the Jurassic (?) Ionia formation and Pleistocene glacial deposits (Catacosinos et al., 2001). Recent debates centered on palynology place the Ionia anywhere from late Early Pennsylvanian to Cretaceous (Cross, 1998; Knapp et al., 2007; Benison et al., 2009; Dickinson et al., 2010).

2.4 DETRITAL FRAMEWORK MODES

Methodology

Standard petrographic thin sections were created from 52 fine- to coarse-grained sandstone samples that were collected to represent the vertical and lateral extent of exposure at

Figure 2.9: The Eaton sandstone of the Grand River Formation at Lincoln Brick Park, Grand Ledge, MI. The characteristic red-orange iron rich sandstone is evident as well as broad, lenticular beds. From right to left, there is a high energy deposit (sand slurry) full of shale rip of clasts and an iron rich sand matrix. The fence on top of the outcrop is approximately three feet tall and provides scale.

each outcrop of the Marshall Sandstone, Parma Sandstone, and Saginaw Formation (Figure 2.11). Marshall Sandstone samples were taken from the south wall of Clancy and Son's quarry in Port Austin, MI, a roadside outcrop in Grindstone City, MI, the Jude Quarry in Napoleon, MI, and additional field locations in quarries near Owosso (Figure 2.5). Parma Sandstone outcrops were taken from the poorly indurated outcrop at Exit 139 on Interstate I-94, a small outcrop near Kalamazoo, and from a quarry in Owosso. Saginaw Formation samples came from several locations around the Lansing area and Eaton Sandstone samples came from exposures in the Eaton County park system. Preparation of the thin sections included staining for potassium feldspar and plagioclase. The samples were then point-counted using a modified version of the Gazzi-Dickinson method (Dickinson, 1970; Ingersoll et al., 1984). Specification of grain type (schist, quartzite, sandstone, etc) within standard rock classification (lithic, metamorphic, sedimentary) enhances knowledge of the source rock type, allowing for both tectonic reconstruction of the Gazzi-Dickinson method and paleogeographic reconstruction of more traditional methods (See Table 2.1). Detrital framework modes were determined by identifying 400 grains according to these parameters (Table 2.1). Recalculated Q-F-L percentages, according to Ingersoll et al. (1984) and Dickinson (1983) are provided in Table 2.2. Raw point count data are presented in Appendix A. Data from the Illinois basin and Appalachian foreland basin were taken from a sampling of previous literature (Appendices B and C).

RESULTS

Descriptions of detrital framework modes

Petrographic analyses of Carboniferous sandstones from the Michigan Basin show a prevalence of monocrystalline quartz (Qm) which typically represents 50-94% of each sample

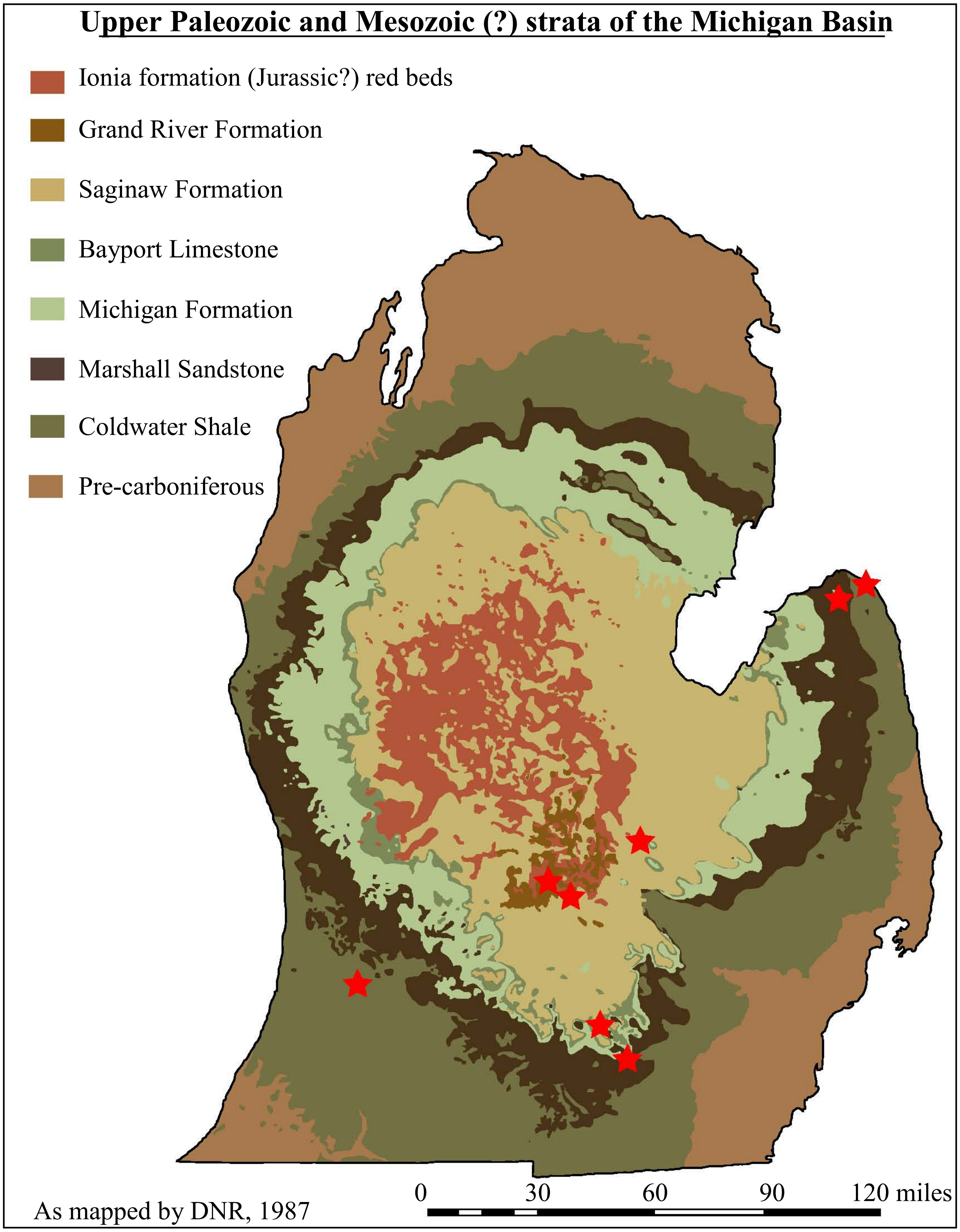

Figure 2.10 Carboniferous geological map of the Michigan Basin. Red stars denote field locations. Small, limited outcrop exposures of Parma Sandstone and Marshall Sandstone are present in areas that are not necessarily shown here, or are covered by location markers. After Milstein, MDNR, 1987.

(Figure 2.12). Significant abundances of polycrystalline quartz (Qp~1-17%) and metamorphic lithic fragments (1-45%) are also present in most samples. Feldspars generally constitute less than ten percent, while sedimentary lithic fragments, chert, and volcanic lithic fragments were uncommon. Variability in the sandstone petrography of the Michigan Basin's Carboniferous strata suggests regional influence on provenance of the basin, either through shifting source areas or variable source types in a single source area.

Marshall Sandstone

Point counts for samples from the Marshall sandstone (n=32) show similarities between its two members. The Early Mississippian Lower Marshall member is typically characterized by a dominance of quartz, few feldspars, and significant abundances of lithic fragments (Q~60%, F~5%, L~35%). Quartz consists predominantly of monocrystalline quartz (Qm), with less than 10% polycrystalline quartz (Qp), and minor chert (C). Feldspars are a minor component, typically dominated by potassium feldspar with few plagioclase grains (Qm~92%, P~1%, K~7%) (Figure 2.14). Metamorphic lithic grains consist primarily of mica-schist and quartz-mica-schist fragments while sporadic occurrences of volcanic grains show up in most samples (Lv~6, Lm~93%). Sedimentary lithic fragments were rare (~1%). The Napoleon member exhibits an increase in quartz abundance, usually offset by decreased feldspar abundance and a lower amount of lithic components as compared to the Lower Marshall Sandstone (Q~75%, F~4%, L~21%). Lithic fragments are dominated by metamorphic grains, with occasional lithic volcanic fragments and sedimentary fragments (Lv~1%, Lm~98%, Ls~1%).

Parma Sandstone

Point counts of the Parma Sandstone (n=10) revealed a quartz arenite with little in the

Table 2.1. Summary of modal composition parameters for siliciclastic point counting. Parameters only include grains that were identified. After Ingersoll et al., 1984.

- Quartz (Q) = Qm + Qp + chert

- Monocrystalline quartz (Qm)
- Polycrystalline quartz (Qp)
- Chert (C)

-Feldspar (F) = P + K

- Plagioclase feldspar (P)
- Potassium feldspar (K)

-Lithic Fragments (L) = Ls + Lm + Lv

- Lithic sedimentary (Ls)
    - Sandstone (Lssn)
    - Mudstone (Lsm)
- Lithic Metamorphic (Lm)
    - Schist (Lms)
    - Gneiss (Lmg)
    - Quartzite (Lmq)
- Lithic Volcanic (Lv)

-Lt =Lv + Ls + Lm + Qp+ chert

way of feldspar and lithic fragments (Q~94%, F~2%, L~4%). Monocrystalline quartz (Qm) accounts for all but ~1% (Qp) of the Q measurement, while mica-schist fragments dominate the lithic component (Lv~8%, Lm~89%, Ls~3%. The small amounts of feldspar are generally badly weathered and of potassium composition (Qm~97.9%, P~.1%, K~2%). Similar compositions were reported in Parma samples studied by Siever and Potter (1956).

Saginaw Formation

Modal composition of the Saginaw Formation (n=13) reveals a sublitharenite composition, dominantly quartz but containing increased abundances of lithic fragments and a small feldspar component (Q~84.5%, F~2.5%, L~13%). The quartz component (Q) is dominantly monocrystalline quartz, while feldspar content is dominated by potassium feldspar (Qm~95.8%, P~.2%, K~ 4%). The lithic constituent is dominated by metamorphic schist fragments, while minor volcanic fragments make an appearance and a very rare mudstone fragment, may occur (Lv~5%, Lm~94.7%, Ls~.3%).

Eaton Sandstone of Grand River Formation

Eaton Sandstone point counts (n=62) were acquired previously by Price and Velbel (2000) in relation to weathering and erosional properties of the formation, rather than provenance. Here the data is reviewed and interpreted for provenance trends. Samples consist of surface and subsurface samples, for which some differences are noted. Average compositions of surface samples for the Eaton are dominantly quartz, with few feldspars and lithic fragments present (Q~95%, F~3%, L~2%). Subsurface samples show less abundant quartz and corresponding increase in lithic fragments (Q~90%, F~2.5%, L~7.5%). Price and Velbel (2000) explain the difference as a result of dissolution of lithic fragments in the subaerially exposed samples.

2.5 INTERPRETATIONS OF DETRITAL FRAMEWORK MODES

Marshall Sandstone

According to provenance fields by Dickinson et al. (1983), the Marshall Sandstone is derived from a recycled orogenic source (Figure 2.16). The dominance of monocrystalline quartz in the Early Mississippian represents sediment that has endured recycling, demonstrating the stability and persistence of quartz, or a proximal igneous source that is enriched in silica. Subordinate feldspar and lithic fragments suggests the former (Pettijohn et al., 1972) resulting in the attrition of these minerals, or a mix of sources with a variety of mineral assemblages contributed to the unit. Many lithofacies in the Marshall Sandstone blanket the basin and can be interpreted as a single depositional environment (Westjohn, 1998). Sediment transport in the Early Mississippian Michigan Basin was primarily northeast to southwest (Potter and Pryor, 1961). Modal composition and metamorphic fragments in the Marshall show that the source type was likely quartz-mica- and mica-schist, lithic arenites, and potential crystalline inclusions.

Parma Sandstone

The Parma Sandstone is primarily monocrystalline quartz and exhibits a transition in upsection provenance, as Parma samples plot along the interface between recycled orogen and continental block fields on Dickinson et al.'s (1983) provenance ternaries. The attrition of feldspar and lithic fragments is all but complete; the few feldspar grains present are partially decomposed to clay minerals and lithic metamorphic fragments are limited. Paleoflow patterns in the Parma and coeval strata of the Illinois basin, Appalachian basin, and thin veneer of basal

Table 2.2: Recalculated modal composition percentages for the Marshall Sandstone, Parma Sandstone, and Saginaw Formation. Common provenance parameters are shown here and plotted in subsequent ternary diagrams. All samples came from sample location shown in Figure 2.11.

		Q-F-L %			Qm-F-Lt %			Qm-P-K %			Lv-Lm-Ls %		
Sample #	**Formation**	**Q**	**F**	**L**	**Qm**	**F**	**Lt**	**Qm**	**P**	**K**	**Lv**	**Lm**	**Ls**
MIB-050911-06	Saginaw Fm	82	1	17	71	5	24	94	2	4	14	72	14
MIB-050911-05	Saginaw Fm	83	2	15	81	2	17	98	0	2	11	82	7
MIB-050911-04	Saginaw Fm	79	4	17	52	6	42	90	0	10	2	97	1
MIB-050911-03	Saginaw Fm	77	1	22	44	2	54	96	0	4	12	84	4
MIB-050911-02	Saginaw Fm	83	2	15	47	8	45	85	1	14	7	93	0
MIB-050911-01	Saginaw Fm	82	2	16	52	8	40	87	2	11	11	83	6
USB-11	Saginaw Fm	72	4	24	60	0	40	100	0	0	10	90	0
USB-9	Saginaw Fm	72	7	21	92	1	7	99	0	1	8	92	0
USB-8	Saginaw Fm	82	3	15	68	6	26	92	1	7	12	88	0
USB-7	Saginaw Fm	73	5	22	67	4	30	95	0	5	6	92	1
SS-12	Parma SS	95	2	3	65	7	27	90	1	9	4	96	0
MIB-050911-15	Parma SS	95	2	3	71	3	25	96	0	4	10	90	0
MIB-050911-14	Parma SS	94	1	5	67	5	28	93	0	7	5	95	0
MIB-050911-13	Parma SS	93	2	5	66	3	31	96	0	4	10	90	0
MIB-050911-12	Parma SS	94	2	4	65	1	34	99	0	1	7	88	5
MIB-050911-11	Parma SS	92	2	6	76	1	23	98	0	2	13	85	2
MIB-050911-10	Parma SS	95	3	2	93	2	5	98	0	2	9	91	0

Table 2.2 (cont'd)

Sample #	Formation	Q-F-L %			Qm-F-Lt %			Qm-P-K %			Lv-Lm-Ls %		
		Q	F	L	Qm	F	Lt	Qm	P	K	Lv	Lm	Ls
MIB-050911-09	Parma SS	96	1	3	91	1	8	99	0	1	6	94	0
MIB-050911-08	Parma SS	95	2	3	90	2	8	98	0	2	0	100	0
MIB-050911-07	Parma SS	94	2	4	89	2	9	98	0	1	24	76	0
MIB-050911-18	Napoleon Marshall SS	75	3	22	90	2	7	97	0	3	0	100	0
MIB-050911-17	Napoleon Marshall SS	74	1	25	93	3	4	97	0	3	22	57	22
MIB-050911-16	Napoleon Marshall SS	80	1	19	92	2	6	98	0	2	0	100	0
SS-32	Marshall SS	79	5	16	92	2	6	98	0	2	9	91	0
SS-35	Marshall SS	87	2	11	90	2	8	98	0	2	0	92	8
SS-9	Marshall SS	59	6	35	80	1	19	98	0	2	5	95	0
SS-10	Marshall SS	49	2	49	79	2	19	97	0	3	6	94	0
MV-H-1	Marshall SS	53	8	39	77	4	19	95	0	5	5	94	2
SS-11	Marshall SS	62	8	30	74	1	24	98	0	1	2	98	0
SS-34	Marshall SS	66	0	34	81	2	17	98	0	2	3	97	0
SS-31	Marshall SS	75	6	19	77	2	21	97	0	3	5	95	0
MIB-042311-21	Lower Marshall SS	58	3	39	54	3	44	95	0	5	8	86	6
MIB-042311-20	Lower Marshall SS	69	3	28	51	3	46	95	2	3	12	88	0
MIB-042311-19	Lower Marshall SS	71	6	23	60	6	34	91	0	8	12	88	0
MIB-042311-18	Lower Marshall SS	66	3	31	57	3	40	95	1	4	10	87	3

Table 2.2 (cont'd)

Sample #	Formation	Q-F-L %			Qm-F-Lt %			Qm-P-K %			Lv-Lm-Ls %		
		Q	F	L	Qm	F	Lt	Qm	P	K	Lv	Lm	Ls
MIB-042311-17	Lower Marshall SS	59	#	31	54	10	36	85	2	13	8	91	2
MIB-042311-16	Lower Marshall SS	62	8	30	53	8	38	86	0	13	7	92	1
MIB-042311-15	Lower Marshall SS	63	7	30	57	7	37	89	3	8	13	87	0
MIB-042311-14	Lower Marshall SS	67	5	28	61	5	34	93	1	6	9	91	0
MIB-042311-13	Lower Marshall SS	62	7	31	54	7	39	89	0	10	9	91	0
MIB-042311-12	Lower Marshall SS	66	1	33	62	1	37	98	0	2	5	95	0
MIB-042311-11	Lower Marshall SS	66	2	32	59	2	39	97	0	2	4	95	1
MIB-042311-10	Lower Marshall SS	59	9	33	52	9	39	85	2	13	3	97	0
MIB-042311-09	Lower Marshall SS	66	2	32	60	2	39	97	0	3	6	94	0
MIB-042311-08	Lower Marshall SS	62	3	35	56	3	41	95	1	3	3	97	0
MIB-042311-07	Lower Marshall SS	64	5	31	57	5	39	92	1	7	3	97	0
MIB-042311-06	Lower Marshall SS	61	4	35	55	4	41	94	2	4	8	92	0
MIB-042311-05	Lower Marshall SS	64	2	35	59	2	39	97	0	2	3	97	0
MIB-042311-04	Lower Marshall SS	62	4	34	58	4	38	94	0	6	8	92	0
MIB-042311-03	Lower Marshall SS	63	4	33	58	4	39	94	0	6	7	93	0
MIB-042311-02	Lower Marshall SS	64	7	29	58	7	35	89	0	11	5	94	1
MIB-042311-01	Lower Marshall SS	60	4	36	56	4	40	93	0	7	10	90	0

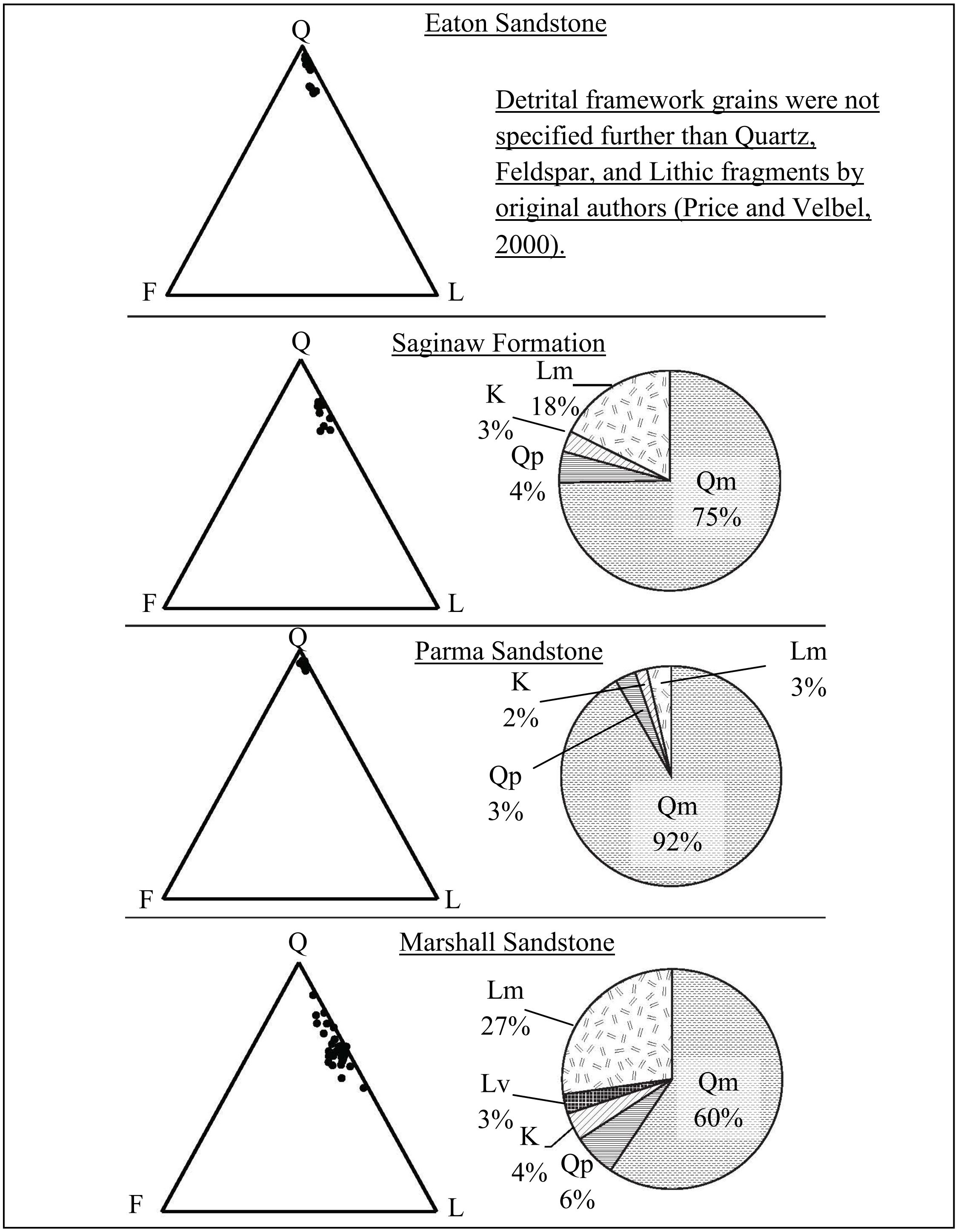

Figure 2.11: Modal compositions and average parameter percentages from the Marshall Sandstone, Parma Sandstone, and Saginaw Formation determined in this study. Standard Q-F-L fields are provided in the ternary diagrams. Ls = sedimentary lithic fragment; Lm = metamorphic lithic fragment; Lv = volcanic lithic fragment; K = Potassium Feldspar, P = Plagioclase, C = Chert, Qp = Polycrystalline quartz, and Qm = Monocrystalline quartz. Sporadic occurrences resulting in a 0 average are excluded.

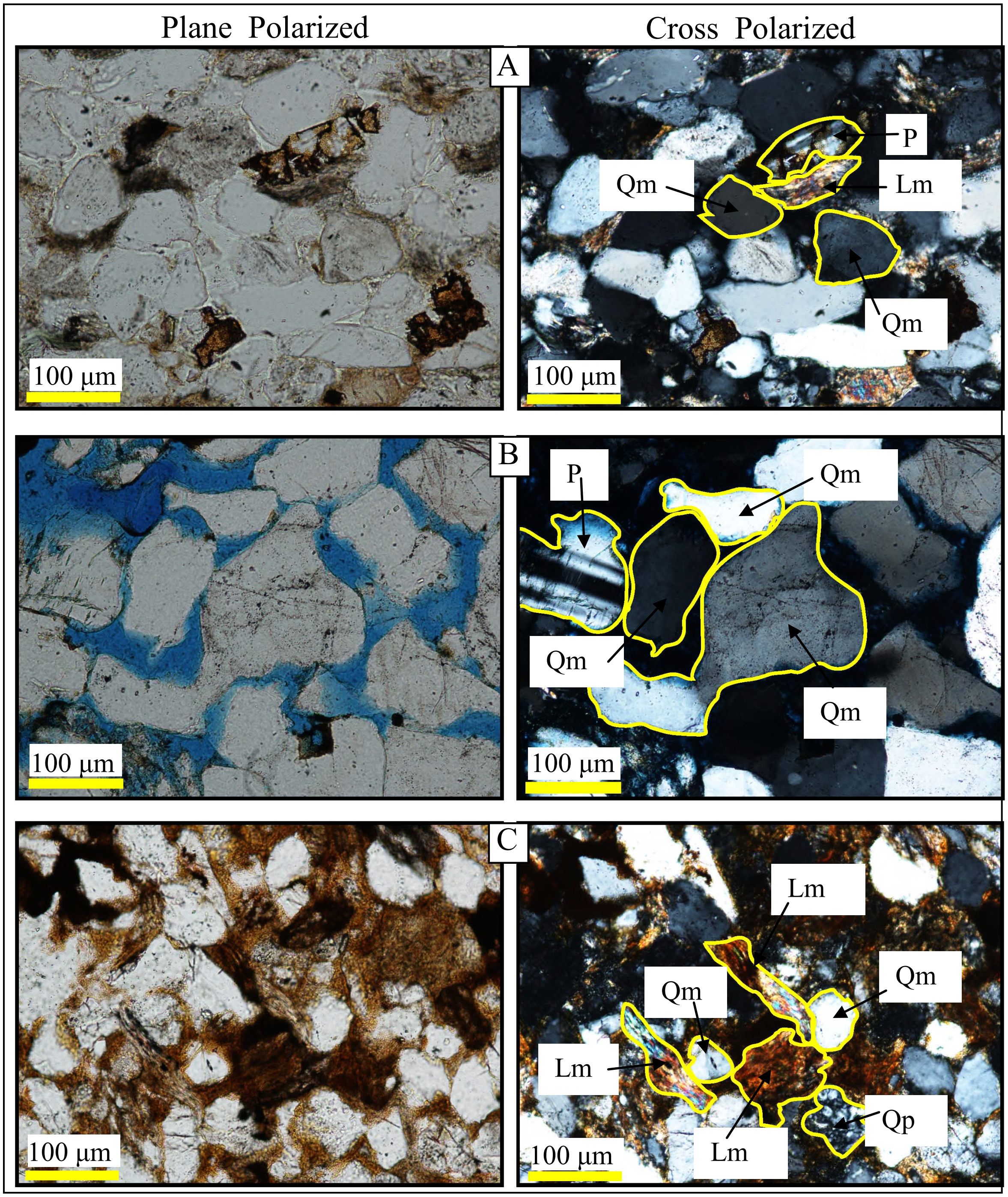

Figure 2.12: Sandstone petrography of the Carboniferous Michigan Basin. Photomicrographs are shown in both plane-polarized light (left) and cross-polarized light (right.), in stratigraphic order. A 100 micrometer scale bar is included in each photograph. A) Typical Saginaw Formation sandstone showing the presence of metamorphic lithic fragments (Lm) and monocrystalline quartz (Qm). B) Characteristic Parma Sandstone, showing primarily monocrystalline quartz (Qm) with minor plagioclase (P). C) More lithic rich Marshall Sandstone is seen containing metamorphic lithic fragments (Lm), polycrystalline quartz (Qp), and monocrystalline quartz (Qm).

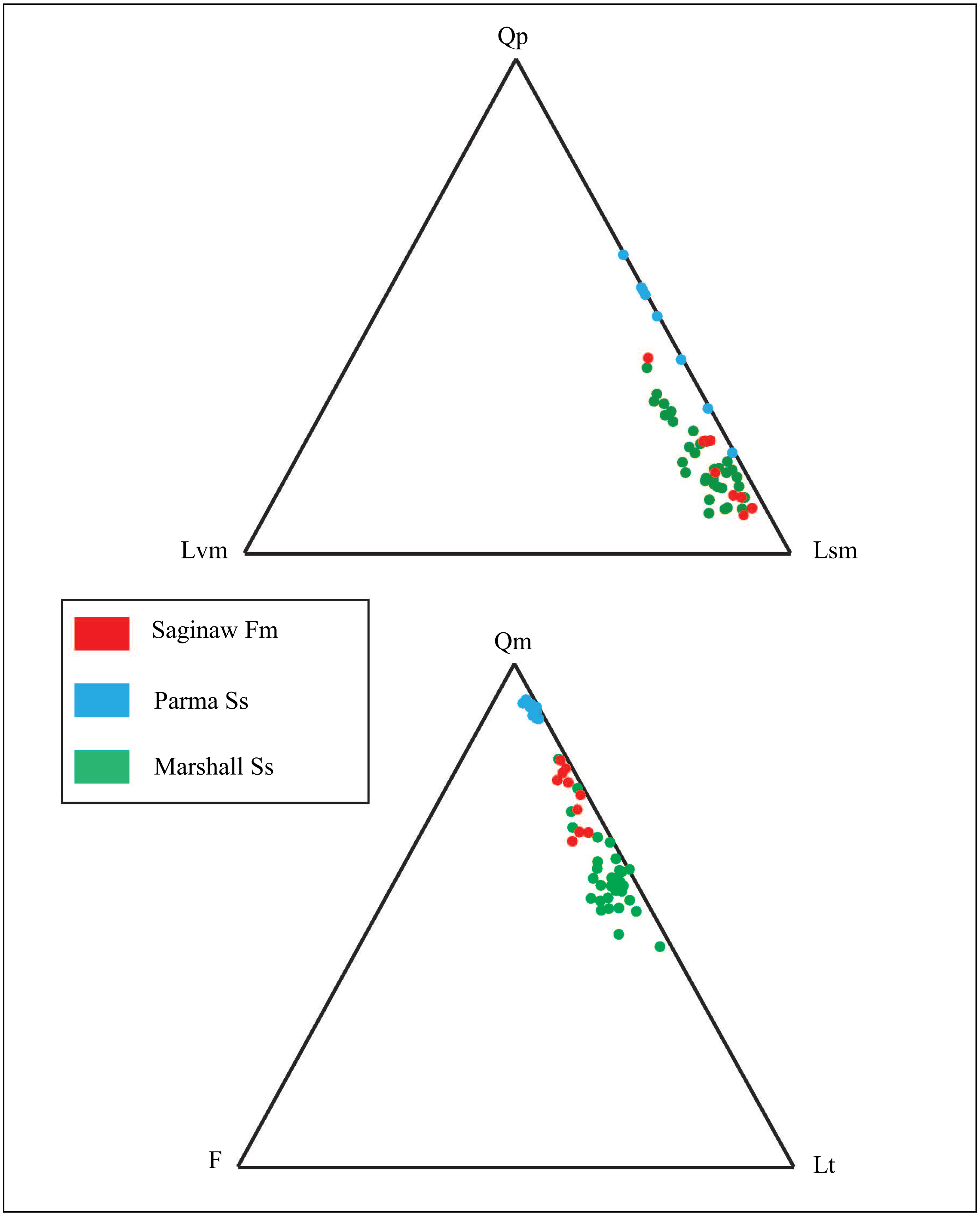

Figure 2.13: Supplementary ternary diagrams of sandstone modal compositions from the Marshall Sandstone, Parma Sandstone, and Saginaw Formation. See Table 2.1 for parameters and Table 2.2 for data. There are 52 samples included in this data set.

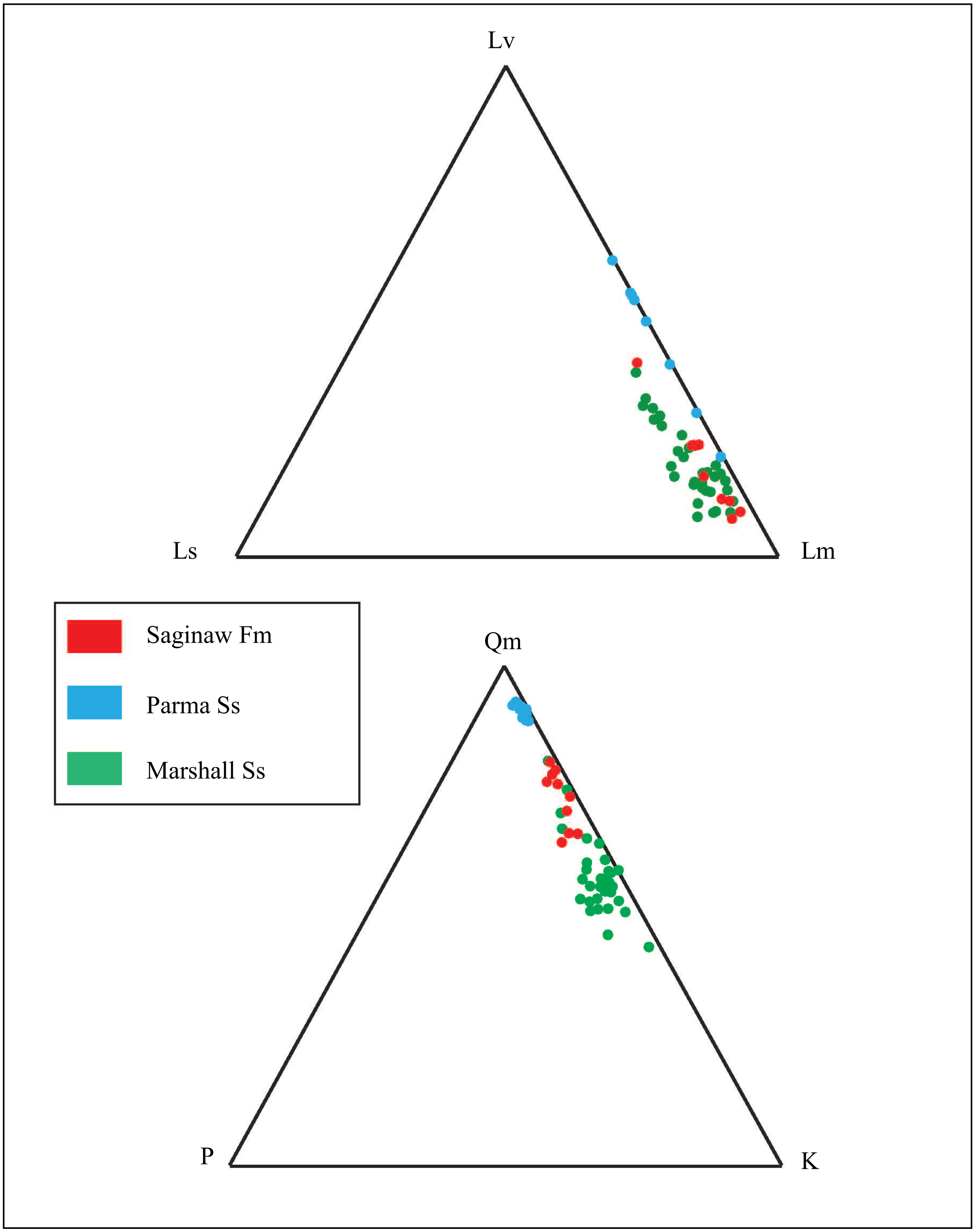

Figure 2.14: Supplementary ternary diagrams of sandstone modal compositions from the Marshall Sandstone, Parma Sandstone, and Saginaw Formation. See Table 2.1 for parameters and Table 2.2 for data. There are 52 samples included in this data set.

Pennsylvanian strata between the basins, demonstrate a NE-SW trend with minor contributions to respective basins from nearby arches (Potter and Siever, 1956). Paleocurrent indicators suggest the source of the Parma Sandstone is likely to the northeast, allowing possible sediment inputs from recycled strata of the Central-Northern Appalachians (Eriksson et al., 2004; Thomas et al., 2004; Becker et al., 2005; Thomas and Becker, 2007; Cawood et al., 2007; Park et al., 2010). The Parma Sandstone is likely derived from multiple sources draining into the headwaters of a large scale river to the northeast of the Michigan Basin. Previously mature quartz arenites or quartzite source types with inclusions from mica-schist sources likely provided sediment for the Parma Sandstone.

Saginaw Formation

The Saginaw Formation shows recycled orogenic provenance in the provenance fields of Dickinson (1983). The relative abundances of feldspar are equivalent to the rest of the Carboniferous section implying consistent weathering of the detritus being provided, potentially due to recycling, and therefore weathering, over the course of a longer period of time. The lithic component increases in the Saginaw as metamorphic fragments are commonly seen. Given the number of possibilities that may have influenced lithic content in the Saginaw, little can be ascertained from the data relating to why the occurrences of lithic fragments are more frequent. Contributions of sediment from different source areas and different source types, differential weathering, and diagenetic weathering all possibly explain differences in detritus from a proximal source, while previous weathering of any kind in numerous generations of recycling is also a possible explanation. Sediment dispersal patterns throughout the Early Pennsylvanian was primarily from the northeast (Potter and Siever, 1956; Potter and Pryor, 1961; Shideler, 1969), although localized paleocurrent measurements from the Late Paleozoic Eaton show a

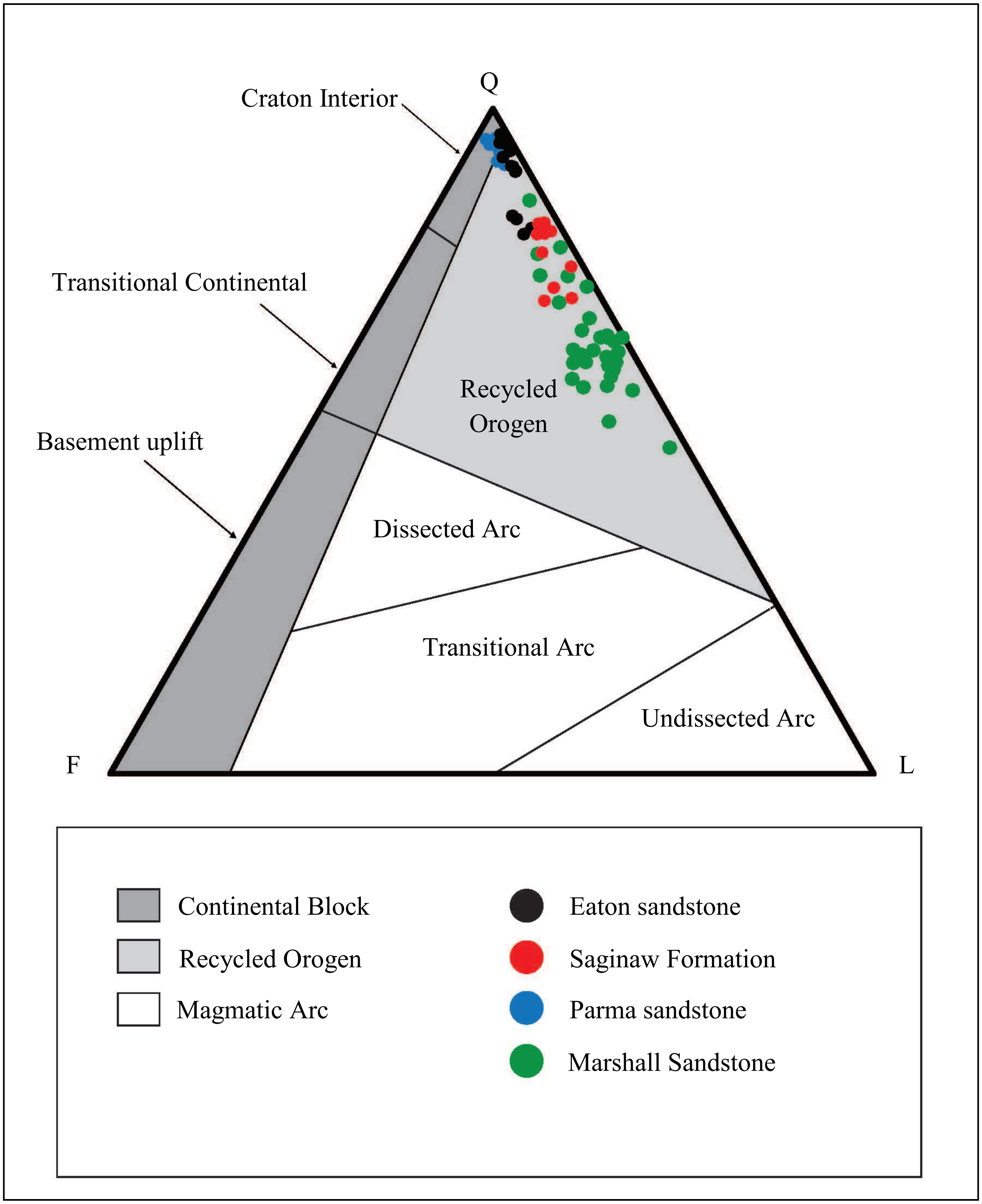

Figure 2.15: Michigan Basin Mississippian and Pennsylvanian data interpreted in the provenance fields of Dickinson et al. (1983). Modal composition points to recycled orogen provenance fields however with minor contributions that are considered to originate in the cratonic interior. 5 Parma samples from Siever and Potter, 1956 are shown. Grand River Formation samples come from Velbel and Price, 2000.

northerly trend and have been interpreted as a meander loop situated at a high angle to a northeast to southwest regional trend (Velbel and Brandt, 1989). Entrenchment of a regional system would allow flood plains to hold and deposit sediment over long periods of time while intrastratal solution could have accounted for the loss of feldspar (Pettijohn, 1941). The source type for this unit is likely a combination of sublitharenite-lithic arenite sandstone, schist containing mica and quartz, and potential crystalline granite or gneiss sources.

Eaton Sandstone (Grand River Group)

Point counts of the Eaton Sandstone done by Price and Velbel (2000) show that the sediment likely came from recycled orogenic sources, per Dickinson et al.'s (1983) interpretations of provenance. A continental block source and quartz arenite classification is also seen in subaerial exposures as a result of diagenetic weathering of schistose lithic fragments (Price and Velbel, 2000). Quartz is the largest component regardless of the sample (70-85%) and suggests recycled material (Pettijohn et al., 1972, Blatt, 1980; Blatt, 1992). A fluvial interpretation has been given for the Eaton Sandstone (Velbel and Brandt, 1989) based on reinterpreted paleoflow data (Martin, 1982) and basal conglomerates (Kelly, 1936); however, brackish-water indicator fossils suggest the fluvial component is part of a larger estuarine/deltaic environment (Velbel and Brandt, 1989). Paleogeographic reconstructions (Blakely, 2011) interpret the system as having entered the basin through what is now the northeastern lower peninsula eventually depositing sediment into deltas in the Illinois basin (Figure 2.3). Sublitharenites and mica/ quartz-mica-schist are likely source types.

2.6 REGIONAL BASIN COMPARISON

Modal Composition and provenance interpretations of the Appalachian Foreland basin

The Central Appalachian foreland (Pennsylvanian-Alabama) has been the focus of several provenance studies that include modal composition components (Ul Hoque, 1968; Martin and Henniger 1969; Graham et al., 1976; Mack et al., 1981; Sheehan, 2002; Reed, 2003; Becker et al., 2005; Sager, 2007; Dodson, 2008; Peavy, 2008) and have provided abundant data to compare to data collected in the Michigan Basin.

In the Appalachian basin, Mississippian sandstones are dominantly quartz (Q~70-100%) with less abundant lithic fragments (L~0-30%), and generally limited abundances of feldspars (Figure 2.16) (F~0-10%) (Ul Hoque, 1968; Mack et al., 1981; Mack et al., 1983; Sheenhan, 2002; Reed, 2003; Sager, 2007). Raw modal composition data are provided in Appendix C. In terms of the provenance fields of Dickinson et al. (1983), the Mississippian sandstones are typically of recycled orogen provenance although several samples with higher relative abundances of quartz are interpreted as continental block.

Pennsylvanian sandstones from the Appalachian show a broader range of composition. Quartz is still dominant, although some samples show a decrease in quartz coupled with an increase is feldspar and lithic fragments (Q~50-98%, F~0-20%, L~2-45%) (Martin and Henniger, 1969: Graham et al., 1976; Reed, 2003; Becker et al., 2006; Dodson, 2008; Peavy, 2008). The apparent shift in modal composition is coeval with the onset of Alleghanian orogenesis, suggesting exhumation of different sources types or locations, providing the increased relative abundances of feldspar and lithic fragments. Much of the Central Appalachian foreland basin contains thick successions of carbonate, fine grained siliciclastics, and occasional

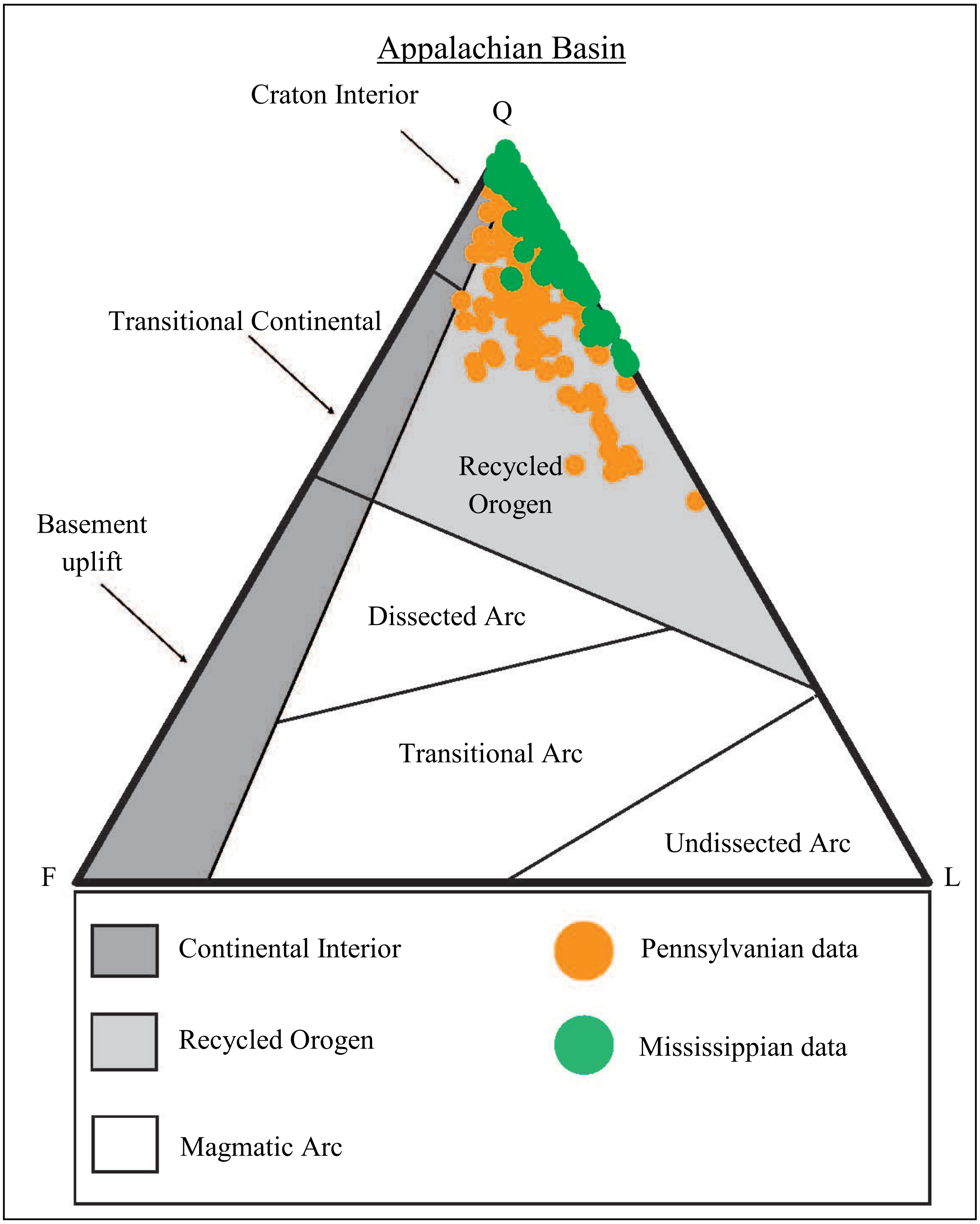

Figure 2.16: Compiled Mississippian and Pennsylvanian modal compositions from the Appalachian orogen. Mississippian data are shown in green, and Pennsylvanian data are orange. Compositions are similar; however Pennsylvanian compositions include more feldspar and lithic fragments (Ul Hoque, 1968; Martin and Henniger 1969; Graham et al., 1976; Mack et al., 1981; Sheehan, 2002; Reed, 2003; Becker et al., 2005; Sager, 2007; Dodson, 2008; Peavy, 2008).

coarse siliciclastics typically coeval with uplift events (Bennison, 1989). This siliciclastic sediment is thought to be recycled from Early Paleozoic orogens and Neo-Mesoproterozoic orogenic events like the Grenville and Granite-Rhyolite provinces (Eriksson et al., 2004; Thomas, 2004; Becker, 2005; Thomas and Becker, 2007). Small intrusions of plutonic material associated with subduction are also present in the Appalachian hinterland (Bennison, 1989). Quartz arenites are present in the Appalachian in both the Mississippian and Pennsylvanian units. Pennsylvanian quartz arenites are present throughout the section, even in the same Early Pennsylvanian units containing increased abundances of feldspar (F~0-15%). Potential inclusions of feldspar in localized areas could be indicative of detritus from exhumed or subaerial plutonic sources. Increased feldspar (<7%) content does not occur anywhere in the Michigan Basin. Documented strata of the Central Appalachian basin do not include mica-quartz-schist or other metapelites. However, similar schistose lithic fragments as those seen in the Michigan Basin are also seen in the siliciclastic dominated strata of the Central Appalachian basin (Meckel, 1967; Aronson and Lewis, 1994; Eriksson et al., 2004). Abundances of metapelite fragments are documented as increasing to the north in present day Pennsylvania and New York (Aronson and Lewis, 1994). This suggests a more northerly source of metapelites for Mid-Late Paleozoic strata in the Appalachian basin. Abrasion and mechanical weathering pose problematic for the endurance of these lithic fragments through one or more recycling episodes, suggesting a probable first cycle metapelite source throughout much of the Carboniferous.

Modal composition and provenance interpretations of the Illinois basin

Modal composition of the Illinois basin is fairly consistent throughout the Carboniferous section. Quartz generally dominates in the Mississippian formations, while feldspar, and lithic fragments are present in less abundant amounts (Q~70-100%, F~0-20%, L~0-35%) (Morris,

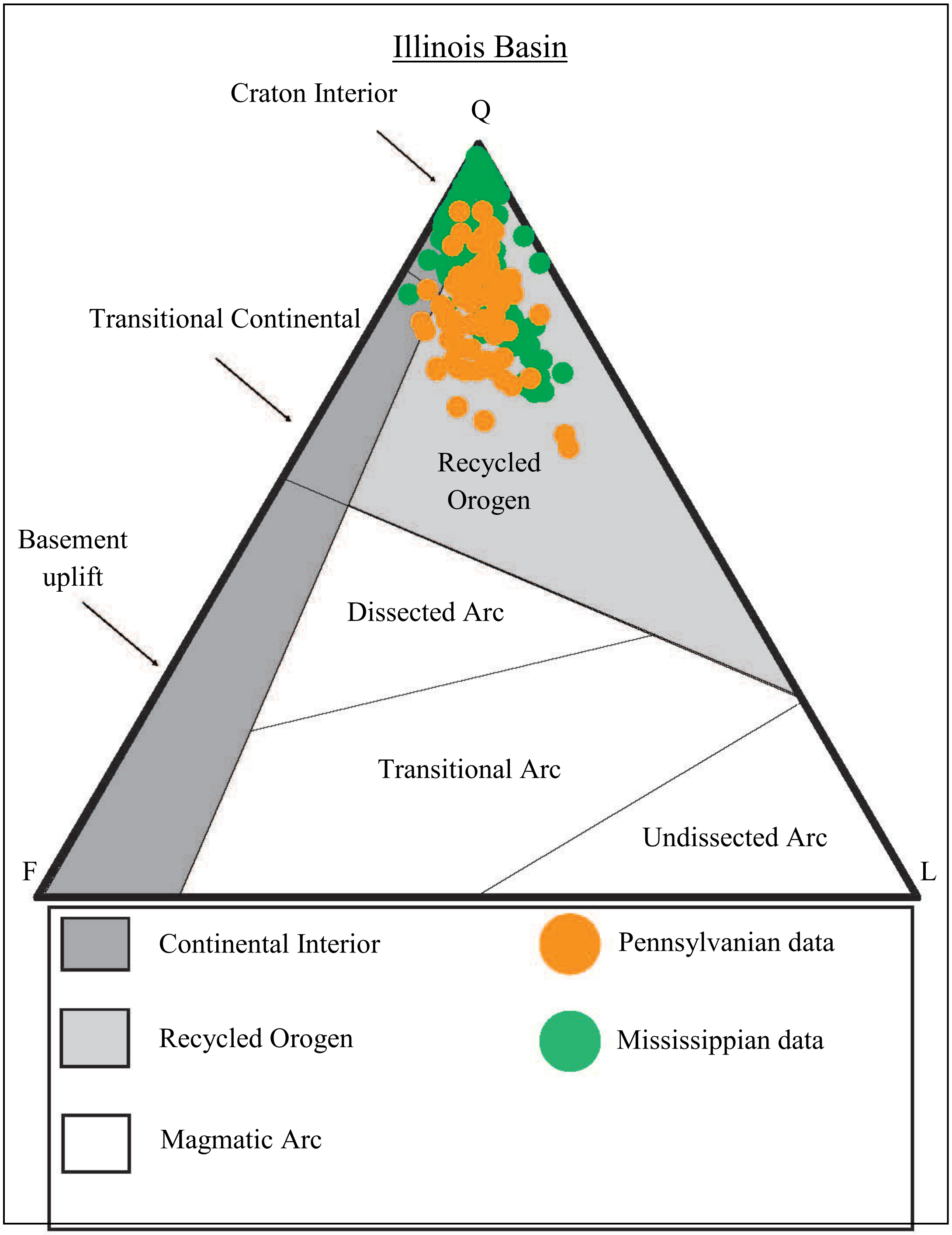

Figure 2.17: Modal compositions of Mississippian (green) and Pennsylvanian (orange) siliciclastic formations in the Illinois basin. Generally, higher relative abundances of feldspar are present compared to the Michigan or Appalachian basin, as a result of contributions coming off the Transcontinental arch to the west. There is little difference between Mississippian and Pennsylvanian compositions within the basin. Data from Siever and Potter, 1956; Siever, 1957; Laury, 1968; Mack et al., 1981; Pitman et al., 1999.

1974; Mack et al., 1981; Pitman et al., 1999) (Figure 2.17). Samples are interpreted primarily as having recycled orogenic provenance while a small percentage of samples display continental block provenance (Dickinson et al., 1983). Mississippian samples from the Illinois basin have greater relative abundances of feldspar and contain roughly twice as many samples as the Pennsylvanian that plot as having continental block provenance. The range of composition in the Mississippian (Q~64-95%, F~1-17%, L~1-30%) is interpreted as the mixing of sediment sources into a single depositional setting.

Pennsylvanian sandstones of the Illinois basin have a smaller compositional range compared to the Mississippian, with lower relative abundances of quartz in nearly half of the samples (n=62) (Q~68-86%, F~ 4-13%, L~6-24%), while the other half are quartz arenites (Q~85-100%, F~0-4%, L~0-14%) (Siever and Potter, 1956; Laury, 1968). Most of these samples plot in Dickinson et al.'s (1983) recycled orogen field, while those samples with relatively abundances of quartz above 95% plot as continent block. Quartz arenites in the Illinois basin are primarily found in the Mid-Pennsylvanian strata; a section of strata which is absent in the Michigan Basin.

Relatively high feldspar content in the Illinois basin is conspicuous. Similar amounts of feldspar are found in only some of the Pennsylvanian samples from the Appalachian basin. These samples typically have 1-2% less feldspar than the Illinois samples. Topographic sediment dispersal limits from east to west into the Appalachian foreland and the rest of the interior continent restricts the possibilities for the introduction of feldspar along the path of transportation. It is more likely that increased feldspar content is a result of local uplift and erosion of the Wisconsin and Ozark domes. Increased feldspar content has also been recorded in the southwestern samples of the Marshall Sandstone in the Michigan Basin (Monnett, 1948). It is likely that feldspar contributions may have come from the Appalachian foreland, but in smaller amounts than a local source. Submergent conditions due to an epeiric sea may have affected Appalachian detritus causing it to be stored or transported within westerly currents (Ettensohn, 2004). Submergent transport and subaerial entrenchment of streams through the interior lowlands between the Findlay and Cincinnati-Waverly Arch system (Happ, 1934) provides a link between Appalachian sedimentation and the Illinois basin.

Rock fragments reported from the Illinois basin potentially distinguish Illinois basin sources from those supply the Michigan and Appalachian basins. Carbonate and sandstone fragments generally dominate the lithic content of the Mississippian strata, but also include occurrences of plutonic and metamorphic polycrystalline quartz (Pitman et al., 1999). Quartzite pebbles and sedimentary fragments of shale and limestone dominate the Pennsylvanian lithic content in the Illinois basin (Siever and Potter, 1956). General paleoflow direction in the region dictates a source from the north-northeast, and the combination of high feldspar content and sedimentary lithic content potentially suggests the Wisconsin dome area, including Precambrian basement and Precambrian – Paleozoic quartzite of the Baraboo range, and local Paleozoic sedimentary cover as potential sources. Plutonic fragments reported only from Mississippian samples imply complete removal of subaerial Wisconsin dome plutonics in the Mississippian or plutonic grains derived from elsewhere.

2.7 DISCUSSION

Provenance trends from coarse siliciclastic dominated formations of the Michigan Basin have been generally interpreted to have primarily recycled orogenic provenance, with several quartz arenite samples plotting in the continental block provenance field (Dickinson et al., 1983). Detrital framework modes from these sandstones are dominated by monocrystalline quartz, lesser amounts of metamorphic lithic fragments, and subordinate relative abundances of feldspar. Quartz dominance, coupled with low relative abundances of feldspar and lithic fragments, suggests probable recycling of these strata (Boswell, 1933; Blatt et al., 1972; Suttner et al., 1981; Pettijohn et a., 1987; Chandler, 1988; Blatt, 1992). Lithic content from the Carboniferous strata of the Michigan Basin also suggest quartz-mica-schist and coarse siliciclastic dominated units as potential sources. Similar lithic content can be seen in the Appalachian basin, particularly in the northern parts of the basin, suggesting a Northern Appalachian source for both the Appalachian and Michigan Basins (Meckel, 1967; Aronson and Lewis, 1994; Eriksson et al., 2004. Higher relative feldspar abundances occur in the Illinois basin than in the Michigan and Appalachian basins. Communication between the Appalachian and Illinois basins during the Pennsylvanian by means of stream entrenchment (Happ, 1934), submergent conditions (Ettensohn, 2004), or combined fluvial and marine transport is probable to a degree; however, increased feldspar and lithic content consisting primarily of quartzite pebbles and sedimentary fragments (Siever and Potter, 1956; Laury, 1968) also suggest the Illinois basin may been derived from local quartzite and sedimentary units.

Exhumed strata in the Alleghanian foreland consists largely of detritus that is age equivalent to Meso-Neoproterozoic provinces (Granite-Rhyolite, Grenville orogeny, passive margin rifting detritus) and Ordovician to Mississippian (Taconic, Acadian) provinces and indicate that much of the sediment is multicyclic in nature (Gray and Zeitler, 1997; Eriksson et al., 2004; Thomas et al., 2004; Becker et al., 2005; Thomas and Becker, 2007; Park et al., 2010). Modal composition data from the Carboniferous Michigan Basin also suggest recycling of sediment. Lithic content in the Michigan Basin is dominated by metamorphic grains including quartz-mica schistose fragments which vary in relative abundance. Lower relative abundances seen in Parma Sandstone and possibly Eaton Sandstone suggest a larger contribution of sediment from mature quartz rich units like quartzite or quartz arenites. Exposed strata in the Central Alleghanian foreland do not typically include metapelites or quartzite (Bennison, 1989). The Northern Appalachian foreland (New England-southeastern Canada) provides a suitable section of quartz and mica rich schist, quartzite, and quartz arenites, which compares well to proposed source types in the Michigan Basin (Bennison, 1995). Simple exhumation, erosion, and deposition of strata from any of these areas could potentially account for compositional differences seen in the Michigan Carboniferous section.

The influence of tectonic uplift on sediment dispersal into the Michigan Basin is apparent. Two shifts in composition to quartz arenites are roughly coeval with major uplift events (Late Mississippian-Early Pennsylvanian initiation of Alleghanian orogenesis; Late Early Pennsylvanian peak of Alleghanian orogenesis). Differences between the composition of the Michigan Basin and the other basins begin to become apparent in the Early Pennsylvanian as well. Modal composition data from Pennsylvanian Appalachian basin generally includes more lithic fragments to the North, while the Michigan Basin experiences a compositional shift to a smaller lithic component. Feldspar also increases in the Appalachian basin during the Pennsylvanian, remains the same in the Illinois basin, and decreases in the Michigan Basin at this time. These compositional differences suggest potential isolation from sources supply the Illinois and Appalachian basins during the Pennsylvanian. Reactivation of the Cincinnati-Waverly-Findlay arch system as a result of the Late Mississippian Laurentian collision with Gondwana may have provided topographical boundaries, allowing sediment input from the only the north and local sources. Such reactivation also may have also been coeval with northwestward shifts in Illinois basin delta fronts (Swann, 1964) and proposed influx of sediment in the Appalachian basin from the north (Robinson and Prave, 1995).

Quartz arenites similar to the Parma Sandstone are not typically derived from crystalline rock (Suttner et al, 1981; Johnsson et al., 1988; Johnsson et al., 1991). Rather attrition of less stable feldspars and lithic fragments is the result sediment recycling, often in multiple cycles (Suttner et al., 1981; Johnsson et al., 1988; Johnsson et al., 1991). The development of the Laurentian craton throughout the Precambrian and early to mid Paleozoic, was the product of numerous convergent and collisional events (Hoffman, 1988). Uplift and subsequent erosion of previously deposited sedimentary strata in conjunction with these collisional events displaced great amounts of sediment around the continent, allowing continual weathering and compositional maturation in the process. The abundance of quartz arenite around the eastern half of the North American continent associated with Precambrian sediment (Gray and Zeitler, 1997; Thomas et al., 2004; Eriksson, 2004; Becker et al. 2005; Thomas and Becker, 2007; Park et al., 2010) suggests that Carboniferous quartz arenite from the Michigan and Illinois basins may have been derived from previously matured, recycled sublitharenite, quartz arenite, and quartzite.

Climatic controls on sediment dispersal and composition

The attrition of minerals as a consequence of climate based weathering has been well constrained and interpreted as primary influence on sediment composition (Basu, 1976; Blatt, 1978; Breyer and Bart, 1978; Mack, 1981; Suttner et al., 1981; Grantham and Velbel, 1988; DeCelles and Hertel, 1989, 1990; Johnsson and Stallard, 1989; Blasi and Manassero, 1990; Johnsson et al., 1990, Johnsson et al., 1991). Variation in quartz, feldspar, and lithic content of a given source is generally influenced by climate, although source rocks, source areas' slope, transport, and post-depositional weathering also greatly contribute (Suttner et al., 1981; Grantham and Velbel, 1988; Johnsson et al., 1991, 1989; Blasi and Manassero, 1990). The production of first cycle quartz arenites is rare and requires a combination of tropical climate, low relief, and slow depositional rates to allow dissolution of less persistent minerals (Suttner et al., 1981; Johnsson et al., 1988; Johnsson et al., 1991). Extended weathering could potentially occur as grains are trapped on expansive floodplains as well (Johnsson et al., 1989; Johnsson et al., 1991). Prevalence of climatically induced quartz arenites decreases in marine settings; however, the climatic imprint cannot impact compositional signatures enough to delete distinctions between source types such as recycled orogen or continental block (Johnsson, 1990). Climatic overprint of a proximal crystalline source would require a long term weathering scenario with very slow sedimentation rates (Suttner et al., 1981; Johnsson et al., 1988; Johnsson et al., 1991).

The Carboniferous is well known as a period of tropical, equatorial climatic conditions. Coal deposits and fossil plants (i.e.: *lycopods*) are interpreted as regional swamps which gave rise to primitive forests (Kelly, 1933; Scotese, 2002; Blakely, 2008) (Figure 2.2). Sediment was likely to become trapped in these swamps during their transport to the North American epicontinental sea, potentially losing minerals to dissolution. Thick, coeval deltaic successions of the coeval in Illinois, Indiana, Michigan, and the Appalachian basin coupled with soft sediment deformation, and transported *Lingula sp.* specimens suggest rapid sedimentation in the continental interior (Velbel and Brandt, 1989). Cyclical deposition, as a result of eustatic fluctuations in the region (Kelly, 1933, 1936; Blaine et al., 1985 dev Klein and Willard, 1989; Swezey, 2009), suggest that the amount of time needed for subaerially weathering, at least in the depositional environment, was not sufficient for the attrition of more persistent minerals (Greb et al., 2008). Potential weathering at the source area or along a dispersal path remains a possible explanation. Eustatic cyclothems and an overfilled Alleghanian basin also provide the possibility for subaqueous transport of Appalachian sediment across the Cincinnati-Waverly-Findlay arches in the late Early Pennsylvanian, providing a link between the Appalachian and Illinois basins (Tankard, 1986). Higher relative abundances of lithic fragments in the Saginaw may be a direct result of a climate driven transgression and subsequent marine connection between the Appalachian foreland and the rest of the eastern continental interior.

Potential Sediment Sources for the Carboniferous Strata of the Michigan Basin

The prevalence of quartz dominated siliciclastic strata in the Mississippian and Pennsylvanian Michigan Basin are in all likelihood the product of recycled or multicycle sediment sources. Modal composition of all strata examined exhibit recycled orogen, or recycled orogen with minor continental block provenance. Differences in these modal compositions suggest at least two different source rock types: one that produces quartz arenites like the Parma Sandstone and another that produces sublitharenite like the Marshall Sandstone and Saginaw Formation strata. Diagenetic alteration of the Eaton Sandstone's composition makes it unclear how exactly it compares to the previous formations, since subsurface data plots in both quartz arenites and sublitharenite fields. Lithic content in all formations examined is dominated by quartz-mica- and mica-schist fragments, interpreted to mean that proximal sources contained similar schist units. Quartz arenites were probably derived from lithologies that were compositionally mature prior to transportation and deposition. With these observations potential sources types for the Carboniferous section are as follows:

- The Marshall Sandstone is probably derived from a stratigraphic package or set of sources that includes quartz-mica schist, mica-schist, sublitharenite-lithic arenite sandstone, and potentially quartz-rich crystalline igneous rocks (granites and gneisses).
- The Parma Sandstone is a probable derivation from highly mature sublitharenite-quartz arenite sandstone, and quartzite; either of which may have included schist fragments. Another possibility is that the quartz rich units did not include schist fragments and said fragments originated elsewhere, eventually combining with the quartz sediment. Coarseness of the quartz grains in the Parma suggests a different source of quartz in the Early Pennsylvanian.
- Sediment in the Saginaw Formation originated in sources that were probably similar to the Marshall Sandstone, and included mica-schist, quartz-mica-schist and sublitharenite-lithic arenites sandstones. It compares particularly well with the composition of the Napoleon Marshall member.
- The origin of the Eaton Sandstone is not as clear as other units due to its diagenetically altered composition. Subsurface samples plot as quartz arenites and sublitharenite, indicating maturity and probable derivation from a previously mature sublitharenite. Schistose fragments remain present (Price and Velbel, 2000) and have to be included as a separate source or included in a previous sublitharenite. The stability of lithic fragments under abrasive, fluvial conditions (Kelly, 1936; Velbel and Brandt, 1989) suggests an influx of separate schist fragments rather than recycled lithic fragments.

Quartz arenite and sublitharenite units are seen in much of the eastern half of North America, from the Transcontinental Arch to the Appalachian range. Thick quartzite units are present in the Wisconsin area (Baraboo Range), the Grenville Central Metasedimentary Belt, and New England area. Current exposures of metapelites are found as part of the Wisconsin Dome and in Appalachians as well as the entire Grenville province. Potential contributions from crystalline rocks, likely granite and gneiss based on the high quartz content, are exposed as plutons along much of the east coast of North America, the Grenville province to the northeast, and the much of the Canadian Shield to the North.

The more compositionally mature sediment of the Parma Sandstone is likely derived from strata containing highly recycled sediment. The larger monocrystalline quartz grains and lower abundances of polycrystalline quartz suggest derivation from different sources than the other strata in this study. A small lithic component containing similar schistose fragments as the rest of the section could be indicative of a shift in geographic source areas, smaller contributions from one source area, or intense weathering of the sediment in situ, en route, or diagenetically. Canadian Shield and northern Grenville sources should not be ruled out based on the potential shift to a larger north to south component in sediment dispersal trends across the region during the Early Pennsylvanian. The continental block interpretation (Dickinson et al., 1983) of the Parma also suggests potential input from interior sources of the Canadian Shield.

Sublitharenite sandstones of Saginaw Formation show a similar composition to that of the Napoleon member of the Marshall Sandstone. Schistose lithic fragments in the Saginaw are consistent with the rest of the strata and are potentially from local sources or Appalachian sources. Similar relative abundances of lithic fragments and polycrystalline quartz also maintain that the Saginaw was derived from a source consistent with that of the Marshall Sandstone.

The Eaton Sandstone shows sublitharenite-quartz arenites in subsurface samples that have avoided significant diagenetic weathering. Schistose fragments in the Eaton remain consistent with the rest of the section, and support the idea that a metapelite source (local or Appalachian) may have consistently contributed to the Michigan Basin throughout the Carboniferous. Given the recycled nature of the strata in the Eaton Sandstone, it can be assumed these occurrences are the result of further uplift during the Alleghanian orogeny. The culmination of the Alleghanian phase of orogenesis in the late Early Pennsylvanian potentially exhumed Early Paleozoic strata contributing sediment from previously mature, Silurian-Ordovician sublitharenite units associated with the Taconic foreland.

Compiled Carboniferous modal composition data from the Appalachian foreland basin and Illinois basin suggest shifting sediment sources within the eastern North America (Ul Hoque, 1968; Martin and Henniger 1969; Graham et al., 1976; Mack et al., 1981; Sheehan, 2002; Reed, 2003; Becker et al., 2005; Sager, 2007; Dodson, 2008; Peavy, 2008). The Mississippian Appalachian basin is typically dominated by extensively recycled sediment sources, likely having been exhumed from passive eastern margin deposits (Gray and Zeitler, 1997; Thomas et al., 2004; Eriksson, 2004; Becker et al. 2005; Thomas and Becker, 2007; Park et al., 2010). Pennsylvanian deposits show an increase in both feldspar and lithic fragment content, indicating an additional first-cycle source or less extensively recycled strata as an exhumed source. Mississippian modal compositions from the Illinois basin suggest increased input of feldspar into the Illinois basin, likely from a local source, while the Michigan Basin received a greater percentage of lithic fragments and the Appalachian foreland strata contained primarily quartz. These differences suggest a source that was not in the Appalachian region. Pennsylvanian quartz arenites in all three basins imply the potential for a similar source or conditions, while relatively high lithic and feldspar content in the Illinois and Appalachian basins suggests yoked basins, not including the Michigan Basin.

2.8 CONCLUSIONS

Modal compositions from Mississippian and Pennsylvanian sandstones in the Michigan Basin are dominated by quartz grains, primarily monocrystalline quartz, along with relatively low abundances of metamorphic lithic grains, and minor occurrences of feldspar. Most clastic formations in the Upper Paleozoic plot in recycled orogen field, with several samples from the Early and Late Early Pennsylvanian plotting in the continental block field (Dickinson et al., 1983). Paleoflow data indicates sources generally from the northeast for the Michigan Basin, as well as with secondary contributions from more local sources. Detrital framework modes of Mississippian and Pennsylvanian strata in the Michigan Basin support the following ideas:

1. Despite similarities in depositional environment, paleoflow direction, and sedimentology, the unconformity-bound Carboniferous units of the Michigan Basin each represent a distinct depositional system. Though two general interpretations are seen, they alternate upsection through time, leading to the conclusion that each unit has changed compared to the one underlying it.

2. Modal composition trends from this study are interpreted as detritus contributions from recycled orogen and continental block sources during the Carboniferous. The Marshall Sandstone and Saginaw Formation are thought to have been derived primarily from recycled orogen sources, probably from the Appalachian foreland, Grenville province,

and Granite-Rhyolite province. The Parma Sandstone and Eaton Sandstone are derived from a combination of similar recycled orogen sources and contributions from continental block sources such as the Superior province. The inclusion of detritus from these areas could also be a result of foreland strata containing recycled sediment.

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CHAPTER 3: HEAVY MINERAL ANALYSIS OF SANDSTONE DOMINATED CABONIFEROUS STRATA IN THE MICHIGAN BASIN: IMPLICATIONS FOR SEDIMENT PROVENANCE AND DISPERSAL PATTERNS OF EASTERN NORTH AMERICA

3.1 INTRODUCTION

Tectonically active margins provide numerous opportunities to explore geomorphologic changes and the evolution of regional provenance. However, areas in a prolonged state of tectonic quiescence contiguous with, but far from active margins are more difficult to understand. Eastern North America contains three commonly defined tectonic provinces: 1) structurally deformed Mesoproterozoic and Paleozoic rocks of the Appalachian and Ouachita orogenic belts, 2) relatively undeformed Paleozoic strata of the Appalachian and Ouachita foreland basins and associated intracratonic basins, and 3) Archean-Proterozoic age rocks of the Canadian Shield and associated provinces. Features generally associated with active margin tectonics are well defined and understood, although many models do not explain how these features interact with more subtle features of the continental interior. Intracratonic basins in the eastern interior of North America are centrally located between tectonic provinces of varied age and lithology, providing a location sensitive to changes in sediment dispersal in much of the region. The intracratonic setting of the Michigan Basin provides an opportunity to explore the evolution of sedimentation and dispersal paths in an area experiencing only subtle changes as a result of regional tectonic activity. Basins of the Great Lakes region have been researched thoroughly in terms of their geological history (Potter and Siever, 1956; Siever and Potter, 1956; Potter and Pryor, 1961; Sleep and Sloss, 1978; Root and Onasch, 1999; Howell and van der Pluijm, 1990; 1999); however, the relationships between intracratonic basins, tectonically active margins, and associated provinces are only loosely constrained.

The Michigan Basin contains a temporally and spatially discontinuous stratigraphic record of mixed clastic, carbonate, and evaporitic strata spanning the Paleozoic that records a complicated subsidence and depositional history (See Chapter 2 for full Geologic Overview). Late Devonian and Early Mississippian siliciclastic strata in the Michigan Basin indicate an initial influx of clastics through a fluvial-deltaic depositional system (Stearns, 1933; Monnett, 1948; Swann, 1954; Ettensohn, 2004). Subsequent deformation, coeval with crustal loading, during Alleghanian orogenesis may have altered sediment dispersal paths, transporting detritus from alternative sources to the Michigan Basin. Analysis of heavy minerals in siliciclastic strata has long been a useful provenance tool (Morton and Hallsworth, 1999). This study compiles previously reported heavy mineral data in an attempt to further enhance the understanding of the provenance of these Carboniferous strata by testing the following hypotheses:

1. Heavy mineral assemblages in the Mississippian and Pennsylvanian coarse clastic strata of the Michigan Basin agree with the changes in provenance indicated by detrital framework modes, demonstrating a distinct shift in heavy minerals in the each overlying unit. Heavy mineral assemblages demonstrating different levels of compositional maturity are likely to depict these distinctions best, as a compositionally mature unit containing only high persistence minerals, overlain by a compositionally immature unit would be clearly distinct.
2. Rock types providing sediment to the Carboniferous Michigan Basin were fairly consistent over time, as is evidenced by the abundance of lithic content by schist fragments. All units would show a relatively similar heavy mineral suite and anything missing is likely to be counted as a result of attrition during the weathering process.

3. The difference in provenance is the result of two depositional systems: a pre-Alleghanian orogeny, Mississippian system and a Pennsylvanian system reflecting ongoing Alleghanian orogenesis. Here the heavy mineral suites would be unique in the Mississippian Marshall Sandstone, while a relatively consistent suite would be present across the Pennsylvanian units (Parma Sandstone, Saginaw Formation, and Eaton Sandstone).

3.2 METHODS

Detrital framework modes of Carboniferous sandstones in the Michigan Basin show variability between quartz arenite and litharenite compositions, providing insight into the maturity and potential sources of these strata (Boothroyd et al., 2011). Upsection compositional variability suggests a minimum of two distinct sediment sources, a recycled orogen, the other a continental block. High compositional maturity of sandstones in some units indicates either a multicycle origin from compositionally mature sandstones or extensive depletion of feldspar and lithic fragments by weathering in the source area or along the dispersal path. Previous accounts of heavy mineral occurrences (Kelly, 1930; Stearns, 1933; Kelly, 1936; Monnett, 1948; Hudson, 1957; Davis and Breadwell, 1978; Martin, 1982; Long et al., 1988; Westjohn et al., 1990; Westjohn and Sibley, 1991; Westjohn et al., 1991; Kramer and Westjohn, 1991; Zacharias, 1992; Price and Velbel, 2000) allow for comparison and interpretation of heavy mineral suites in the Mississippian and Pennsylvanian strata. Heavy mineral suites were compiled from previous work and reorganized according to order of persistence (Table 3.1).

Pettijohn's (1941) order of persistence refers to a simple ranking system in which relative frequency of occurrence of a mineral over time is measured. "Persistence" refers to historical data trends relating occurrence and abundance over time; Pettijohn (1941) demonstrated that increasingly older sedimentary rocks have increasing lower abundances and fewer occurrences of most heavy minerals than younger rocks. A larger number indicates higher frequency with younger age relative to older sediments while a lower rank is assigned to a mineral that persists even in older sediments. Negative numbers refer to a mineral more abundant in older sediment than younger sediment. Siliciclastic units containing dominantly low ranked minerals (more persistent) can be considered more compositionally mature (Pettijohn et al., 1972; Blatt et al., 1980; Blatt, 1982). The observations compiled in Table 3.1 are considered with the following assumptions:

- Heavy minerals were correctly identified by the previously published primary research;
- Minerals shown in the table provide an accurate representation of the entire formation;
- The absence of a more persistent mineral with the presence of a less persistent mineral implies the absence of the more persistent mineral from a proximal source rock, and;
- The absence of less persistent minerals in the presence of more persistent minerals cannot clearly be attributed to attrition or to the lack of less persistent minerals in a proximal source rock.

Cassiterite, chlorite, and leucoxene were included in the data due to their presence in reported mineral suites. Environments of formation were taken from published mineralogy text (Imbirie and van Andel, 1964; Briggs, 1965; Stattegger, 1987; Dill, 1998; Blatt et al., 2006; Mange and Wright, 2007; Dyar, 2008) and are used to interpret general categories of ultimate source rocks.

3.3 HEAVY MINERAL META-ANALYSIS

As in the modal composition data, variations can be seen between several of the formations; however, the heavy mineral suites allow us to explore these variations in a finer level of detail. In the original primary literature, the Marshall Sandstone is reported as an undifferentiated formation, an eastern assemblage, and a western assemblage; these subdivisions are shown in Table 3.1, as they were reported in original publications.

Marshall Sandstone

The Marshall Sandstone contains a heavy mineral suite that varies spatially across the basin. In the order of Pettijohn's (1941) order of persistence (Table 3.1), the suite of minerals ranges from very persistent muscovite (-2), rutile (-1), zircon (1), and tourmaline (2) to non-persistent actinolite (21), and also includes cassiterite, chlorite, and leucoxene. Among minerals of intermediate persistence, monazite (3), staurolite (9), kyanite (10), andalusite (13) – sillimanite (18), and diopside (20) are absent. Eastern and western assemblages vary in the content of several heavy minerals. The western assemblages is generally distinguished by the scarcity of rutile, the dominance of garnet as the most abundant heavy mineral, the presence of pink zircon, relatively unweathered hornblende, and the presence of actinolite (Stearns, 1933; Monnett, 1948). The eastern assemblage generally consists of more severely weathered heavy minerals, and is conspicuous by the scarcity of garnet and hornblende, as well as the absence of pink zircon, and actinolite (Stearns, 1933; Monnett, 1948).

Parma Sandstone

Fewer heavy minerals are reported from the Early Pennsylvanian Parma Sandstone, and those that are reported represent a narrow increment of persistence compared to the Marshall

Sandstone. Muscovite (-3), zircon (1) tourmaline (2), and garnet (4) are present in abundance, and hornblende (12) was also identified. Assuming hornblende has been correctly identified, a range of moderately persistent minerals are missing: monazite (3), biotite (5) – epidote (11). Rutile is not reported directly from the Parma but is mentioned as common in coeval strata of the Illinois basin (Siever and Potter, 1956).

Saginaw Formation

Upsection in the younger Pennsylvanian strata, the Saginaw Formation displays the most compositionally mature suite of minerals; muscovite (-2), zircon (1), and tourmaline (2). It should be noted that reported heavy minerals are only the most common. Further minerals are likely present, but these are unknown. Rutile (-3) is absent from the Saginaw.

Eaton Sandstone

The Late Early Pennsylvanian Eaton Sandstone is reported as having a diverse heavy mineral suite compared to most of the Pennsylvanian strata. Muscovite (-2), zircon (1), tourmaline (2), monazite (3), garnet (4), apatite (6), staurolite (9), kyanite (10), and hypersthene (19), as well as cassiterite are present. Notably absent minerals include rutile (-1), biotite (5), ilemnite (7), magnetite (8), and epidote (11) – sillimanite (18). Rutile (-3) is absent from the entire Pennsylvanian section

3.4 PROVENANCE INTERPRETATIONS

Many heavy minerals occur in a variety of mineral forming settings providing the opportunity to look for commonly occurring rock types. the presence of a large range of heavy

Table 3.1: Heavy minerals of the Carboniferous sandstones in the Michigan Basin. Persistence after Pettijohn, 1941. Data from: (1) Kelly, 1930; (2) Stearns,1933; (3) Kelly, 1936; (4) Monnett, 1948; (5) Siever and Potter, 1956; (6) Hudson, 1957; (7) Shideler, 1969; (8) Martin, 1982; (9) Westjohn et al., 1990; (10) Westjohn and Sibley, 1991; (11) Westjohn et al., 1991; (12) Zacharias, 1992; (13) Price, 1994. * denotes scarcity. The "east + west" Marshall column represents minerals reported from entire basin

Eaton sandstone   Saginaw Formation   Parma sandstone   Marshall Sandstone

Heavy Minerals	Order of persistence	Environment of Formation	Unit
Anatase	-3	Felsic igneous rocks, eclogite, granofels	
Muscovite	-2	Felsic igneous rocks, Si-undersaturated igneous rocks, metapelites, eclogite	Eaton, Saginaw, Parma, Marshall
Rutile	-1	Felsic igneous rocks, eclogite, granofels	Marshall
Zircon	1	Felsic-intermediate igneous rocks, gneiss	Eaton, Saginaw, Parma, Marshall
Tourmaline	2	Felsic igneous rocks	Eaton, Saginaw, Parma, Marshall
Monazite	3	Felsic igneous rocks, Si undersaturated igneous rocks	Eaton
Garnet	4	Eclogite, blueschist, chert,gneiss, metapelites: garnet-sillimanite zones,	Eaton, Parma, Marshall
Biotite	5	Felsic -Intermediate igneous rocks, metapelites, gneiss, greenschist,	Marshall
Apatite	6	Felsic igneous rocks, Si undersaturated igneous rocks, gneiss	Eaton, Marshall
Ilemnite	7	Felsic-mafic igneous rocks, gneiss, greenschist-granofels	Marshall
Magnetite	8	Felsic-mafic igneous rocks, gneiss, peridotite, chert	Marshall
Staurolite	9	Metapelites-staurolite zone	Eaton
Kyanite	10	Eclogite, metapelites-kyanite zone	Eaton
Epidote	11	Felsic-intermediate igneous rocks, gneiss, marble, greenschist, amphibolite	Marshall
Hornblende	12	Felsic-intermediate igneous rocks, amphibolite	Parma, Marshall
Andalusite	13	Felsic igneous, mid grade metapelites	
Topaz	14	Felsic igneous rocks	
Sphene	15	Felsic - intermediate igneous rocks, greenschist, granofels	
Zoisite	16	Eclogite	
Augite	17	Intermediate-ultramafic igneous rocks,	
Sillimanite	18	Metapelites - Sillimanite zone	
Hypersthene	19	Mafic igneous rocks	Eaton, Marshall
Diopside	20	Ultramafic igneous rocks, marble, granofels, chert, marble, gneiss,	
Actinolite	21	Greenschist	Marshall

minerals is indicative of compositionally immature sandstone (Pettijohn et al., 1972; Blatt et al., 1980; Blatt, 1982). Initial assumptions still holding, it can be inferred that absences of minerals within our range of persistence lower than the least persistent mineral present can be attributed to their absence from the proximal source. Numerous environments of formation are possible for many of the minerals, although the most common source rock types include felsic – intermediate igneous rocks, gneiss, greenschist, and eclogite. Several diagnostic minerals are present, including tourmaline, which forms only in felsic igneous rocks, and actinolite, a mineral exclusive to greenschist (Ehlers, 1972; Redfern et al., 1989; Spear, 1993; Morse, 1994; Young, 2003). Many of these minerals are persistent enough to survive through recycling, making it difficult to distinguish a proximal source type.

Marshall Sandstone

Heavy mineral suites of the Marshall Sandstone are interpreted as a combination of sediment derived from felsic igneous sources, gneissic terranes, and greenschist facies, although proximal sources may have been recycled and previously included these minerals. Abundant rutile is present in only the eastern assemblage. Western assemblages from the Marshall contain minerals of similar persistence, but in difference abundances or with different characteristics. The western suite of minerals is dominated by purple garnet (4) and contains pink zircon, which is not seen in the eastern assemblage. Each of these is characteristic of Precambrian-Cambrian units in the Wisconsin/Huronian regions. Actinolite (21) serves as an indicator mineral as well, being formed in primarily in greenschist (Redfern et al., 1989; Spear, 1993). Chlorite, epidote, ilmenite, and biotite are also found within greenschist, as well as other lithologies. Pink zircon is characteristic of Huronian (pre-Penokean) and Lake Superior assemblages to the north and northwest of the basin (Tyler, 1963; Morgan and Auer, 1941). High abundances of garnet are characteristic of Precambrian-Cambrian coarse siliciclastic units from Huronian rocks in Wisconsin as well (Tyler, 1963). The eastern assemblage contains minerals of a similar persistence, just with different characteristics. Minerals of the same general environments of formation (felsic igneous rocks, gneiss, and greenschist) are present for both sets as well, suggesting increased attrition of the eastern assemblage or a mixing of sediment types near the middle of the basin (Stearns, 1933). The absence of actinolite and pink zircon, combined with the limited presence of weathered hornblende, and scarcity of garnet leads suggest a different source for the eastern assemblage (Stearns, 1933). Occurrences of felsic igneous rocks, greenschist formations, gneissic terranes, and siliclastic formations containing sediment from all of these are present in Keweenawan/Huronian(pre-Penokean)/Lake Superior rocks to the north-northwest, the Grenville province to the northeast, and the Appalachians to the east of the Michigan Basin, allowing for the possibility of numerous sources. Greenschists in the Keweenawan and northwestern region of the Grenville province would be in close proximity to suggested headwaters of the Michigan river (Swann, 1963, 1964; Archer and Greb, 1995) but may have also come down slope from the Huronian rocks in the Wisconsin dome area, as indicated by zircon and garnet characteristics. High concentrations of tourmaline, as well as zircon and other persistent minerals in the eastern assemblage indicate recycling.

Parma Sandstone

Heavy minerals of the Parma Sandstone are compositionally mature as compared to the Marshall. The presence of muscovite (-2), zircon (1), tourmaline (2), and garnet (4) are indicative of felsic igneous and metamorphic sources; however, such source rocks cannot be identified as proximal sources with any certainty from these persistent heavy minerals due to their persistence during recycling from older rocks. Rutile is not directly reported from the

Parma Sandstone, but it is said to be common in age equivalent sandstones in the Illinois basin (Siever and Potter, 1956). This raises the possibility for recycling of heavy minerals and attrition of less persistent minerals either during earlier cycles or by intense attrition during production, dispersal, deposition and/or diagenesis of the Parma. The presence of hornblende does not change probable felsic igneous or gneissic sources. Garnet, however, suggests input from a mid-grade metapelite. Amphibolite grade metamorphic facies are present to the west and to the North in the Chocolay group of the Superior Province (LaBerge and Myer, 1984), as well as northern portions of the Grenville province, as is greenschist. Garnetiferous schist in the Grenville province and Adirondack region are nearby garnet rich sources (McCartney, 1931). Hornblende is unlikely to persist through one or more episodes of recycling as the mineral weathers quickly in a number of environments (Frankel, 1977; Velbel, 1989; Anand and Gilkes, 2003) and is probably from a local crystalline source.

Saginaw Formation

The Saginaw Formation exhibits the most compositionally mature heavy mineral suite, with only muscovite (-2), zircon (1), and tourmaline (2) having been reported as the most dominant minerals (Kelly, 1936). Occurrences of other minerals are not reported. These more persistent minerals are generally derived from felsic igneous and gneissic lithologies. High relative abundances of these more persistent minerals are indicative of continental margin derivation (Nechaev and Ishphording, 2003); however, the eastern margin has been episodically active since the Proterozoic, and therefore continental margin signatures are prevalent throughout many clastic formations. Less persistent minerals may be absent as a result of destruction in the Saginaw source area and/or depositional system, recycling from compositionally mature sedimentary rocks lacking these minerals, or may have simply not been reported. A higher relative abundance of lithic fragments also suggests that mechanical weathering of less persistent minerals is improbable, and that additional minerals are likely present. Knowing the entire suite of heavy minerals is essential in understanding how the Saginaw relates to the other units in the Michigan Basin. The disappearance of rutile from the Pennsylvanian section suggests a different source from the Early Mississippian.

Eaton sandstone (Grand River Formation)

The Late Early Pennsylvanian Eaton sandstone heavy minerals indicate an evolving set of sources contributing sediment to the Michigan Basin. Persistent minerals (muscovite – tourmaline) derived from felsic igneous and gneissic regions are present, with the additional presence of monazite and apatite implying an influx of sediment from newly exposed felsic and gneissic sources or a reactivation of a source area similar to that contributing to the Mississippian Marshall Sandstone. Hypersthene, typically associated with mafic rocks, is rare but present in the Eaton. The presence of numerous less persistent minerals and monazite, which was not present in the Marshall, suggests a source containing sediment derived from different felsic igneous or gneissic rocks. Also present are a series of minerals typically associated with a number of metamorphic lithologies, particularly metapelites. Staurolite (9) and kyanite (10) are particularly diagnostic as they originate from mid-to high grade metapelites of the respective kyanite and staurolite zones (Redfern et al., 1989; Spears, 1993). Mafic lithologies as well as chert can be found from the Wisconsin highlands to the northwest – to the Grenville and Appalachian provinces to the east, providing numerous potential sources. Sediment dispersal paths of the Eaton Sandstone and paleogeographic reconstructions from the Late Early Pennsylvanian indicate a southwesterly trend (Shideler, 1969) making it probable that sources were located to the present day northeast. The occurrence of less persistent minerals suggests influence from more local or less extensively weathered sources. Newly exposed felsic igneous and gneissic sources were more likely to the north.

3.5 DISCUSSION

The absence of moderately persistent minerals from assemblages presents an interesting problem. The occurrence of less persistent minerals contradicts any possibility of attrition of such minerals from a proximal source area. Rather, gaps in the mineral suite should be attributed to the scarcity or absence of the absent minerals from the proximal source. The frequency of felsic igneous rocks and gneiss as potential sources coupled with variable mineral suites, and fairly consistent NE-SW sediment dispersal suggests several possibilities: 1) igneous and metamorphic proximal sources of differing composition in the same region, 2) the integration of igneous and metamorphic sources from a broad area in a large scale fluvial system, and 3) the inclusion of mineral suites from numerous sources in a recycled or multi-cycle setting. The variety of absent minerals implies that there were likely variable compositions; however, attrition of more persistent minerals and survival of less persistent minerals is impossible. This presence of mineral suites containing less persistent minerals and missing more persistent minerals must involve recycled sediment. Derivation of these mineral suites from a single coarse siliciclastic, recycled unit explains the consistency of lithic source content seen in the modal composition data but not upsection variability in the mineral assemblages. Exhumation of three or four compositionally distinct units, each containing significant amounts of quartz and mica-rich schist are needed.

Derivation of Michigan Basin siliciclastic strata from Appalachian sources with minor contributions from local sources is generally accepted though difficult to prove as adequate sources surround much of the Michigan Basin presently, and recycled Meso-Neoproterozoic and Early-Mid Paleozoic sediment covered much of the eastern continental interior in the Mid-Late Paleozoic (Stearns, 1933; Kelly, 1936; Monnett, 1948, Potter and Siever, 1956; Siever and Potter, 1956; Potter and Pryor, 1961; Shideler, 1969, Ells, 1979; Fisher et al., 1988). Mineral assemblages here suggest that local sources are a probable secondary source, at least in the Early Mississippian, with an Alleghanian induced shift in provenance in the Pennsylvanian. The relative compositional immaturity of the Marshall Sandstone, seen in both modal composition and heavy mineral assemblages, is consistent with unobstructed Acadian sediment dispersal across the Great Lakes region (Tankard, 1986; Ettensohn, 2004) and secondary input from the Huronian (Paleoproterozoic pre-Penokean) rocks of Wisconsin dome or nearby Canadian Shield. Increasing Early Pennsylvanian compositional maturity revealed by detrital framework modes, and a moderately mature heavy mineral suite further suggest input from a local source, as well as a mature source. The inclusion of multiple sources is favorable for the explanation of consistent additions of quartz mica-schist to multicyclic sediment, most recently derived from Alleghanian exhumed Early-Mid Paleozoic strata. The disappearance of highly persistent rutile in the Pennsylvanian section also exposes the waxing and waning of multiple sources.

The overlying Pennsylvanian strata show a distinct shift in compositional maturity. Heavy mineral assemblages from the Parma Sandstone and Saginaw Formation are both compositionally mature, despite the presence of garnet and hornblende in the Parma. The Saginaw also seems to be incompletely reported, as only the most common minerals (zircon and tourmaline) were reported. Based on the previously established idea that absent minerals reflect either attrition or absence from a source, it is demonstrated by the presence of different mineral suites in the Parma and Saginaw that varied depositional systems were in play at the respective times of deposition. A compositionally immature heavy mineral suite in the overlying Eaton further depicts the differences between the heavy mineral suites of the Carboniferous units. Heavy minerals in the Eaton show a range of persistence near that of the Marshall but with a different set of minerals. Low persistence minerals in the assemblage are unlikely to have survived intense weathering or multiple cycles, and reveal newly exposed strata or a shift toward a source of a different composition. These shifts in provenance demonstrate distinct depositional systems during the Mississippian, earliest Pennsylvanian, and the remainder of the Early Pennsylvanian.

3.6 CONCLUSIONS

Deformation as a result of active margin tectonics has the potential to influence sediment dispersal in the tectonically quiescent areas of the continental interior. Heavy mineral suites of the Michigan Basin's Mississippian and Pennsylvanian coarse siliciclastic dominated formations clearly define at least three distinct sources or sets of sources (Early Mississippian, earliest Pennsylvanian, late Early Pennsylvanian). The changes in sediment sources are approximately coeval with collisional events during the Alleghanian orogeny. Distinct minerals and characteristics of minerals help constrain source areas for much of the Carboniferous section. Based on these observations the following conclusions can be made:

1. Heavy mineral suites in the Carboniferous sandstones of the Michigan Basin are distinct and are interpreted as distinct depositional systems rather than a single system or a

division only between the Mississippian and Pennsylvanian. Shifts from compositionally immature to mature across the Mississippian-Pennsylvanian boundary, and from mature to immature within the Early Pennsylvanian best supports the idea of a dynamic environment with variable provenance throughout the Carboniferous.

2. Source rocks throughout the Carboniferous are generally inconsistent. Contributions from the west (Huronian greenschist, distinct zircon and garnet characteristics) are present in the Mississippian. Garnet, potentially derived from garnet-grade schist of the Wisconsin dome or Grenville province, is seen in the Early Pennsylvanian. Kyanite- and staurolite-grade metapelites from the Grenville-Northern Appalachian range supply sediment during the Late Early Pennsylvanian. Constant input of zircon and tourmaline is likely derived from a number of granite, gneiss, quartzite, and sublitharenite sources in the region. Unchanging paleocurrent and sediment dispersal patterns suggest a common depositional region for newly exhumed strata, prior to transportation into the Michigan Basin.

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CHAPTER 4: PRELIMINARY U-PB DETRITAL ZIRCON AGES AND PROVENANCE TRENDS FROM THE UPPER PALEOZOIC STRATA OF THE MICHIGAN BASIN

4.1 INTRODUCTION

Late Paleozoic models of sedimentation in eastern North America describe widespread sedimentary cover as a result of massive prograding Alleghanian clastic wedges (Thomas, 1988; Ettensohn, 2004). These wedges deposited up to several kilometers of sediment in the Appalachian foreland basin, overfilling it, and spreading out across the continental interior (Tankard, 1986; Castle, 2001). Topographic lows at the distal extent of the Appalachian foreland, such as the Michigan and Illinois basins, are thought to have received sediment from these events, recording changes sedimentation rates and dispersal patterns associated with the Late Paleozoic uplift and exhumation. Strata exhumed by the Alleghanian orogeny are generally considered to be a mix of recycled or multicyclic Meso-Neoproterozoic (Granite-Rhyolite province, Grenville province, passive margin, and syn-rift strata) and Paleozoic (Taconic-Acadian) age sediment (Gray and Zietler, 1997; Eriksson et al., 2004; Thomas et al., 2004; Becker et al., 2005; Thomas and Becker, 2007; Park et al., 2010). Incorporation of this Central Appalachian sediment into Mississippian and Pennsylvanian sandstones of the Michigan and Illinois basins is generally accepted based on paleocurrent data, sediment isopachs, and depositional settings (Stearns, 1933; Monnett, 1948; Potter and Siever, 1956; Siever and Potter, 1956; Potter and Pryor, 1961; Swann, 1963, 1964, 1965; Shideler, 1969). Local Mesoproterozoic–Cambrian sources from around the basins have also been proposed as a result of modal composition and heavy mineral content (Stearns, 1933; Monnett, 1948, Siever and Potter, 1956). Relationships between the Appalachian foreland, Michigan Basin, and Illinois basin remain poorly constrained (Pirtle, 1932; Kelly, 1936; Quinlan and Beaumont, 1984; Howell and van der Pluijm, 1990, 1999; Root and Onasch, 1999).

Alleghanian influence on sediment dispersal patterns in the eastern interior are also poorly understood. Low-lying interior areas are typically supplied with sediment from local, gravity driven sedimentation during tectonic quiescence. The Michigan Basin, for example, sits between the highlands of the Wisconsin dome and arch to the west, the Canadian Shield, and associated provinces to the north, the Grenville province to the immediate east, and geographically bounding structural arches around the southern half of the basin and would expect to receive sediment from all topographic highs given a lack of external variables like continental tilt or significant regional relief. Sediment dispersal patterns in the Michigan Basin have been shown to be dominantly northeast to southwest (Potter and Siever, 1956; Potter and Pryor, 1956; Shideler, 1969), limiting contributions from the arches to the south, and Wisconsin highlands to the west, and including sediment from regional-scale clastic wedges.

Detrital framework modes and heavy mineral analysis reveal shifts in provenance, coeval with uplift events on the eastern margin of Laurentia (see Chapters 2 and 3). All units are dominated by monocrystalline quartz ($Qm > 50\%$) and contain little feldspar ($F < 5\%$). The Mississippian Marshall Sandstone contains a relatively high abundance of lithic fragments compared to Pennsylvanian strata, as well as a compositionally immature mineral suite, partially derived from nearby greenschist sources to the northwest. The highest abundances of feldspar come from southwestern samples of the Marshall Sandstone further indicating secondary, west-east local sediment dispersal (Stearns, 1933; Monnett, 1948). Compositional maturity increases in the Early Pennsylvanian Parma Sandstone as the unit is dominated by monocrystalline quartz ($Qm \sim 92\%$) and contains a heavy mineral suite dominated by highly persistent muscovite, zircon, and tourmaline, but also includes garnet and hornblende (Siever and Potter, 1956). This shift is roughly coeval with the onset of Alleghanian orogenesis. The Early Pennsylvanian Saginaw Formation contains increased abundances of lithic fragments and a heavy mineral suite dominated by zircon and tourmaline (Kelly, 1936). Further occurrences of minerals are not documented though are thought to be present. Late Early Pennsylvanian samples from the Eaton Sandstone show increased abundances of quartz, bordering on a quartz arenite composition, but also contain a diverse suite of heavy minerals spanning the range of persistency. Kyanite- and staurolite-grade metapelites of the Grenville or Northern Appalachians are thought to be sources. All units are thought to contain recycled sediment as they typically plot in Dickinson et al.'s (1983) recycled orogen field, with the most quartz-rich samples (Q>95%) plotting in the continental block field.

The dominance of highly persistent and stable zircon over other heavy minerals in all strata, allows for a comparative study of zircon igneous ages. The aim of this study is to further constrain the understanding of sediment dispersal patterns and proximal source areas for these strata using U-Pb detrital zircon geochronology. Much of the interpretation of source areas listed above is based on source lithology compared to heavy mineral suites and modal composition. Tests of the following hypotheses will help to constrain quantitative ages, initial igneous sources, and generalized sediment dispersal patterns for the Carboniferous strata of the Michigan Basin:

1. Sediment from coarse siliciclastic dominated units of the Carboniferous Michigan Basin is recycled Appalachian sediment and will therefore contain Mesoproterozoic-Mid Paleozoic ages found in strata from the Central Appalachian basin. Granite-Rhyolite, Grenville/Keweenaw, Iapetan syn-rift, and Taconic-Acadian age equivalent strata will be present.

2. Derivation of sediment from sources other than recycled Appalachian strata will produce primary age peaks that do not match up with those seen in the Central Appalachian strata. The Michigan Basin, sitting amongst many potential sources will contain sources not seen in the Central Appalachian basin.
3. The alignment of provenance shifts in the Early Pennsylvanian and Late Early Pennsylvanian seen in previous data sets will be seen in the detrital zircon signature as well. Maturity often comes with repeated cycles and age, therefore zircon peaks in the Parma Sandstone will show a greater relative probability of older Precambrian (Mesoproterozoic - Archean) age grains.

4.2 METHODS

Detrital zircons obtained for U-Pb detrital zircon geochronology come from 5 samples of Mississippian and Pennsylvanian sandstone outcrops, which are last relict strata of the Late Paleozoic exposed in the Great Lakes area. Marshall Sandstone from two samples of Lower Marshall Sandstone, Parma Sandstone, Saginaw Formation, and Eaton Sandstone of the Grand River group were all obtained and processed for detrital zircon samples. Forty kilograms of each sample were crushed, ground, and run across a Wilfley table to separate sediment for density. Metallic minerals were then removed from the remaining dense minerals and sediment using a hand magnet. Further density separation was done using dense heavy liquids, typically allowing only zircon and apatite to settle out. The remaining zircon and apatite crystals were run through a Franz magnetic separator to ensure zircons alone were being dated.

After heavy mineral separation, the remaining grains were sent to the Arizona Laserchron center at the University of Arizona for mounting. The center's LA-ICPMS was used to measure isotopic ratios of uranium, lead, and thorium from which decomposition of samples were determined, providing an initial crystallization age. Samples were run by myself and Dr. Brian Hampton with the aid of Mark Pecha. Discordant data, typically zircons which have experienced lead loss as a result of metamorphism, were removed from the data set, leaving only crystallization ages. Interpretations of maximum depositional age for each unit are also loosely constrained by the youngest crystallization age in a sample (Dickinson and Gehrels, 2009).

4.3 U-PB DETRITAL ZIRCON AGES

U-Pb detrital zircon ages for the Late Paleozoic strata of the Michigan Basin show consistent age peaks throughout much of the section (Figure 4.1). General occurrences of peaks at 420-470, 1000-1050, 1130-1160, and 1300-1500 Ma are all present. Secondary peaks are seen in only two of the units and show increased number of grains from 1600-1800, 1800-1900, and 2500-2800 Ma.

Marshall Sandstone (**MIB-062510-01**): This sample of Marshall Sandstone contains primary peaks of 450-500, 1015, 1226, 1461 Ma. Peaks are strong with few grains outside of peaks.

Marshall Sandstone (**MIB-062510-02**): This sample of Marshall Sandstone contains primary peak ages of449, 1012, 1149, and 1493 Ma. Other reported ages are 350-390, 600-800, 1300-1350, 1600-1900, 2000-2100, and 2700-2800 Ma. These occurrences contain generally contain 1-3 grain each.

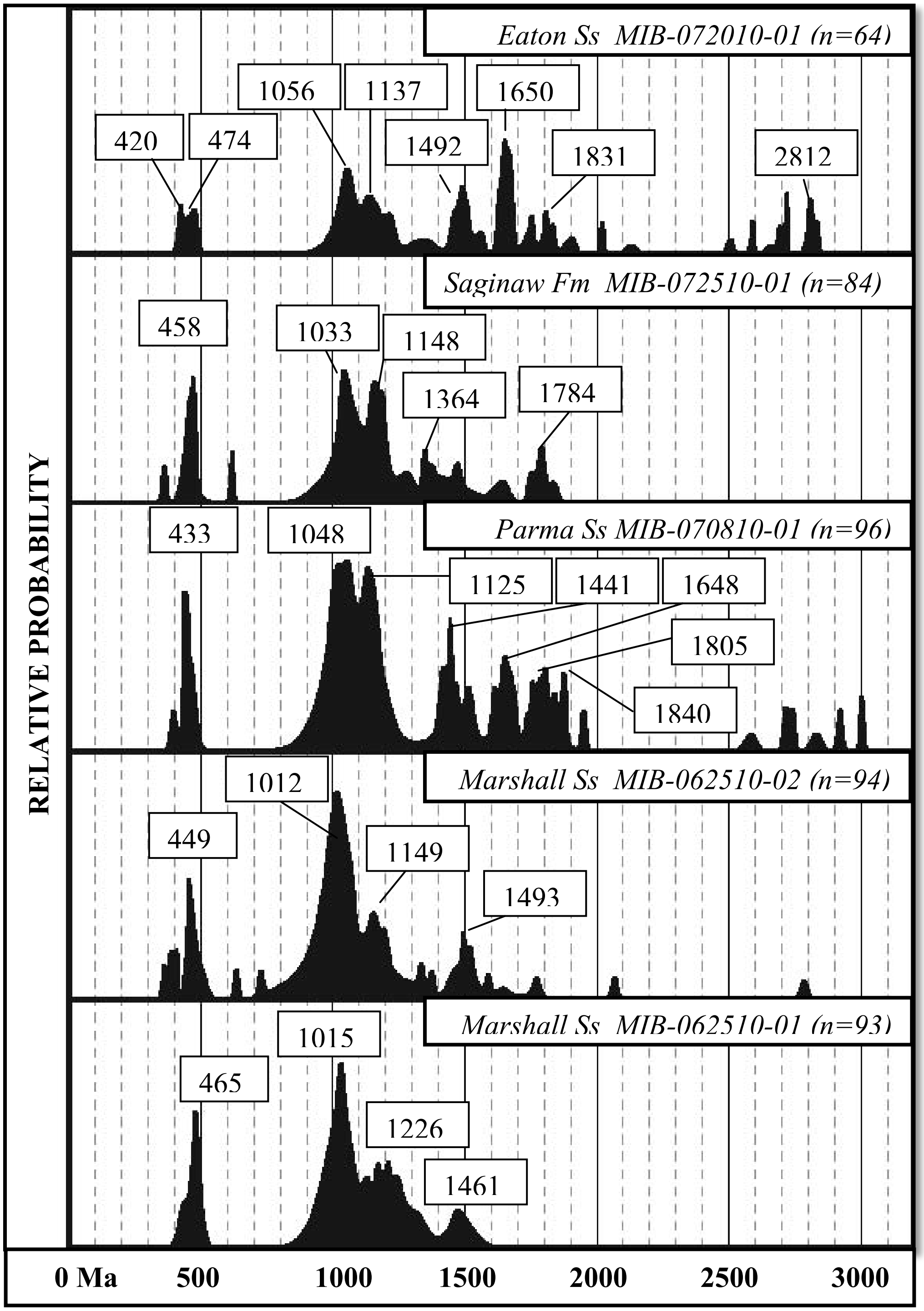


Figure 4.1: Relative probability plot of U-Pb detrital zircon ages for the Marshall Sandstone, Parma Sandstone, Saginaw Formation, and Eaton Sandstone. Primary ages through the entire section are 420-470, 1000-1150, and 1300-1500 Ma. Secondary peaks are 1600-1800, 1800-1900, and 2600-2800 Ma, and are present in Early and Late Early Pennsylvanian strata. Increased abundances of older sediment are present in the Early and late Early Pennsylvanian units.

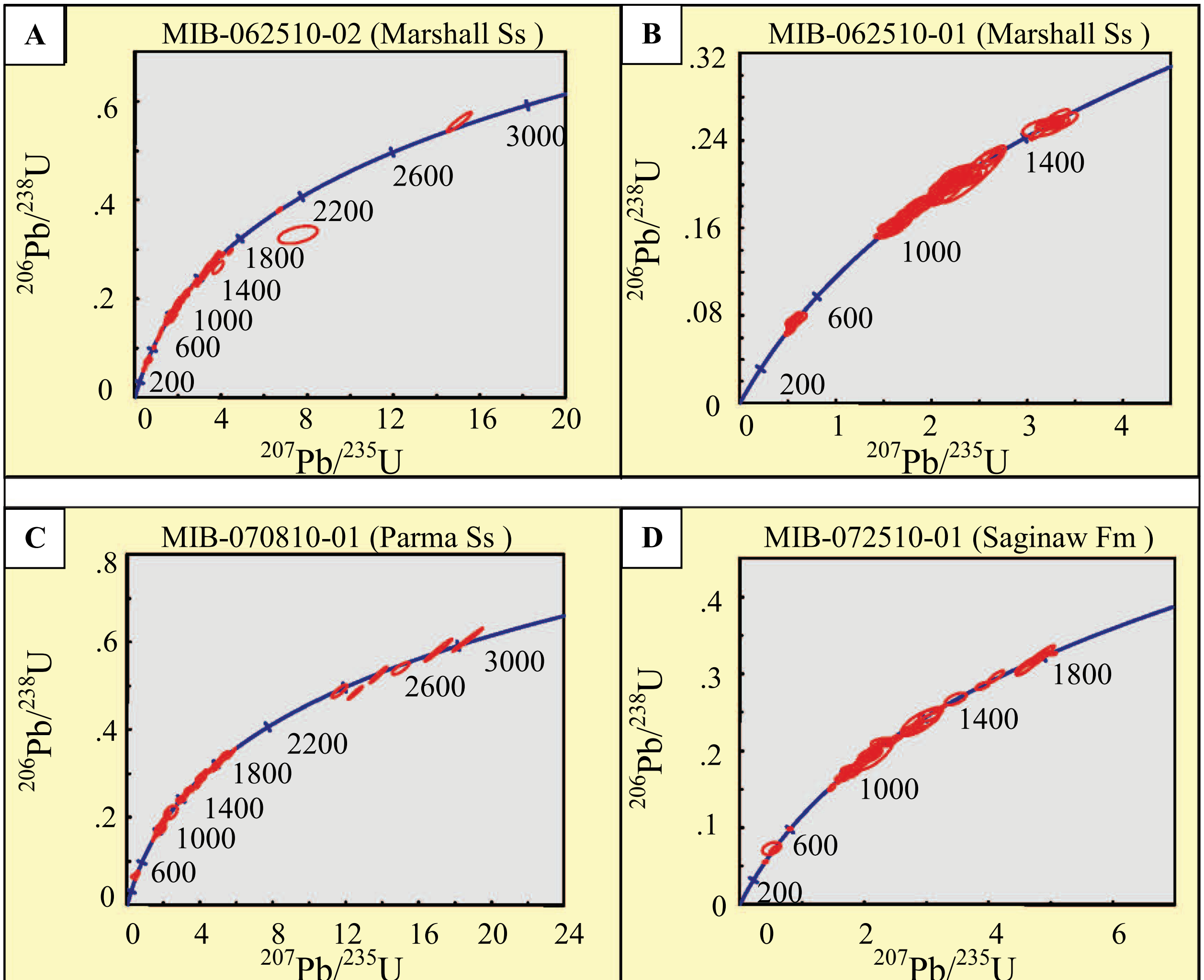
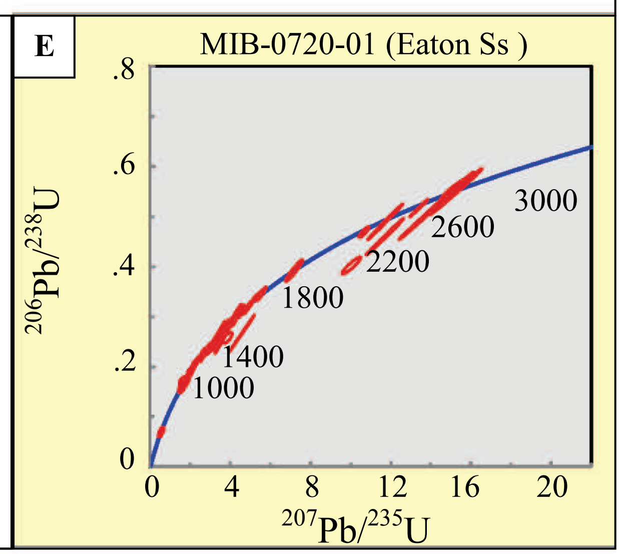


Figure 4.2: Concordia diagrams for Mississippian-Pennsylvanian sandstones from the Michigan Basin. Discordant data was removed from study. A) Marshall Sandstone (MIB-062510-01) B) Marshall Sandstone (MIB-062510-02) C) Parma Sandstone (MIB-070810-01) D) Saginaw Fm (MIB-072510-01) E) Eaton Sandstone (MIB-072010-01).



Parma Sandstone (**MIB-070810-01**): Primary peak ages from the Parma Sandstone include 433, 1048, 1125, 1441. Secondary peak ages with significant numbers of grains include 1600-1650, 1800-1900, and 1900-2000 Ma. Increased abundances of grains ranging from 2500-3000 Ma are also present, as are grains of an 390 Ma age.

Saginaw Formation (**MIB-072510-01**): Primary peaks for the Saginaw include 458, 1033, 1148, 1364, and 1784 Ma ages. Other ages present are 350, 600-700, 1200-1300, 1400-1500, and 1600-1900 Ma.

Eaton Sandstone (**MIB-072010-01**): Primary peak ages of the Eaton Sandstone are 420-470, 1056, 1137, 1492, and 1650 Ma. Secondary peaks include 1300-1500, 1700-1800, and 2500-2900 Ma.

4.4 INITIAL MAGMATIC SOURCE PROVINCE INTERPRETATIONS

Detrital zircons found in Late Paleozoic strata contain grains of a wide range of ages (Archean-Mississippian) which have been derived from numerous igneous provinces throughout Precambrian and Paleozoic times. Descriptions of igneous provinces with age equivalent origin to our zircons are provided below and seen in Figure 4.2.

***Laurentian craton and associated provinces*:** The stable craton of Laurentia and associated provinces are some of the oldest (Archean-Paleoproterozoic) potential sources for zircons supplied to the Michigan Basin and include the Archean Superior province (2.6-2.8 Ga), the Paleoproterozoic Trans-Hudson province (1800-1900 Ma), Penokean orogen (1800-1900 Ma), and Yavapai-Mazatzal/Central Plains/Labrador province (1600-1800 Ma) (Hoffman, 1999).

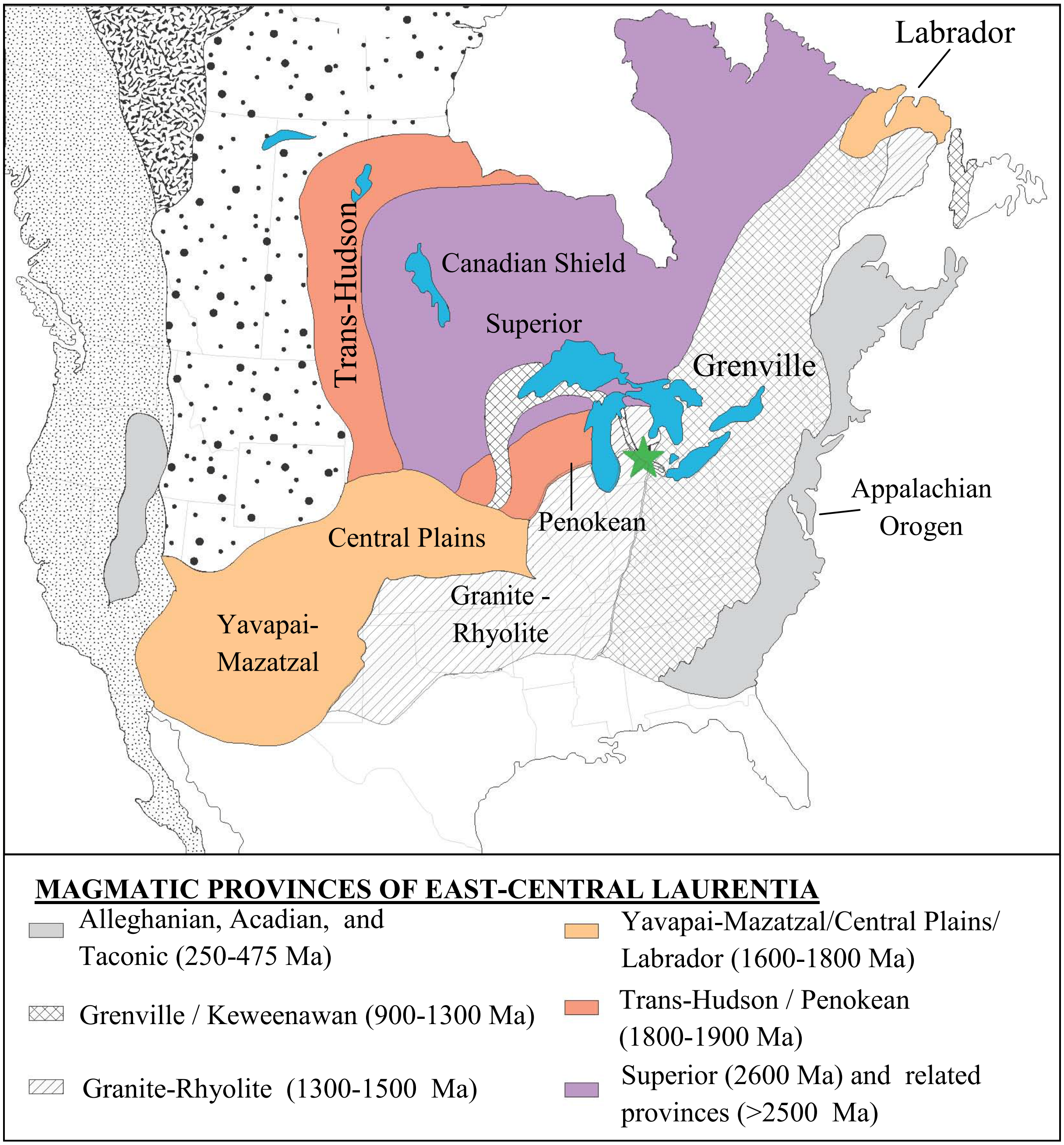


Figure 4.3: Magmatic provinces of North America. Provinces relevant to the project are named. The Michigan Basin is situated centrally to a large number of provinces. The Penokean and Superior provinces are to west and northwest. The Superior province sits to the north, while the Grenville and Appalachian provinces lie to the east. Modified from Park et al., 2010. After Hoffman, 1989.

The Mesoproterozoic Granite-Rhyolite province (1300-1500 Ma) rounds out the interior igneous provinces.

Grenville Province: The Grenville province is the result of a Mesoproterozoic – Neoproterozoic (1300-900 Ma), three stage collisional event during the final assembly of Rodinia, during a time in which numerous continental collisions occurred. Grenville age equivalent signatures in detrital zircon records are prevalent due to the enormous amount of zircon produced during these events, and the widespread tectonic activity. In North America, Grenville basement makes up much of the eastern interior spanning from northern Canada to Mexico (Drahovzal et al., 1992; Van Schmus et al., 1993; Lidiak, 1996). Three stages of zircon production associated with collisional events generally characterize this province: 1) The Elziverian Orogeny (1350-1220 Ma), 2) The Shawinigan Orogeny (1160-1190 Ma), and 3) the Ottawan orogeny (980-1090 Ma) (Rivers, 1997; Heumann et al., 2006). Previous studies have shown that the Grenville province was a primary contributor of sediment in all stages of Appalachian orogenesis (Gray and Zeitler 1997; McLennan et al., 2001; Eriksson et al., 2004; Thomas et al., 2004; Becker et al., 2005, Thomas and Becker, 2007; Park et al., 2010)

Laurentian eastern margin tectonic provinces: The eastern margin of Laurentia underwent a series of tectonically active and passive cycles during Neoproterozoic through Early-Mid Paleozoic time. Neoproterozoic Iapetan rifting of Laurentia from Rodinia began in the Early Neoproterozoic (~800) and ended, after failure, and eventual rifting of the southern margin in the Late Neoproterozoic (~550 Ma) (Hoffman, 1999). Syn-rift volcanics of the southern Appalachian range are thought to be major sediment contributors to the Taconic and Acadian forelands (Thomas et al., 2004). Plutonism associated with subduction and collision during Appalachian orogenies (490-350 Ma) is also thought to have contributed to the

Appalachian foreland (Gray and Zeitler 1997; McLennan et al., 2001; Eriksson et al., 2004; Thomas et al., 2004; Becker et al., 2005, Thomas and Becker, 2007; Park et al., 2010)

Michigan Basin Interpretation

Widespread sedimentation originating from the Acadian and Alleghanian orogeny is generally assumed to have infiltrated the Michigan Basin during the Mississippian and Pennsylvanian (Stearns, 1933; Monnett, 1948; Potter and Siever, 1956; Siever and Potter, 1956; Potter and Pryor, 1961, Shideler, 1969). Dominance of Appalachian related sediment should be expected to yield age ranges from many of the sources listed above, as multicycle sediment makes up much of the Appalachian foreland basin. Detrital zircon samples from the Michigan Basin yield a similar range of ages with certain source areas seeming turning on and off in the Early and late Early Pennsylvanian.

Marshall Sandstone: The detrital zircon signature in the Early Mississippian Michigan Basin is dominated by Grenville age equivalent grains of the Ottawan and Shawinigan orogenies. Taconic and Acadian age equivalent grains are also present, as is a significant contribution of Granite-Rhyolite age grains. Notably, a single grain, approximately 350 Ma, is present and indicative of New England plutonism during the Acadian. Other grains of Penokean/Trans-Hudson, Yavapai-Mazatzal/Central Plains/Labrador, and Archean age are also present, likely indicating recycling of sediment.

Parma Sandstone: Detrital zircons in the Parma exhibit a shift toward older Paleoproterozoic and Archean age grains. The sample is still dominated by Taconic and Grenville age equivalent zircons but the percentage of Yavapai-Mazatzal/Central Plains/Labrador grains increases to nearly 25% of the total signature. An increase in Granite-Rhyolite age equivalent grains occurs,

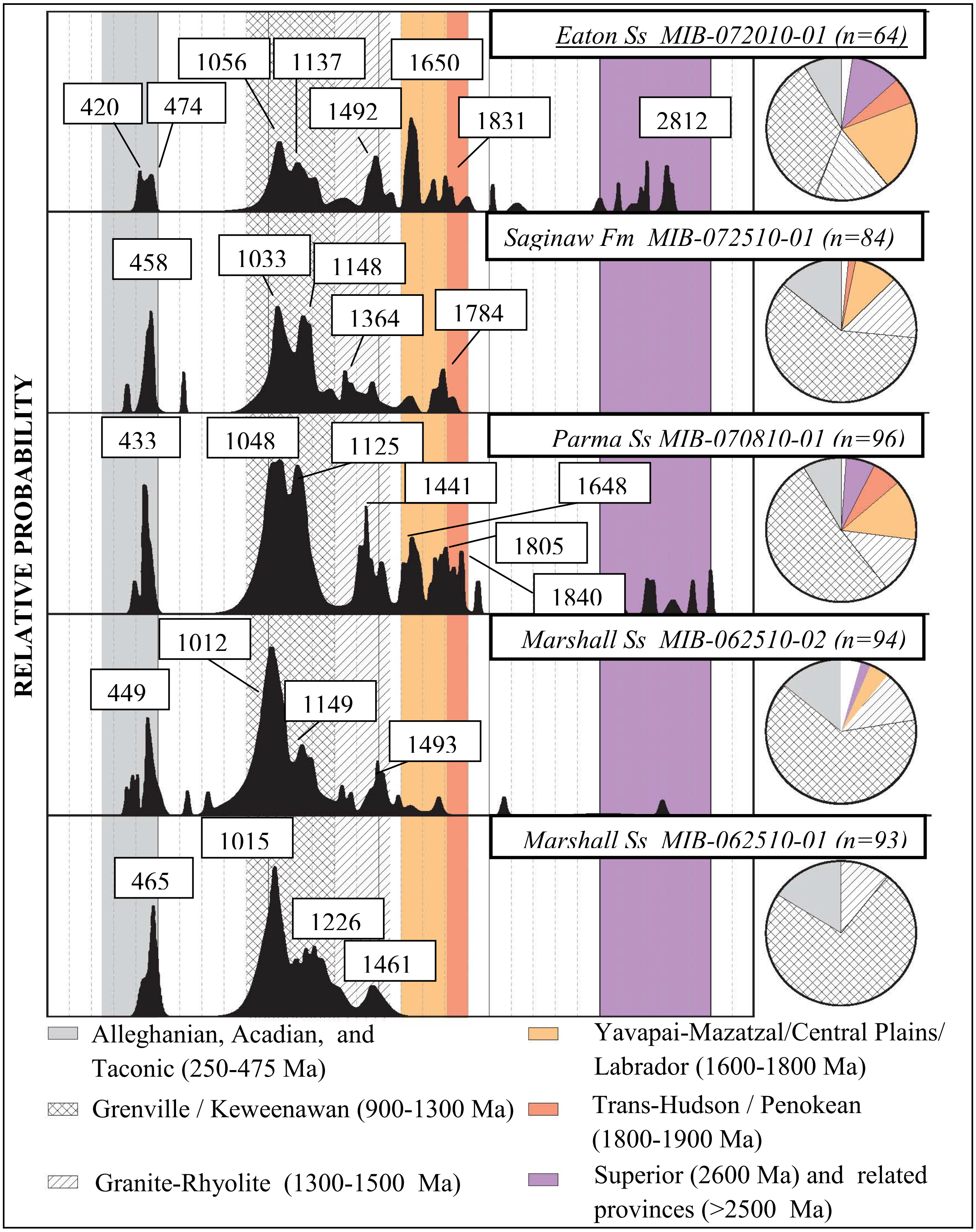


Figure 4.4: Interpreted relative probability plot U-Pb age spectra of the Marshall Sandstone, Parma Sandstone, Saginaw Formation and Eaton Sandstone. Early and Late Early Pennsylvanian influxes of Paleoproterozoic-Archean (Yavapai-Mazatzal/Central Plains/ Labrador, Trans-Hudson/Penokean, Superior Provinces) are coeval with periods of Alleghanian uplift.

and a single grain having a 390 Ma age is present. This shift is roughly coeval with compositional maturity shifts in the modal composition trends and heavy mineral trends seen in previous chapters.

<u>Saginaw Formation</u>: The Saginaw Formation shows similarities to the Marshall Sandstone signature, which is in line with previously reported sediment from the Central Appalachian basin. Taconic-Acadian and Grenville age equivalent grains dominate the signature. Secondary amounts of Granite-Rhyolite, Yavapai-Mazatzal/Central Plains/ Labrador are present. Several grains of potential syn-rift origin are present as is a single grain with an age~350. This shift back to younger sediment is in line with a shift back toward compositional immaturity in the modal composition data.

<u>Eaton Sandstone</u>: The Eaton Sandstone shows a distinct shift back toward older sediment. Detrital zircons grains age equivalent to the Grenville and Taconic provinces are muted by an influx of Paleoproterozoic-Archean sediment. Primary peaks at 1492 Ma and 1650 Ma, as well as the inclusion of Archean (2500-2800 Ma) show this transition. This shift to older sediment is in line with a slight shift to a more mature modal composition data set, as well as an immature heavy mineral suite. These shifts are also roughly coeval with peak uplift during the Alleghanian.

4.5 DISCUSSION

Detrital zircon signatures from Mississippian and Pennsylvanian sandstones in the Michigan Basin provide an insight into the origin of the sediment contained in them. Generally compared to detrital zircon signatures of the Appalachian basin (Gray and Zeitler 1997;

McLennan et al., 2001; Eriksson et al., 2004; Thomas et al., 2004; Becker et al., 2005, Thomas and Becker, 2007; Park et al., 2010) the primary peaks and ages ranges appear quite similar. Due to the central location of the Michigan Basin to many of the proposed source areas the possibility for a combination of the recycled ages of the Appalachian derived sediment with primary contributions from those same source areas is high and significant variations in the detrital zircon signature are not expected. Generally, northeast to southwest paleoflow also suggest that shifts in provenance are probably the result of differential contributions to In this case, subtle changes in the basin mark shifts in provenance.

Early Mississippian detrital zircon peaks are generally consistent with signatures of recycled sediment in the Appalachian foreland basin, which contain dominant primary peaks of Taconic, Grenville, and Granite-Rhyolite province age equivalent strata (Gray and Zeitler 1997; McLennan et al., 2001; Eriksson et al., 2004; Thomas et al., 2004; Becker et al., 2005, Thomas and Becker, 2007; Park et al., 2010). The Marshall Sandstone is roughly age equivalent to this 350 Ma grain, indicating that Appalachian sediment was probably not recycled, and being transported directly to the Michigan Basin during the Early Mississippian. Several grains of syn-rift age material, a common component of Appalachian foreland sediment, are also seen and suggest Appalachian input of sediment into the Michigan Basin. Early Mississippian contributions from Huronian (Penokean) or Superior rocks of the areas surrounding the Michigan Basin from west-north primarily contain Paleoproterozoic-Archean age grains (>1700 Ma) (Fairbairn et al., 1969; Van Wyck and Norman, 2004) which are not seen.

Early Pennsylvanian zircon ages from the Parma Sandstone show an increase in abundance of Archean and Paleo-Mesoproterozoic age. Superior province (2.8-2.6 Ga), Trans-Hudson/Penokean (1.9-1.8), Yavapai-Mazatzal/Central Plains/ Labrador (1.8-1.6) age equivalent grains represent nearly a quarter of the grain ages seen in the Parma Sandstone. The Grenville peaks dominate the age spectrum with significant Taconic age contributions as well. The youngest age in the Parma is approximately 390 Ma; a Devonian age grain, typical of the Acadian orogeny. The Early Pennsylvanian Michigan Basin was receiving sediment derived from the Appalachian; however, the abundance of Yavapai-Mazatzal/Central Plains/Labrador sediment is not something reported from Appalachian sediments (Gray and Zeitler 1997; McLennan et al., 2001; Eriksson et al., 2004; Thomas et al., 2004; Becker et al., 2005, Thomas and Becker, 2007; Park et al., 2010). The additional Yavapai Mazatzal/Central Plains/Labrador is likely explained by provinces immediately north of the basin (Fairbairn et al., 1969; Van Wyck and Norman, 2004). Contributions from separate Appalachian and Canadian Shield sources are evident, and are likely picked up by the Michigan River en route to the Michigan Basin. Due to the relatively low abundance of this age material in the Marshall Sandstone, this is assumed to be newly exposed material. Initial uplift of the Alleghanian range is coeval with this shift in provenance.

The Saginaw Formation shows a characteristic Appalachian foreland signature with prominent Taconic and Grenville age equivalent peaks and limited Meso-Neoproterozoic age grains. The presence of a 350 Ma grain and syn-rift age equivalent grains, though few in number, are indicative of an Appalachian source. The absence of grains older than Mesoproterozoic is also consistent with an Appalachian source.

Detrital contributions to the Eaton Sandstone contain a similar age range as though that contributed to the Parma Sandstone; however, the proportions of grain ages are different. In the Late Early Pennsylvanian, Taconic and Grenville peaks typical of an Appalachian detrital signature are overtaken by a Paleoproterozoic peak of 1650 Ma, and increased abundances of other Paleoproterozoic and Archean age grains. Simplicity dictates that sources near the Michigan Basin containing these older grains are responsible. Precambrian-Cambrian quartzite in the Wisconsin area is dominated by 1700-1800 Ma (Fairbairn et al., 1969; Van Wyck and Norman, 2004). Similarly, Huronian (pre-Penokean) and Superior province rocks to the North of the basin also contain Paleoproterozoic – Archean age grains associated with the Yavapai-Mazatzal/Central Plains/Labrador, Trans-Hudson/Penokean, and Superior provinces (Fairbairn et al., 1969; Van Wyck and Norman, 2004).

Evidence of multiple sources, at times simultaneously providing sediment to the Michigan Basin, is given by detrital zircon ages from the Carboniferous strata of the Michigan Basin. Subtle shifts in regional sediment dispersal paths have been documented in the Early Pennsylvanian, though general NE-SW throughout the Carboniferous is shown by sediment dispersal patterns, sediment isopachs, and paleocurrent data (Potter and Siever, 1956; Potter and Pryor, 1961; Swann, 1963, 1964; Robinson and Prave, 1995).. Drainage of Northern Appalachian sources to the northeast of the basin requires initial northwest (down slope) transportation. Archean-Paleoproterozoic sediment being deposited during the Early and Late Early Pennsylvanian could reflect exhumation of recycled strata from numerous locations to the northeast of the Michigan Basin.

4.6 CONCLUSIONS

1. U-Pb detrital zircon samples from Late Paleozoic strata of the Michigan Basin include primary peaks of 420-470, 1000-1150, and 1300-1500 Ma which are typical of recycled orogen strata in the Appalachian foreland basin. Secondary peaks include ages of 1600-

1800, 1800-1900, and 2600-2800 Ma which are not common in the Appalachian basin. Occurrences of several grains with the ages of approximately ~350, 600-730, and 2000-2200 Ma may specify Appalachian sources.

2. High abundances of Paleoproterozoic-Archean age zircons; an age not typically characteristic of the recycled Appalachian basin, is present in Early and late Early Pennsylvanian strata of the Michigan Basin and suggests input from a source other than the Appalachian basin. Paleoflow dictates, NE-SW flow; and probable derivation from the NE, but regional inclusion of these age grains by recycling delimits understanding of their proximal origin.
3. Provenance shifts, which include significant amounts of older Paleoproterozoic-Archean grains (Yavapai-Mazatzal/Central Plains/Labrador, Trans-Hudson/Penokean, and Superior Provinces), are present in Early and late Early Pennsylvanian strata deposited during periods of Alleghanian uplift. Inclusion of this sediment may be attributed to exhumation of local, age equivalent rocks to the west and north of the basin Michigan Basin.
4. Upsection variability in the detrital zircon signature in each overlying units reveals an evolving landscape that provides unique depositional systems during the Early Mississippian, earliest Pennsylvanian (Morrowan), and several during the remainder of the Early Pennsylvanian (Atokan).

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CHAPTER 5: CONCLUSIONS

The observations made from the modal composition, heavy mineral, and U-Pb detrital zircon age data sets in this study have provide the basis for several conclusions (Table 5.1). Modal composition data from the Michigan Basin shows a population of sublitharenite samples (Marshall Sandstone and Saginaw Formation) and quartz arenites samples (Parma Sandstone and Eaton Sandstone), all of which appear to contain recycled sediment, likely from two sources or sets of sources. Heavy mineral analysis of these strata shows distinct compositional differences between the Marshall Sandstone, Parma Sandstone and Eaton Sandstone, with little information for the Saginaw Formation. All strata appear to be recycled based on the high abundances of persistent minerals; however, contributions from greenschist are present in the Marshall Sandstone; quartz arenite/quartzite in the Parma Sandstone; recycled strata in the Saginaw Formation; and quartz arenite/quartzite plus metapelites in the Eaton Sandstone. U-Pb detrital zircon ages show further distinctions between the strata, as the Parma and Eaton Sandstones typically contain a larger abundance of Archean-Paleoproterozoic age grains, while the Marshall Sandstone and Saginaw Formation contain primarily Mesoproterozoic-Mississippian age grains. Based on these observations, the conclusions for this project are:

1. Late Paleozoic (Mississippian-Pennsylvanian) coarse-siliciclastic dominated units from the Michigan Basin show distinct variations in provenance data for each unit across modal composition, heavy minerals present, and U-Pb detrital zircon age data sets throughout the Carboniferous section. The Marshall Sandstone of the Early Mississippian is shown to be relatively immature by modal composition and contains elevated abundances of schistose lithic fragments. Heavy mineral suites which contain a range of high-low persistence minerals indicating recycled strata and contributions from

greenschist, granite, and gneiss. The Marshall Sandstone's detrital zircon age spectra show Mesoproterozoic to Mid-Paleozoic age zircons, and do not include Archean-Paleoproterozoic age zircons seen in other samples. The Late Mississippian-Early Pennsylvanian Parma Sandstone show compositionally mature patterns; quartz dominated modal composition and a heavy mineral assemblage containing primarily high persistence zircon, tourmaline, rutile, and muscovite. Detrital zircon ages from the Parma Sandstone include Archean-Paleoproterozoic age peaks along with the primary Mesoproterozoic to Mid-Paleozoic age peaks. Early Pennsylvanian samples from the Saginaw Formation have modal composition with high relative abundances of lithic fragments and a decreased compositional maturity. Heavy minerals are unremarkable as the reported suite is not a complete representation. U-Pb ages from the Saginaw show Mesoproterozoic to Mid-Paleozoic age peaks. The Eaton Sandstone has quartz arenite-sublitharenite composition, and a suite of heavy minerals containing low persistence and common high persistence minerals. High-grade metamorphic minerals and relatively low abundances of lithic fragments suggest a new source type. Detrital zircon ages show Archean-Paleoproterozoic age grains similar to the Parma Sandstone. The variation seen in the Carboniferous section of the Michigan Basin demonstrates distinct controls on sources during deposition of each Carboniferous unit.

The Carboniferous strata in the Michigan Basin are primarily derived from recycled strata. With the exception of several quartz arenite samples of the Parma Sandstone and Eaton Sandstone, all Carboniferous samples plot in Dickinson et al.'s (1983) recycled orogen field. High abundances of quartz are indicative of the attrition of less stable feldspar and lithic fragments.

Table 5.1: Data sets, observations, and first order interpretations from this study of the Michigan Basin.

Chapter: Data Set	Main observation	Interpretation
Ch 2: Modal composition	Higher relative quartz abundances (Q. Arenite) in Parma Ss and Eaton Ss	All strata recycled, but Parma Ss and Eaton Ss are derived from quartz arenites/quartzite, while Marshall Ss and Saginaw Fm are from sublitharenite and metamorphic sources.
Ch 3: Heavy mineral analysis	Mineral suites differentiate between the Marshall Ss, The Parma Ss, and the Eaton Ss. The Saginaw Formation remains unclear.	At least 3 distinct source types are present: 1)The Marshall Ss, from a sublitharenite source with contributions from greenschist, 2) The Parma Ss, from a very mature quartz arenite/quartzite, and 3) The Eaton Ss, from a recycled source including metapelites. The Saginaw may be included with the Parma Ss source, the Eaton Ss source, or may be completely different.
Ch 4: U/Pb detrital zircon ages	Mesoproterozoic-Mid Paleozoic age grains are primary peaks in all strata. Paleoproterozoic-Archean age grains are also included in primary peaks in the Parma Ss and Eaton Ss due to a higher relative abundance.	Older detritus is being contributed to the basin during Late-Mississippian to Early Pennsylvanian time (Parma Ss), as well as in the Late Early Pennsylvanian (Eaton Ss). Contributions from a new source area or newly exhumed strata are likely.

Heavy mineral suites in this study also help to determine source rock lithology. Actinolite in the Marshall Sandstone indicates contributions from a greenschist source, while kyanite and staurolite in the Eaton Sandstone are indicative of metasediments. Further correlation between heavy minerals and source lithology is difficult, as zircon, tourmaline, and rutile, while formed in distinct environments, are highly persistent and capable of undergoing numerous cycles of lithification and erosion. The high abundances of zircon and tourmaline compared to less persistent minerals suggest recycled sediment.

Differences seen in the modal composition and heavy mineral data sets are relatively subtle in the determination of provenance. All samples contain relatively similar age peaks with the exception of increased abundances of Archean-Paleoproterozoic age grains in the Parma Sandstone (Early Pennsylvanian) and Eaton Sandstone (Late Early Pennsylvanian). Geochronologic profiles are very similar to those reported from the Appalachian basin (Gray and Zeitler, 1997; Eriksson et al., 2004; Thomas et al., 2004; Becker et al., 2005; Thomas and Becker, 2007; Park et al., 2010); however, the Archean-Paleoproterozoic range is a rare occurrence in those data sets. Grains that are age equivalent to certain events such as the Taconic/Acadian orogenies almost certainly point to the Appalachians as a source. Archean-Paleoproterozoic age grains, not common in Appalachian strata suggest a different source and may potentially indicate sources from the continent interior.

Consideration must be given to previous work on regional paleocurrent, sediment dispersal, and sediment isopach data sets which are all in agreement pertaining to a NE-SW distribution of sediment during the Pennsylvanian (Potter and Siever, 1956; Potter and Pryor, 1961; Shideler, 1969). Ettensohn's (2004) suggestion of a large east to west component during the entire Carboniferous, particularly in the Mississippian, invokes drainage from the Appalachians toward the Michigan Basin. There have been several attempts to explain variation in sedimentation within the basins of the eastern continental interior which may be relevant to the variation seen in this study.

The idea of a continent-scale, axial drainage system is well documented on relict orogens and can be seen firsthand in the Holocene mountain ranges. The Himalaya, for example, has the Indus and Ganges river systems, draining axially toward their respective marine deltas. A similar component is thought to have been present on the interior side of the Appalachian range. Swann (1963) proposed the Michigan River as a northeast to southwest continental-scale, axial drainage system. Detritus from the Northern Appalachian range and potentially the Canadian Shield were transported to the southwest, eventually being deposited in marginal marine and deltaic environments in the Michigan and Illinois basins. Archer and Greb (1995) suggested a similar system, on an Amazon scale to drain the Appalachian range down to the present-day Gulf of Mexico, during lowstand conditions. Stream avulsions and shifts due to tectonic activity in the Pennsylvanian could potentially have shifted the headwaters of this river toward more continental sources during the Alleghanian collisional episodes, and returned post-erosion to the headwaters originally being drained prior to orogenesis. Crustal loading and unloading on the active margin may have resulted in forebulge migration, effectively directing the river toward and away from the range (Ettensohn, 2004). Further loading to the south as a result of the Late Pennsylvanian Ouachitan orogeny is thought to effectively tilted the continent in a more southerly direction, driving a more north-south paleocurrent, which is seen across the eastern interior (Robinson and Prave, 1999).

Differential exhumation as a result of Alleghanian orogenesis may also explain the distinct depositional systems seen in the Carboniferous strata of the Michigan Basin. A simple unroofing complex from a single area in the Appalachian foreland can also explain the results of this study. Strata in the Appalachian foreland have been shown to include grains as old as Archean and given the subtle differences seen in the Michigan Basin provenance data it is well within reason that a single source area may have accounted for all the sediment. Exhumation of different stratigraphic packages anywhere along an axial stream system may also account for fluctuation in the provenance of the Carboniferous Michigan Basin.

The results of this study do not allow for discrimination between these models. Rather, they demonstrate that the four Carboniferous sandstones are the result of four seemingly distinct depositional systems. In order to further discern the appropriate model from the others, detrital zircon comparisons to all relict foreland basins in Eastern North America, as well as the nearby intracratonic basins, are needed. Understanding the age spectrum of Carboniferous strata in each basin would allow for the modeling of likely sediment dispersal paths and potential sources.

APPENDICES

APPENDIX A

Raw modal composition percentages from the Michigan Basin. Authors of previous work used varied methods; Price and Velbel (2000) counted quartz, feldspars, and lithic fragments as part of a mineral occurrence study while Siever and Potter (1956) counted all detrital framework grains. The result of this is missing percentages for certain framework grains.

Table A1: Raw modal composition percentages from the Michigan Basin.

Sample #	Formation	Author	Q	F	L	Qm	Qp	Chert	P	K	Lv	Lm	Ls
MIB-042311-21	Lower Marshall Ss	Boothroyd	50.8	2.3	34.4	46.8	3.5	0.5	0.0	2.3	2.8	29.6	2.0
MIB-042311-20	Lower Marshall Ss	Boothroyd	67.6	2.8	27.7	50.0	16.8	0.8	1.3	1.5	3.3	24.4	0.0
MIB-042311-19	Lower Marshall Ss	Boothroyd	70.8	5.6	22.9	59.0	11.0	0.8	0.3	5.3	2.8	20.1	0.0
MIB-042311-18	Lower Marshall Ss	Boothroyd	64.9	2.8	30.6	56.1	8.5	0.3	0.3	2.5	3.0	26.6	1.0
MIB-042311-17	Lower Marshall Ss	Boothroyd	59.3	9.6	30.3	53.3	5.5	0.5	1.3	8.3	2.3	27.5	0.5
MIB-042311-16	Lower Marshall Ss	Boothroyd	62.0	8.3	29.4	53.0	8.5	0.5	0.3	8.0	2.0	27.1	0.3
MIB-042311-15	Lower Marshall Ss	Boothroyd	62.8	6.6	29.6	56.0	6.8	0.0	1.8	4.8	3.8	25.8	0.0
MIB-042311-14	Lower Marshall Ss	Boothroyd	65.0	4.6	27.3	58.5	5.0	1.5	0.8	3.8	2.5	24.8	0.0
MIB-042311-13	Lower Marshall Ss	Boothroyd	62.0	6.6	30.9	53.5	8.0	0.5	0.3	6.3	2.8	28.1	0.0
MIB-042311-12	Lower Marshall Ss	Boothroyd	63.6	1.3	32.3	59.8	3.3	0.5	0.0	1.3	1.5	30.8	0.0
MIB-042311-11	Lower Marshall Ss	Boothroyd	64.9	1.8	31.7	58.3	6.3	0.3	0.3	1.5	1.3	30.1	0.3
MIB-042311-10	Lower Marshall Ss	Boothroyd	56.3	8.5	31.4	49.8	6.5	0.0	1.0	7.5	0.8	30.6	0.0
MIB-042311-09	Lower Marshall Ss	Boothroyd	64.8	1.8	31.1	58.0	6.5	0.3	0.0	1.8	2.0	29.1	0.0
MIB-042311-08	Lower Marshall Ss	Boothroyd	61.0	2.6	34.3	55.0	5.5	0.5	0.8	1.8	1.0	33.3	0.0
MIB-042311-07	Lower Marshall Ss	Boothroyd	62.1	4.6	30.2	54.3	7.0	0.8	0.3	4.3	0.8	29.4	0.0
MIB-042311-06	Lower Marshall Ss	Boothroyd	60.6	3.5	34.9	54.8	5.8	0.0	1.0	2.5	2.8	32.1	0.0
MIB-042311-05	Lower Marshall Ss	Boothroyd	63.6	1.6	34.4	58.8	4.5	0.3	0.3	1.3	1.0	33.4	0.0
MIB-042311-04	Lower Marshall Ss	Boothroyd	60.1	3.8	33.3	56.3	3.5	0.3	0.0	3.8	2.5	30.8	0.0
MIB-042311-03	Lower Marshall Ss	Boothroyd	63.1	3.5	33.4	57.3	5.3	0.5	0.0	3.5	2.5	30.9	0.0
MIB-042311-02	Lower Marshall Ss	Boothroyd	63.8	7.3	28.3	57.3	6.0	0.5	0.0	7.3	1.5	26.5	0.3
MIB-042311-01	Lower Marshall Ss	Boothroyd	58.4	4.3	34.4	53.8	4.3	0.3	0.0	4.3	3.6	30.8	0.0
SS-32	Marshall Ss	Boothroyd	79.0	4.8	16.7	71.5	7.5	0.0	1.3	3.5	2.3	12.1	2.3
SS-35	Marshall Ss	Boothroyd	85.8	1.8	11.4	80.8	5.0	0.0	0.0	1.8	1.3	9.3	0.8
SS-9	Marshall Ss	Boothroyd	57.5	5.5	34.9	51.0	6.5	0.0	0.0	5.5	0.8	33.8	0.3
SS-10	Marshall Ss	Boothroyd	47.8	2.0	46.9	42.5	4.3	1.0	0.0	2.0	5.5	39.6	1.8
MV-H-1	Marshall Ss	Boothroyd	51.6	7.8	37.3	45.0	5.8	0.8	0.3	7.5	2.5	34.8	0.0
SS-11	Marshall Ss	Boothroyd	63.5	7.8	29.9	52.5	11.0	0.0	1.0	6.8	3.3	24.8	1.8
SS-34	Marshall Ss	Boothroyd	60.8	0.0	31.3	54.5	5.5	0.8	0.0	0.0	3.0	28.3	0.0

Table A1 (cont'd)

Sample #	Formation	Author	Q	F	L	Qm	Qp	Chert	P	K	Lv	Lm	Ls
SS-31	Marshall Ss	Boothroyd	75.6	6.1	18.6	68.0	7.3	0.3	0.8	5.3	2.3	16.3	0.0
MIB-050911-18	Napoleon Marshall Ss	Boothroyd	74.8	2.5	22.1	65.5	9.0	0.3	0.0	2.5	2.3	19.8	0.0
MIB-050911-17	Napoleon Marshall Ss	Boothroyd	73.6	0.8	25.5	64.8	8.5	0.3	0.0	0.8	1.8	22.4	1.3
MIB-050911-16	Napoleon Marshall Ss	Boothroyd	79.6	1.3	19.1	75.8	3.8	0.0	0.0	1.3	2.5	16.3	0.3
SS-12	Parma Ss	Boothroyd	95.6	0.8	3.6	91.8	3.8	0.0	0.0	0.8	0.3	3.3	0.0
MIB-050911-15	Parma Ss	Boothroyd	94.6	2.0	3.4	93.3	1.3	0.0	0.0	2.0	0.3	3.1	0.0
MIB-050911-14	Parma Ss	Boothroyd	94.0	1.3	4.9	91.0	3.0	0.0	0.0	1.3	0.3	4.6	0.0
MIB-050911-13	Parma Ss	Boothroyd	93.5	2.1	4.6	90.5	3.0	0.0	0.3	1.8	0.0	4.6	0.0
MIB-050911-12	Parma Ss	Boothroyd	94.2	1.6	4.1	89.4	4.8	0.0	0.3	1.3	1.0	3.1	0.0
MIB-050911-11	Parma Ss	Boothroyd	89.3	2.3	5.8	87.8	1.5	0.0	0.0	2.3	0.0	5.8	0.0
MIB-050911-10	Parma Ss	Boothroyd	91.0	2.8	2.3	89.0	2.0	0.0	0.3	2.5	0.5	1.3	0.5
MIB-050911-09	Parma Ss	Boothroyd	95.6	1.5	2.8	92.3	3.3	0.0	0.0	1.5	0.0	2.8	0.0
MIB-050911-08	Parma Ss	Boothroyd	94.8	2.0	3.3	92.0	2.8	0.0	0.0	2.0	0.3	3.0	0.0
MIB-050911-07	Parma Ss	Boothroyd	94.3	2.0	3.9	89.8	4.5	0.0	0.0	2.0	0.0	3.6	0.3
USB-11	Saginaw Fm	Boothroyd	70.1	3.5	23.9	65.0	4.8	0.3	0.0	3.5	1.5	22.1	0.3
USB-9	Saginaw Fm	Boothroyd	70.8	7.3	20.9	64.5	6.3	0.0	0.8	6.5	0.8	20.1	0.0
USB-8	Saginaw Fm	Boothroyd	81.3	3.3	15.1	71.0	10.0	0.3	0.3	3.0	1.5	13.6	0.0
USB-7	Saginaw Fm	Boothroyd	72.6	5.1	21.1	66.0	6.3	0.3	0.3	4.8	1.0	20.1	0.0
MIB-050911-06	Saginaw Fm	Boothroyd	81.9	1.3	16.7	79.3	2.3	0.3	0.0	1.3	0.8	15.9	0.0
MIB-050911-05	Saginaw Fm	Boothroyd	82.4	2.3	14.4	77.8	4.3	0.3	0.0	2.3	0.8	13.6	0.0
MIB-050911-04	Saginaw Fm	Boothroyd	78.0	4.0	17.0	76.5	1.5	0.0	0.0	4.0	0.8	15.9	0.3
MIB-050911-03	Saginaw Fm	Boothroyd	76.1	1.3	21.9	73.8	2.3	0.0	0.3	1.0	0.5	21.4	0.0
MIB-050911-02	Saginaw Fm	Boothroyd	82.8	1.5	15.1	80.5	2.0	0.3	0.0	1.5	0.5	14.6	0.0
MIB-050911-01	Saginaw Fm	Boothroyd	81.3	2.3	16.0	76.5	4.8	0.0	0.0	2.3	0.8	15.2	0.0
	Saginaw Fm	Siever	95.0	0.5	0.0								
Outcrop	Eaton Ss	Price and Velbel	61.5	2.9	2.2								
Outcrop	Eaton Ss	Price and Velbel	61.5	2.9	2.2								
Outcrop	Eaton Ss	Price and Velbel	67.6	3.4	0.8								

Table A1 (cont'd)

Sample #	Formation	Author	Q	F	L	Qm	Qp	Chert	P	K	Lv	Lm	Ls
Outcrop	Eaton Ss	Price and Velbel	64.8	2.6	1.3								
Outcrop	Eaton Ss	Price and Velbel	68.8	1.8	1.5								
Outcrop	Eaton Ss	Price and Velbel	60.0	3.6	1.9								
Outcrop	Eaton Ss	Price and Velbel	64.2	3.1	1.1								
Outcrop	Eaton Ss	Price and Velbel	56.7	3.7	1.0								
Outcrop	Eaton Ss	Price and Velbel	56.7	3.7	1.0								
Outcrop	Eaton Ss	Price and Velbel	67.0	1.7	0.8								
Outcrop	Eaton Ss	Price and Velbel	58.5	1.2	0.5								
Outcrop	Eaton Ss	Price and Velbel	64.1	1.1	2.5								
Outcrop	Eaton Ss	Price and Velbel	61.9	3.5	0.8								
Outcrop	Eaton Ss	Price and Velbel	59.7	1.3	1.1								
Outcrop	Eaton Ss	Price and Velbel	59.7	1.3	1.1								
Outcrop	Eaton Ss	Price and Velbel	66.4	1.5	0.9								
Outcrop	Eaton Ss	Price and Velbel	65.4	1.4	0.3								
Outcrop	Eaton Ss	Price and Velbel	69.1	1.4	1.4								
Outcrop	Eaton Ss	Price and Velbel	66.8	1.4	0.9								
Outcrop	Eaton Ss	Price and Velbel	66.8	1.4	0.9								
Outcrop	Eaton Ss	Price and Velbel	64.7	1.2	2.6								
Outcrop	Eaton Ss	Price and Velbel	64.4	2.7	1.6								
Outcrop	Eaton Ss	Price and Velbel	64.5	2.6	0.6								
Outcrop	Eaton Ss	Price and Velbel	73.6	1.0	0.0								
Outcrop	Eaton Ss	Price and Velbel	66.4	2.1	0.0								
Outcrop	Eaton Ss	Price and Velbel	73.2	0.6	2.3								
Outcrop	Eaton Ss	Price and Velbel	69.1	1.5	1.2								
Outcrop	Eaton Ss	Price and Velbel	68.7	0.8	2.2								
Outcrop	Eaton Ss	Price and Velbel	74.6	1.6	1.6								
Outcrop	Eaton Ss	Price and Velbel	74.8	1.9	0.9								
Outcrop	Eaton Ss	Price and Velbel	69.1	2.1	0.6								

Table A1 (cont'd)

Sample #	***Formation***	***Author***	***Q***	***F***	***L***	***Qm***	***Qp***	***Chert***	***P***	***K***	***Lv***	***Lm***	***Ls***
Outcrop	Eaton Ss	Price and Velbel	61.1	1.6	2.6								
Outcrop	Eaton Ss	Price and Velbel	68.7	1.6	2.1								
Outcrop	Eaton Ss	Price and Velbel	64.3	1.7	1.1								
Outcrop	Eaton Ss	Price and Velbel	67.5	2.0	0.3								
Outcrop	Eaton Ss	Price and Velbel	65.1	1.4	0.0								
Outcrop	Eaton Ss	Price and Velbel	72.1	2.1	1.2								
Outcrop	Eaton Ss	Price and Velbel	73.9	1.6	1.0								
Outcrop	Eaton Ss	Price and Velbel	61.2	3.2	1.4								
Outcrop	Eaton Ss	Price and Velbel	72.5	2.2	1.0								
Outcrop	Eaton Ss	Price and Velbel	68.5	0.6	0.0								
Outcrop	Eaton Ss	Price and Velbel	66.7	1.1	0.3								
Outcrop	Eaton Ss	Price and Velbel	65.6	1.3	2.5								
Outcrop	Eaton Ss	Price and Velbel	64.5	2.7	1.7								
Outcrop	Eaton Ss	Price and Velbel	58.9	1.3	0.9								
Outcrop	Eaton Ss	Price and Velbel	61.1	1.5	2.4								
Outcrop	Eaton Ss	Price and Velbel	56.7	3.1	1.8								
Outcrop	Eaton Ss	Price and Velbel	65.9	2.0	1.2								
subsurface	Eaton Ss	Price and Velbel	61.9	3.8	8.3								
subsurface	Eaton Ss	Price and Velbel	61.2	4.0	10.0								
subsurface	Eaton Ss	Price and Velbel	66.8	4.3	8.3								
subsurface	Eaton Ss	Price and Velbel	59.9	2.8	10.1								
subsurface	Eaton Ss	Price and Velbel	69.2	1.3	5.7								
subsurface	Eaton Ss	Price and Velbel	69.7	0.6	2.0								
subsurface	Eaton Ss	Price and Velbel	67.9	0.6	3.8								
subsurface	Eaton Ss	Price and Velbel	66.0	1.2	4.9								
subsurface	Eaton Ss	Price and Velbel	66.2	1.6	3.4								
subsurface	Eaton Ss	Price and Velbel	78.1	1.3	2.7								

Table A1 (cont'd)

Sample #	*Formation*	*Author*	*Q*	*F*	*L*	*Qm*	*Qp*	*Chert*	*P*	*K*	*Lv*	*Lm*	*Ls*
subsurface	Eaton Ss	Price and Velbel	74.2	0.6	3.4								
subsurface	Eaton Ss	Price and Velbel	71.1	1.4	5.1								
subsurface	Eaton Ss	Price and Velbel	67.7	1.2	5.6								
	Parma Ss	Siever and Potter	86.5	2.0	4.0	86.5	2.0					7.0	2.0
	Parma Ss	Siever and Potter	93.0	1.5	0.0	93.0	0.0					3.5	0.0
	Parma Ss	Siever and Potter	88.5	3.0	4.5	88.5	0.5					3.5	0.5
	Parma Ss	Siever and Potter	71.0	2.0	2.0	71.0	1.0					10.0	1.0
	Parma Ss	Siever and Potter	94.5	3.0	1.5	94.5	1.5					10.5	1.5

APPENDIX B

Compiled and normalized Appalachian basin QFL data.

Table B1: Compiled and normalized Appalachian basin QFL data.

Location	***Fm***	***Author***	***Q***	***F***	***L***	***Qm***	***Qp***	***P***	***K***	***Lv***	***Lm***	***Ls***
Pennsylvania	Pottsville	Becker et al.,	92%	0%	8%	92%						
Pennsylvania	Pottsville	Becker et al.,	97%	2%	1%	97%						
West Virginia	Mauch Chunk Gp	Becker et al.,	71%	9%	20%	68%						
Virginia	Mauch Chunk Gp	Becker et al.,	94%	3%	3%	93%						
Georgia	Mauch Chunk Gp	Becker et al.,	97%	1%	3%	96%						
Alabama	Montevallo - Pottsville	Becker et al.,	48%	5%	47%	33%						
Pennsylvania	Murrysville (Berea)	Sager	71%	0%	3%	57%	8%				3%	
Pennsylvania	Murrysville (Berea)	Sager	69%	0%	5%	58%	6%				5%	
Pennsylvania	Murrysville (Berea)	Sager	59%	1%	10%	47%	7%				10%	
Pennsylvania	Murrysville (Berea)	Sager	78%	0%	4%	38%	36%				4%	
Ohio	Conemaugh	Dodson	80%	12%	8%	67%	13%					
Ohio	Monongahela	Dodson	84%	8%	8%	75%	9%					
Ohio	Monongahela	Dodson	80%	14%	5%	74%	6%					
Ohio	Monongahela	Dodson	89%	5%	5%	73%	16%					
Alabama	Pottsville	Graham et al.,	58%	7%	36%							
Alabama	Pottsville	Graham et al.,	67%	8%	24%							
Alabama	Pottsville	Graham et al.,	60%	5%	36%							
Alabama	Pottsville	Graham et al.,	63%	6%	31%							
Alabama	Pottsville	Graham et al.,	60%	7%	33%							
Alabama	Pottsville	Graham et al.,	66%	5%	28%							
Alabama	Pottsville	Graham et al.,	64%	6%	30%							
Alabama	Pottsville	Graham et al.,	58%	7%	35%							
Alabama	Pottsville	Graham et al.,	57%	8%	35%							
Alabama	Pottsville	Graham et al.,	58%	5%	37%							
Alabama	Pottsville	Graham et al.,	68%	5%	27%							
Alabama	Pottsville	Graham et al.,	59%	7%	35%							
Alabama	Pottsville	Graham et al.,	62%	6%	32%							
Pennsylvania	Dunkard Gp	Martin and Henniger	62%	5%	9%	61%	1%					9%

Table B1 (cont'd)

Location	Fm	Author	Q	F	L	Qm	Qp	P	K	Lv	Lm	Ls
Pennsylvania	Dunkard Gp	Martin and Henniger	56%	4%	8%	55%	1%					8%
Pennsylvania	Mauch Chunk Gp	Hoque	88%	3%	1%	80%	8%					
Pennsylvania	Mauch Chunk Gp	Hoque	94%	2%	0%	85%	9%					
Pennsylvania	Mauch Chunk Gp	Hoque	90%	3%	1%	81%	8%					
Pennsylvania	Mauch Chunk Gp	Hoque	74%	7%	9%	53%	20%					
Pennsylvania	Mauch Chunk Gp	Hoque	81%	4%	5%	66%	15%					
Alabama	Pottsville	Peavy	75%	8%	17%							
Alabama	Pottsville	Peavy	58%	12%	30%							
West Virginia	Price Fm	Sheehan	80%	1%	11%							
West Virginia	Price Fm	Sheehan	78%	2%	12%							
West Virginia	Price Fm	Sheehan	73%	1%	16%							
West Virginia	Price Fm	Sheehan	65%	2%	20%							
West Virginia	Price Fm	Sheehan	81%	0%	13%							
West Virginia	Price Fm	Sheehan	76%	2%	12%							
West Virginia	Price Fm	Sheehan	72%	1%	9%							
West Virginia	Price Fm	Sheehan	75%	0%	6%							
West Virginia	Price Fm	Sheehan	76%	4%	12%							
West Virginia	Price Fm	Sheehan	67%	1%	19%							
West Virginia	Price Fm	Sheehan	74%	0%	13%							
West Virginia	Price Fm	Sheehan	80%	0%	10%							
West Virginia	Price Fm	Sheehan	74%	0%	13%							
West Virginia	Price Fm	Sheehan	74%	2%	14%							
West Virginia	Price Fm	Sheehan	77%	1%	10%							
West Virginia	Price Fm	Sheehan	73%	0%	9%							
West Virginia	Price Fm	Sheehan	65%	1%	15%							
West Virginia	Price Fm	Sheehan	76%	0%	13%							
West Virginia	Price Fm	Sheehan	62%	0%	26%							

Table B1 (cont'd)

Location	Fm	Author	Q	F	L	Qm	Qp	P	K	Lv	Lm	Ls
West Virginia	Price Fm	Sheehan	64%	0%	20%							
West Virginia	Price Fm	Sheehan	70%	0%	17%							
West Virginia	Price Fm	Sheehan	56%	0%	23%							
West Virginia	Price Fm	Sheehan	47%	0%	19%							
West Virginia	Price Fm	Sheehan	43%	0%	5%							
West Virginia	Price Fm	Sheehan	64%	0%	11%							
West Virginia	Price Fm	Sheehan	79%	0%	11%							
West Virginia	Price Fm	Sheehan	72%	0%	11%							
West Virginia	Price Fm	Sheehan	79%	0%	8%							
West Virginia	Price Fm	Sheehan	71%	0%	18%							
West Virginia	Price Fm	Sheehan	70%	0%	14%							
West Virginia	Price Fm	Sheehan	70%	0%	15%							
West Virginia	Price Fm	Sheehan	72%	0%	16%							
West Virginia	Price Fm	Sheehan	73%	0%	17%							
West Virginia	Price Fm	Sheehan	58%	0%	12%							
West Virginia	Price Fm	Sheehan	93%	0%	1%							
West Virginia	Price Fm	Sheehan	44%	0%	17%							
West Virginia	Price Fm	Sheehan	33%	0%	11%							
West Virginia	Price Fm	Sheehan	56%	0%	4%							
West Virginia	Price Fm	Sheehan	87%	0%	7%							
West Virginia	Price Fm	Sheehan	85%	0%	10%							
West Virginia	Price Fm	Sheehan	84%	0%	7%							
West Virginia	Price Fm	Sheehan	74%	0%	0%							
West Virginia	Price Fm	Sheehan	74%	0%	3%							
West Virginia	Price Fm	Sheehan	61%	0%	6%							
West Virginia	Price Fm	Sheehan	74%	0%	5%							
West Virginia	Price Fm	Sheehan	49%	0%	6%							

Table B1 (cont'd)

Location	Fm	Author	Q	F	L	Qm	Qp	P	K	Lv	Lm	Ls
West Virginia	Price Fm	Sheehan	58%	0%	18%							
West Virginia	Price Fm	Sheehan	69%	0%	7%							
West Virginia	Price Fm	Sheehan	81%	0%	3%							
West Virginia	Price Fm	Sheehan	65%	0%	8%							
West Virginia	Price Fm	Sheehan	46%	0%	1%							
West Virginia	Price Fm	Sheehan	64%	0%	7%							
West Virginia	Price Fm	Sheehan	56%	0%	3%							
West Virginia	Price Fm	Sheehan	68%	2%	6%							
West Virginia	Price Fm	Sheehan	38%	0%	4%							
West Virginia	Price Fm	Sheehan	49%	0%	4%							
West Virginia	Price Fm	Sheehan	62%	0%	5%							
West Virginia	Price Fm	Sheehan	87%	1%	12%							
West Virginia	Price Fm	Sheehan	85%	2%	13%							
West Virginia	Price Fm	Sheehan	81%	2%	18%							
West Virginia	Price Fm	Sheehan	74%	3%	23%							
West Virginia	Price Fm	Sheehan	86%	0%	14%							
West Virginia	Price Fm	Sheehan	84%	2%	14%							
West Virginia	Price Fm	Sheehan	88%	1%	11%							
West Virginia	Price Fm	Sheehan	92%	0%	8%							
West Virginia	Price Fm	Sheehan	83%	4%	13%							
West Virginia	Price Fm	Sheehan	77%	1%	22%							
West Virginia	Price Fm	Sheehan	85%	0%	15%							
West Virginia	Price Fm	Sheehan	89%	0%	11%							
West Virginia	Price Fm	Sheehan	84%	0%	15%							
West Virginia	Price Fm	Sheehan	82%	2%	16%							
West Virginia	Price Fm	Sheehan	88%	1%	11%							
West Virginia	Price Fm	Sheehan	89%	0%	11%							

Table B1 (cont'd)

Location	Fm	Author	Q	F	L	Qm	Qp	P	K	Lv	Lm	Ls
West Virginia	Price Fm	Sheehan	81%	1%	19%							
West Virginia	Price Fm	Sheehan	85%	0%	15%							
West Virginia	Price Fm	Sheehan	70%	0%	29%							
West Virginia	Price Fm	Sheehan	76%	1%	23%							
West Virginia	Price Fm	Sheehan	80%	0%	20%							
West Virginia	Price Fm	Sheehan	71%	0%	29%							
West Virginia	Price Fm	Sheehan	100%	0%	0%							
West Virginia	Price Fm	Sheehan	97%	0%	4%							
West Virginia	Price Fm	Sheehan	91%	1%	9%							
West Virginia	Price Fm	Sheehan	94%	0%	6%							
West Virginia	Price Fm	Sheehan	89%	0%	11%							
West Virginia	Price Fm	Sheehan	76%	0%	24%							
West Virginia	Price Fm	Sheehan	90%	0%	10%							
West Virginia	Price Fm	Sheehan	96%	0%	4%							
West Virginia	Price Fm	Sheehan	96%	0%	4%							
West Virginia	Price Fm	Sheehan	89%	1%	11%							
West Virginia	Price Fm	Sheehan	99%	0%	1%							
West Virginia	Price Fm	Sheehan	90%	0%	10%							
West Virginia	Price Fm	Sheehan	94%	0%	6%							
West Virginia	Price Fm	Sheehan	90%	3%	8%							
West Virginia	Price Fm	Sheehan	90%	0%	10%							
West Virginia	Price Fm	Sheehan	93%	0%	7%							
West Virginia	Price Fm	Sheehan	93%	0%	7%							
West Virginia	Grafton	Reed	232	6	12	215	17	0	6	0	12	0
West Virginia	Grafton	Reed	277	2	5	263	14	0	2	0	4	1
West Virginia	Grafton	Reed	317	4	15	294	23	0	4	0	9	6

Table B1 (cont'd)

Location	Fm	Author	Q	F	L	Qm	Qp	P	K	Lv	Lm	Ls
West Virginia	Grafton	Reed	321	3	13	303	18	0	3	0	7	6
West Virginia	Grafton	Reed	214	4	16	206	8	0	4	0	16	0
West Virginia	Grafton	Reed	248	6	28	234	14	0	6	0	23	5
West Virginia	Grafton	Reed	233	10	26	216	17	0	10	0	25	1
West Virginia	Grafton	Reed	249	7	17	220	29	0	7	0	16	1
West Virginia	Saltsburg	Reed	248	5	20	210	38	0	5	0	16	4
West Virginia	Saltsburg	Reed	321	2	25	285	36	0	2	0	10	15
West Virginia	Saltsburg	Reed	289	7	27	257	32	0	7	0	19	8
West Virginia	Saltsburg	Reed	310	1	10	283	27	0	1	0	5	5
West Virginia	Saltsburg	Reed	331	1	16	309	22	0	1	0	8	8
West Virginia	Saltsburg	Reed	283	3	31	260	23	0	3	0	20	11
West Virginia	Saltsburg	Reed	286	1	12	275	11	0	1	0	9	3
West Virginia	Saltsburg	Reed	292	7	17	272	20	0	7	0	16	1
West Virginia	Saltsburg	Reed	293	5	7	277	16	0	5	0	6	1
West Virginia	Saltsburg	Reed	280	1	13	259	21	0	1	0	7	6
West Virginia	Saltsburg	Reed	214	4	74	138	76	0	4	0	27	47
West Virginia	Saltsburg	Reed	233	4	66	181	52	0	4	0	48	18
West Virginia	Saltsburg	Reed	266	2	31	208	58	0	2	0	11	20
West Virginia	Saltsburg	Reed	305	0	35	254	51	0	0	0	21	14
West Virginia	Saltsburg	Reed	226	5	64	170	56	0	5	0	44	20
West Virginia	Saltsburg	Reed	305	3	45	269	36	0	3	0	22	23
West Virginia	Saltsburg	Reed	276	7	32	234	42	0	7	0	14	18
West Virginia	Saltsburg	Reed	317	5	24	287	30	0	5	0	13	11
West Virginia	Satsburg	Reed	278	5	28	233	45	0	5	0	11	17
West Virginia	Satsburg	Reed	306	4	39	274	32	0	4	0	21	18
West Virginia	Satsburg	Reed	258	5	59	208	50	0	5	0	40	19
West Virginia	Satsburg	Reed	238	2	51	214	24	0	2	0	45	6

Table B1 (cont'd)

Location	Fm	Author	Q	F	L	Qm	Qp	P	K	Lv	Lm	Ls
West Virginia	Satsburg	Reed	224	0	98	175	49	0	0	0	80	18
West Virginia	Satsburg	Reed	140	0	27	106	34	0	0	0	27	0
West Virginia	Satsburg	Reed	271	7	38	237	34	0	7	0	33	5
West Virginia	Satsburg	Reed	237	5	77	202	35	0	5	0	70	7
West Virginia	Satsburg	Reed	241	0	53	203	38	0	0	0	49	4
West Virginia	Satsburg	Reed	190	2	30	182	8	0	2	0	25	5
West Virginia	Satsburg	Reed	257	3	47	227	30	0	3	0	36	11
West Virginia	Saltsburg	Reed	211	0	42	182	29	0	0	0	38	4
West Virginia	Saltsburg	Reed	312	0	7	260	52	0	0	0	6	1
West Virginia	Buffalo	Reed	341	1	6	312	29	1	0	0	3	3
West Virginia	Buffalo	Reed	286	3	29	260	26	0	3	0	22	7
West Virginia	Buffalo	Reed	249	4	28	211	38	0	4	0	22	6
West Virginia	Buffalo	Reed	284	3	29	239	45	0	3	0	23	6
West Virginia	Buffalo	Reed	324	0	19	246	78	0	0	0	10	9
West Virginia	Mahoning	Reed	341	0	19	318	23	0	0	0	9	10
West Virginia	Mahoning	Reed	289	3	14	249	40	0	3	0	12	2
West Virginia	Mahoning	Reed	321	0	11	303	18	0	0	0	6	5
West Virginia	Mahoning	Reed	315	4	14	265	50	0	4	0	13	1
West Virginia	Mahoning	Reed	320	0	8	275	45	0	0	0	2	6
West Virginia	Mahoning	Reed	337	1	10	285	52	0	1	0	8	2
West Virginia	Mahoning	Reed	342	0	6	296	46	0	0	0	4	2
West Virginia	Mahoning	Reed	256	0	57	198	58	0	0	0	31	26
West Virginia	Mahoning	Reed	291	3	39	239	52	0	3	0	37	2
West Virginia	Mahoning	Reed	318	1	2	270	48	0	1	0	2	0
West Virginia	Mahoning	Reed	231	2	59	194	37	0	2	0	36	23
West Virginia	Mahoning	Reed	257	6	37	218	39	0	6	0	28	9
West Virginia	Mahoning	Reed	282	6	35	245	37	0	6	0	21	14

Table B1 (cont'd)

Location	Fm	Author	Q	F	L	Qm	Qp	P	K	Lv	Lm	Ls
West Virginia	Mahoning	Reed	327	1	8	281	46	0	1	0	3	5
West Virginia	Mahoning	Reed	316	1	17	292	24	0	1	0	12	5
West Virginia	Mahoning	Reed	263	2	47	203	60	0	2	0	27	20
West Virginia	Mahoning	Reed	242	0	53	192	50	0	0	0	37	16
West Virginia	Mahoning	Reed	238	1	63	210	28	0	1	0	27	36
West Virginia	Mahoning	Reed	241	1	46	193	48	0	1	0	34	12
West Virginia	Mahoning	Reed	242	1	43	211	31	0	1	0	31	12
West Virginia	Mahoning	Reed	224	2	55	184	40	0	2	0	40	15
West Virginia	Mahoning	Reed	251	2	54	209	42	0	2	0	37	17
West Virginia	Nuttall	Reed	298	13	24	288	10	0	13	0	22	2
West Virginia	Nuttall	Reed	307	16	7	294	13	0	16	0	6	1
West Virginia	Nuttall	Reed	348	9	2	327	21	0	9	0	2	0
West Virginia	Nuttall	Reed	343	11	2	324	19	0	11	0	2	0
West Virginia	Nuttall	Reed	291	4	10	279	12	0	4	0	9	1
West Virginia	Nuttall	Reed	248	12	39	230	18	0	12	0	37	2
West Virginia	Nuttall	Reed	285	11	28	269	16	0	11	0	28	0
West Virginia	Nuttall	Reed	177	11	13	168	9	0	11	0	12	1
West Virginia	Nuttall	Reed	275	6	33	259	16	0	6	0	32	1
West Virginia	Nuttall	Reed	277	8	29	257	20	0	8	0	27	2
West Virginia	Nuttall	Reed	281	11	17	254	27	0	11	0	17	0
West Virginia	Bee Rock	Reed	246	30	31	226	20	2	28	0	17	14
West Virginia	Bee Rock	Reed	253	27	40	229	24	1	26	0	17	23
West Virginia	Bee Rock	Reed	226	28	47	201	25	4	24	0	22	25
West Virginia	Bee Rock	Reed	268	20	53	239	29	2	18	0	17	36
West Virginia	Bee Rock	Reed	266	31	55	237	29	2	29	0	15	40
West Virginia	Bee Rock	Reed	256	14	45	237	19	2	12	0	20	25

Table B1 (cont'd)

Location	Fm	Author	Q	F	L	Qm	Qp	P	K	Lv	Lm	Ls
West Virginia	Bee Rock	Reed	245	41	29	218	27	4	37	0	11	18
West Virginia	Bee Rock	Reed	262	51	23	241	21	2	49	0	7	16
West Virginia	Council	Reed	248	32	57	228	20	1	31	0	19	38
West Virginia	Council	Reed	225	30	54	206	19	2	28	0	18	36
West Virginia	Council	Reed	257	28	61	243	14	0	28	2	18	41
West Virginia	Council	Reed	229	21	70	220	9	1	20	0	25	45
West Virginia	Council	Reed	234	21	71	221	13	2	19	0	22	49
West Virginia	Guyandot	Reed	327	1	14	317	10	0	1	0	10	4
West Virginia	Guyandot	Reed	241	4	15	236	5	2	2	0	10	5
West Virginia	Guyandot	Reed	271	1	26	257	14	0	1	0	24	2
West Virginia	Guyandot	Reed	275	4	28	268	7	1	3	0	24	4
West Virginia	Guyandot	Reed	270	12	34	263	7	5	7	0	31	3
West Virginia	Guyandot	Reed	271	28	23	269	2	6	22	0	22	1
West Virginia	Guyandot	Reed	284	30	11	269	15	3	27	0	11	0
West Virginia	Guyandot	Reed	276	24	16	267	9	4	20	0	16	0
West Virginia	Guyandot	Reed	263	14	17	242	21	2	12	0	12	5
West Virginia	Guyandot	Reed	250	13	22	227	23	3	10	0	19	3
West Virginia	Guyandot	Reed	237	19	8	219	18	4	15	0	7	1
West Virginia	Guyandot	Reed	203	12	23	191	12	1	11	0	19	4
West Virginia	Guyandot	Reed	246	9	29	219	27	0	9	0	24	5
West Virginia	Guyandot	Reed	251	16	30	233	18	2	14	0	25	5
West Virginia	Guyandot	Reed	243	21	39	222	21	2	19	0	30	9
West Virginia	Guyandot	Reed	227	9	24	211	16	0	9	0	22	2
West Virginia	U. Quartz Arenite	Reed	237	35	55	227	10	5	30	0	27	28
West Virginia	U. Quartz Arenite	Reed	231	44	37	220	11	7	37	0	12	25
West Virginia	U. Quartz Arenite	Reed	222	54	37	210	12	8	46	2	16	19
West Virginia	U. Quartz Arenite	Reed	253	59	38	241	12	2	57	0	18	20

Table B1 (cont'd)

Location	Fm	Author	Q	F	L	Qm	Qp	P	K	Lv	Lm	Ls
West Virginia	U. Quartz Arenite	Reed	253	49	45	240	13	5	44	0	20	25
West Virginia	U Raleigh	Reed	279	5	3	269	10	1	4	0	3	0
West Virginia	U Raleigh	Reed	302	2	14	288	14	0	2	0	13	1
West Virginia	U Raleigh	Reed	324	3	5	302	22	0	3	0	3	2
West Virginia	U Raleigh	Reed	337	0	5	331	6	0	0	0	5	0
West Virginia	U Raleigh	Reed	319	7	5	313	6	0	7	0	5	0
West Virginia	U Raleigh	Reed	338	1	6	332	6	0	1	0	5	1
West Virginia	U Raleigh	Reed	307	9	3	290	17	0	9	0	2	1
West Virginia	U Raleigh	Reed	333	0	5	330	3	0	0	0	5	0
West Virginia	U Raleigh	Reed	310	1	6	300	10	0	1	0	5	1
West Virginia	U Raleigh	Reed	351	0	1	340	11	0	0	0	1	0
West Virginia	U Raleigh	Reed	308	9	1	294	14	0	9	0	1	0
West Virginia	U Raleigh	Reed	305	5	6	298	7	0	5	0	5	1
West Virginia	U Raleigh	Reed	310	1	6	308	2	0	1	0	4	2
West Virginia	U Raleigh	Reed	289	9	18	274	15	0	9	0	17	1
West Virginia	U Raleigh	Reed	325	0	10	324	1	0	0	0	9	1
West Virginia	U Raleigh	Reed	286	7	36	260	26	0	7	0	31	5
West Virginia	U Raleigh	Reed	271	6	26	259	12	0	6	0	26	0
West Virginia	U Raleigh	Reed	279	4	24	262	17	0	4	0	14	10
West Virginia	U Raleigh	Reed	368	0	4	368	0	0	0	0	4	0
West Virginia	U Raleigh	Reed	331	4	2	317	14	0	4	0	2	0
West Virginia	U Raleigh	Reed	264	1	12	233	31	0	1	0	8	4
West Virginia	L.Raleigh	Reed	282	2	28	278	4	0	2	0	22	6
West Virginia	L.Raleigh	Reed	291	11	15	266	25	0	11	0	13	2
West Virginia	L.Raleigh	Reed	307	2	5	305	2	0	2	0	5	0
West Virginia	L.Raleigh	Reed	153	6	25	128	25	0	6	0	18	7
West Virginia	L.Raleigh	Reed	248	2	70	209	39	0	2	0	55	15

Table B1 (cont'd)

Location	***Fm***	***Author***	***Q***	***F***	***L***	***Qm***	***Qp***	***P***	***K***	***Lv***	***Lm***	***Ls***
West Virginia	L.Raleigh	Reed	285	0	29	281	4	0	0	0	20	9
West Virginia	L.Raleigh	Reed	280	2	17	265	15	0	2	0	10	7
West Virginia	L.Raleigh	Reed	339	1	10	332	7	0	1	0	5	5
West Virginia	L.Raleigh	Reed	281	9	44	244	37	0	9	0	30	14
West Virginia	Unnamed (98-SE-1)	Reed	275	25	49	259	16	2	23	0	19	30
West Virginia	Unnamed (98-SE-1)	Reed	272	26	38	260	12	7	19	0	21	17
West Virginia	Unnamed (98-SE-1)	Reed	250	17	31	232	18	1	16	0	15	16
West Virginia	Unnamed (98-SE-1)	Reed	259	13	55	246	13	0	13	0	21	34
West Virginia	Unnamed (98-SE-1)	Reed	214	23	84	206	8	3	20	0	31	53
West Virginia	Unnamed (98-SE-1)	Reed	235	21	38	221	14	4	17	0	18	20
West Virginia	Unnamed (98-SE-1)	Reed	266	23	51	256	10	2	21	0	18	33
West Virginia	Unnamed (98-SE-1)	Reed	239	21	61	226	13	3	18	0	25	36
West Virginia	Unnamed (98-SE-1)	Reed	255	27	55	242	13	0	27	0	24	31
West Virginia	Quinnimont	Reed	250	15	34	215	35	0	15	0	28	6
West Virginia	Quinnimont	Reed	290	10	19	252	38	0	10	0	17	2
West Virginia	Quinnimont	Reed	325	6	2	285	40	0	6	0	2	0
West Virginia	Quinnimont	Reed	339	2	5	263	76	0	2	0	3	2
West Virginia	Unnamed (98-SE-1)	Reed	263	8	43	249	14	0	8	0	16	27
West Virginia	Unnamed (98-SE-1)	Reed	264	28	48	252	12	0	28	0	24	24
West Virginia	Unnamed (98-SE-1)	Reed	257	24	44	247	10	1	23	0	21	23
West Virginia	Unnamed (98-SE-1)	Reed	246	30	42	238	8	3	27	0	25	17
West Virginia	Unnamed (98-SE-1)	Reed	270	30	33	258	12	0	30	0	12	21
West Virginia	Unnamed (98-SE-1)	Reed	263	23	39	253	10	2	21	0	12	27
West Virginia	Unnamed (98-SE-1)	Reed	260	32	34	250	10	0	32	0	11	23
West Virginia	Unnamed (98-SE-1)	Reed	279	30	26	266	13	3	27	0	13	13
West Virginia	White Rock	Reed	254	13	34	248	6	1	12	0	13	21
West Virginia	White Rock	Reed	273	21	37	258	15	2	19	0	12	25

Table B1 (cont'd)

Location	Fm	Author	Q	F	L	Qm	Qp	P	K	Lv	Lm	Ls
West Virginia	White Rock	Reed	260	15	27	248	12	2	13	0	15	12
West Virginia	White Rock	Reed	273	16	45	259	14	0	16	0	15	30
West Virginia	White Rock	Reed	280	13	36	264	16	1	12	0	9	27
West Virginia	Glady Fork	Reed	293	12	23	283	10	0	12	0	8	15
West Virginia	Glady Fork	Reed	271	10	41	268	3	0	10	0	9	32
West Virginia	Glady Fork	Reed	249	12	40	245	4	0	12	0	8	32
West Virginia	Glady Fork	Reed	265	4	87	255	10	0	4	0	2	85
West Virginia	Glady Fork	Reed	335	3	26	329	6	0	3	0	2	24
West Virginia	Princeton	Reed	335	3	26	329	6	0	3	0	2	24
West Virginia	Princeton	Reed	307	6	31	295	12	0	6	0	5	26
West Virginia	Princeton	Reed	327	2	35	322	5	0	2	0	3	32
West Virginia	Princeton	Reed	330	10	36	315	15	0	10	0	7	29
West Virginia	Princeton	Reed	335	6	26	326	9	0	6	0	1	25
West Virginia	Stony Gap	Reed	322	6	17	317	5	0	6	0	5	12
West Virginia	Stony Gap	Reed	332	10	7	328	4	0	10	0	1	6
West Virginia	Stony Gap	Reed	365	5	4	365	0	0	5	0	2	2
West Virginia	Stony Gap	Reed	337	6	14	335	2	0	6	0	1	13
West Virginia	Stony Gap	Reed	352	5	11	351	1	0	5	0	1	10
West Virginia	Stony Gap	Reed	309	17	34	302	7	0	17	0	5	29
West Virginia	Stony Gap	Reed	344	4	8	339	5	0	4	0	2	6
West Virginia	Stony Gap	Reed	339	4	7	338	1	0	4	0	1	6
West Virginia	Stony Gap	Reed	325	7	13	323	2	0	7	0	3	10
West Virginia	Stony Gap	Reed	345	8	4	345	0	0	8	0	3	1
Appalachian Basin		Siever	64.50	4.00	2.50							
Appalachian Basin		Siever	51.50	5.50	0.00							
Appalachian Basin		Siever	31.50	3.50	0.00							
Appalachian Basin		Siever	40.50	7.50	0.00							

Table B1 (cont'd)

Location	Fm	Author	Q	F	L	Qm	Qp	P	K	Lv	Lm	Ls
Appalachian Basin		Siever	64.00	5.00	0.00							
Appalachian Basin		Siever	61.50	4.00	0.50							
Appalachian Basin		Siever	38.50	3.50	0.50							
Appalachian Basin		Siever	95.50	1.50	0.50							
Appalachian Basin		Siever	67.50	2.00	1.50							
Appalachian Basin		Siever	68.00	0.50	2.00							
Appalachian Basin		Siever	79.00	4.00	1.50							
Appalachian Basin		Siever	61.50	3.50	0.50							
Appalachian Basin		Siever	61.50	6.50	0.50							
Appalachian Basin		Siever	80.00	0.00	3.00							
Appalachian Basin		Siever	95.50	0.50	1.00							
Appalachian Basin		Siever	91.00	0.50	0.00							
Appalachian Basin		Siever	67.00	5.50	1.00							
Appalachian Basin		Siever	79.00	4.50	0.00							
Appalachian Basin		Siever	95.00	1.00	0.00							
Appalachian Basin		Siever	82.00	4.00	0.00							
Appalachian Basin		Siever	95.50	0.50	0.00							
Appalachian Basin		Siever	97.00	1.50	0.50							
Appalachian Basin		Siever	90.00	1.90	0.60							
Appalachian Basin		Siever	85.30	1.40	0.50							
Appalachian Basin		Siever	86.70	2.30	1.00							
Appalachian Basin		Siever	86.50	0.50	1.50							
Appalachian Basin		Siever	79.50	0.00	1.50							
Appalachian Basin		Siever	91.00	0.50	2.00							

APPENDIX C

Compiled Illinois basin point count data

Table C1: Compiled Illinois basin point count data

Location	Fm	Author	Q	Qm	Qp	P	K	F	Lv	Lm	Ls
Illinois	Babylon	Siever and Potter	89.5		1.5			1.0			2.5
Illinois	Babylon	Siever and Potter	99.0		0.0			0.0			0.0
Illinois	Babylon	Siever and Potter	92.5		0.5			0.0			0.5
Illinois	Babylon	Siever and Potter	98.0		0.0			0.0			0.0
Illinois	Tradewater Gp	Siever and Potter	91.0		0.0			0.0			0.0
Illinois	Babylon	Siever and Potter	88.0		0.5			0.0			1.0
Illinois	Babylon	Siever and Potter	90.0		0.0			0.0			0.0
Illinois	Tradewater Gp	Siever and Potter	98.0		1.5			0.0			1.5
Illinois	Tradewater Gp	Siever and Potter	3.0		0.5			0.0			0.5
Illinois	Tradewater Gp	Siever and Potter	75.0		0.5			0.0			1.5
Illinois	Tradewater Gp	Siever and Potter	50.0		3.5			0.0			6.0
Illinois	Tradewater Gp	Siever and Potter	72.0		0.5			0.0			3.0
Illinois	Tradewater Gp	Siever and Potter	41.5		0.5			2.0			4.0
Illinois	Pounds	Siever and Potter	91.5		0.5			0.0			1.0
Illinois	Makanda (lower)	Siever and Potter	94.0					0.0			1.0
Illinois	Pounds	Siever and Potter	87.5		1.0			0.5			2.0
Illinois	Pounds	Siever and Potter	67.5		0.5			0.5			0.5
Illinois	Pounds (basal)	Siever and Potter	66.5		0.0			1.0			0.5
Illinois	Drury	Siever and Potter	95.5		0.5			0.0			0.5
Illinois	Drury	Siever and Potter	88.5		0.0			0.0			0.0
Illinois	Caseyville	Siever and Potter	85.5		2.0			0.0			3.0
Illinois	Caseyville	Siever and Potter	86.0		0.5			0.0			3.0
Illinois	Caseyville	Siever and Potter	88.5		1.0			0.5			4.5
Illinois	Caseyville	Siever and Potter									
Illinois	Caseyville	Siever and Potter	95.5		0.5			0.0			0.5
Illinois	Caseyville	Siever and Potter	93.0		0.0			0.0			0.0
Illinois	Caseyville	Siever and Potter	91.5		0.0			0.5			0.0
Illinois	Caseyville	Siever and Potter	90.5		1.0			0.5			1.0
Illinois	Caseyville	Siever and Potter	97.0		0.0			0.0			0.0
Illinois	Caseyville	Siever and Potter	79.5		1.5			0.5			1.5
Illinois	Caseyville	Siever and Potter	96.0		1.0			0.0			1.0
Illinois	Battery	Siever and Potter	65.5		0.0			0.0			0.0
Illinois	Battery Rock	Siever and Potter	72.5		0.0			0.0			1.5
Illinois	Battery Rock	Siever and Potter	97.0		0.0			0.0			0.0
Illinois	Lick Creek	Siever and Potter	94.5		0.0			1.0			0.0
Illinois	Wayside	Siever and Potter	97.0		0.0			0.0			0.0
Iowa	Pleasantview	Laury	33.7	30.0	3.7			4.3			
Iowa	Pleasantview	Laury	61.0	51.3	9.7			8.3			

Table C1 (cont'd)

Location	Fm	Author	Q	Qm	Qp	P	K	F	Lv	Lm	Ls
Iowa	Pleasantview	Laury	51.0	43.3	7.7			3.3			
Iowa	Pleasantview	Laury	55.0	47.7	7.7			3.3			
Iowa	Pleasantview	Laury	60.2	52.2	8.0			6.4			
Iowa	Pleasantview	Laury	63.0	53.0	10.0			7.3			
Iowa	Pleasantview	Laury	61.0	49.1	11.3			7.0			
Iowa	Pleasantview	Laury	63.3	57.0	6.3			8.0			
Iowa	Pleasantview	Laury	59.7	52.0	7.7			8.6			
Iowa	Pleasantview	Laury	60.3	54.0	6.3			5.3			
Iowa	Pleasantview	Laury	42.6	36.8	5.8			5.2			
Iowa	Pleasantview	Laury	39.3	34.3	5.0			3.3			
Iowa	Pleasantview	Laury	62.7	55.3	7.4			8.0			
Iowa	Pleasantview	Laury	55.7	45.0	10.7			7.7			
Iowa	Pleasantview	Laury	64.0	63.3	0.7			4.3			
Iowa	Pleasantview	Laury	64.7	56.0	8.7			11.0			
Iowa	Pleasantview	Laury	56.1	48.9	7.2			6.3			
Illinois	Pleasantview	Laury	53.7	48.3	5.4			4.7			0.4
Illinois	Pleasantview	Laury	66.9	60.3	5.7			5.7			
Illinois	Pleasantview	Laury	67.7	61.0	6.7			7.3			1.4
Illinois	Pleasantview	Laury	66.0	59.0	7.0			4.0			0.3
Illinois	Pleasantview	Laury	63.4	57.2	6.2			5.4			0.5
Illinois	Pleasantview	Laury	50.7	44.7	6.0			6.7			0.7
Illinois	Pleasantview	Laury	64.7	59.6	5.1			4.7			1.0
Illinois	Pleasantview	Laury	57.7	52.2	5.5			5.7			0.8
Illinois	Pleasantview	Laury	58.1	52.8	5.3			6.1			0.5
Illinois	Blue river Gp	Pitman et al.,	65.0					5.0			
Illinois	Blue river Gp	Pitman et al.,	58.0					11.0			
Illinois	Blue river Gp	Pitman et al.,	63.0					7.0			
Illinois	Blue river Gp	Pitman et al.,	60.0					5.0			
Illinois	Blue river Gp	Pitman et al.,	48.0					6.0			
Illinois	Blue river Gp	Pitman et al.,	53.0					7.5			
Illinois	Blue river Gp	Pitman et al.,	54.0					10.0			
Illinois	Blue river Gp	Pitman et al.,	67.0					3.0			
Illinois	Blue river Gp	Pitman et al.,	52.0					10.0			
Illinois	Blue river Gp	Pitman et al.,	49.0					7.0			
Illinois	Blue river Gp	Pitman et al.,	52.0					1.0			
Illinois	Blue river Gp	Pitman et al.,	52.0					3.0			
Illinois	Blue river Gp	Pitman et al.,	62.0					10.0			
Illinois	Blue river Gp	Pitman et al.,	57.0					5.0			

Table C1 (cont'd)

Location	Fm	Author	Q	Qm	Qp	P	K	F	Lv	Lm	Ls
Illinois	Blue river Gp	Pitman et al.,	60.0					9.0			
Illinois	Blue river Gp	Pitman et al.,	63.0					7.0			
Illinois	Blue river Gp	Pitman et al.,	46.0					5.0			
Illinois	Blue river Gp	Pitman et al.,	68.0					3.0			
Illinois	Blue river Gp	Pitman et al.,	72.0					3.0			
Illinois	Blue river Gp	Pitman et al.,	59.0					6.0			
Illinois	Blue river Gp	Pitman et al.,	55.0					3.5			
Illinois	Blue river Gp	Pitman et al.,	65.0					7.0			
Illinois	Blue river Gp	Pitman et al.,	56.0					5.0			
Illinois	Blue river Gp	Pitman et al.,	64.0					3.0			
Illinois	Blue river Gp	Pitman et al.,	63.0					4.0			
Illinois	Blue river Gp	Pitman et al.,	38.0					3.0			
Illinois	Blue river Gp	Pitman et al.,	57.0					13.0			
Illinois	Blue river Gp	Pitman et al.,	38.0					7.5			
Illinois	Blue river Gp	Pitman et al.,	62.0					3.5			
Illinois	Blue river Gp	Pitman et al.,	54.0					5.0			
Illinois	Blue river Gp	Pitman et al.,	54.0					8.0			
Illinois	Blue river Gp	Pitman et al.,	58.0					13.0			
Illinois	Blue river Gp	Pitman et al.,	45.5					10.0			
Illinois	Blue river Gp	Pitman et al.,	61.0					9.0			
Illinois	Blue river Gp	Pitman et al.,	62.0					7.0			
Illinois	Blue river Gp	Pitman et al.,	54.0					9.0			
Illinois	Blue river Gp	Pitman et al.,	40.0					4.0			
Illinois	Blue river Gp	Pitman et al.,	69.5					2.5			
Illinois	Blue river Gp	Pitman et al.,	46.0					5.0			
Illinois	Blue river Gp	Pitman et al.,	58.0					6.0			
Illinois	Blue river Gp	Pitman et al.,	58.0					4.0			
Illinois	Blue river Gp	Pitman et al.,	62.5					6.0			
Illinois	Blue river Gp	Pitman et al.,	44.0					6.0			
Illinois	Blue river Gp	Pitman et al.,	58.0					8.5			
Illinois	Blue river Gp	Pitman et al.,	59.5					10.0			
Illinois	Blue river Gp	Pitman et al.,	58.0					9.0			
Illinois	Blue river Gp	Pitman et al.,	57.0					11.0			
Illinois	Blue river Gp	Pitman et al.,	64.0					11.0			
Illinois	Blue river Gp	Pitman et al.,	45.0					11.0			
Illinois	Blue river Gp	Pitman et al.,	59.0					3.0			
Illinois	Blue river Gp	Pitman et al.,	72.0					1.0			
Illinois	Blue river Gp	Pitman et al.,	53.0					8.0			

Table C1 (cont'd)

Location	Fm	Author	Q	Qm	Qp	P	K	F	Lv	Lm	Ls
Illinois	Blue river Gp	Pitman et al.,	59.5					3.0			
Illinois	Blue river Gp	Pitman et al.,	61.0					4.0			
Illinois	Blue river Gp	Pitman et al.,	52.0					4.0			
Illinois	Blue river Gp	Pitman et al.,	60.5					5.5			
Illinois	Blue river Gp	Pitman et al.,	58.0					6.0			
Illinois	Blue river Gp	Pitman et al.,	60.0					3.0			
Illinois	Blue river Gp	Pitman et al.,	54.0					3.0			
Illinois	Blue river Gp	Pitman et al.,	65.0					2.0			
Illinois	Blue river Gp	Pitman et al.,	64.0					2.0			
Illinois	Blue river Gp	Pitman et al.,	64.0					1.0			
Illinois	Blue river Gp	Pitman et al.,	54.0					3.0			
Illinois	Blue river Gp	Pitman et al.,	71.0					1.0			
Illinois	Blue river Gp	Pitman et al.,	70.0					1.0			
Illinois	Blue river Gp	Pitman et al.,	61.0					2.0			
Illinois	Blue river Gp	Pitman et al.,	65.5					2.5			
Illinois	Blue river Gp	Pitman et al.,	64.0					2.0			
Illinois	Blue river Gp	Pitman et al.,	52.0					1.5			
Illinois	Blue river Gp	Pitman et al.,	54.0					7.0			
Illinois		Siever	54.5					1.0			
Illinois		Siever	30.5					1.0			
Illinois		Siever	43.0					1.5			
Illinois		Siever	50.5					2.5			
Illinois		Siever	64.0					5.5			
Illinois		Siever	65.5					4.0			
Illinois		Siever	59.0					2.0			
Illinois		Siever	59.0					8.5			
Illinois		Siever	67.0					4.0			
Illinois		Siever	55.0					5.0			
Illinois		Siever	67.5					7.0			
Illinois		Siever	66.0					4.0			
Illinois		Siever	59.5					3.0			
Illinois		Siever	56.0					4.5			
Illinois		Siever	69.5					5.5			
Illinois		Siever	66.0					5.5			
Illinois		Siever	62.5					2.0			
Illinois		Siever	70.5					4.0			
Illinois		Siever	67.5					3.5			
Illinois		Siever	70.0					0.0			

Table C1 (cont'd)

Location	Fm	Author	Q	Qm	Qp	P	K	F	Lv	Lm	Ls
Illinois		Siever	67.0					0.5			
Illinois		Siever	92.5					0.0			
Illinois		Siever	88.9					0.1			
Illinois		Siever	58.5					7.0			
Illinois		Siever	61.0					2.0			
Illinois		Siever	53.5					2.5			
Illinois		Siever	63.5					4.0			
Illinois		Siever	68.5					3.5			
Illinois		Siever	43.5					2.5			
Illinois		Siever	59.5					3.5			
Illinois		Siever	60.5					1.5			
Illinois		Siever	76.0					1.0			
Illinois		Siever	50.0					3.0			
Illinois		Siever	53.5					2.5			
Illinois		Siever	78.5					3.5			
Illinois		Siever	60.5					2.0			
Illinois		Siever	90.5					3.0			
Illinois		Siever	81.5					3.0			
Illinois		Siever	72.0					6.0			
Illinois		Siever	78.0					6.0			
Illinois		Siever	51.5					2.0			
Illinois		Siever	59.5					1.5			
Illinois		Siever	54.5					2.0			
Illinois		Siever	93.5					4.0			
Illinois		Siever	69.0					0.0			
Illinois		Siever	83.5					0.0			
Illinois		Siever	66.5					1.0			
Illinois		Siever	27.5					0.0			
Illinois		Siever	67.5					7.0			
Illinois		Siever	65.5					1.0			
Illinois		Siever	71.5					4.0			
Illinois		Siever	83.5					1.5			
Illinois		Siever	66.0					3.0			
Illinois		Siever	76.0					0.5			
Illinois		Siever	87.5					0.5			
Illinois		Siever	97.0					0.0			
Illinois		Siever	86.0					0.0			
Illinois		Siever	85.5					0.0			

Table C1 (cont'd)

Location	Fm	Author	Q	Qm	Qp	P	K	F	Lv	Lm	Ls
Illinois		Siever	55.0					4.5			
Illinois		Siever	50.0					2.0			
Illinois		Siever	59.0					3.0			
Illinois		Siever	63.0					4.0			
Illinois		Siever	61.5					4.0			
Illinois		Siever	55.0					3.5			
Illinois		Siever	62.0					1.5			
Illinois		Siever	58.0					3.0			
Illinois		Siever	58.0					4.0			
Illinois		Siever	58.0					4.0			
Illinois		Siever	53.5					3.0			
Illinois		Siever	54.5					2.5			
Illinois		Siever	63.5					1.5			
Illinois		Siever	63.0					3.0			
Illinois		Siever	61.0					6.5			
Illinois		Siever	74.0					1.5			
Illinois		Siever	77.5					0.5			
Illinois		Siever	83.5					0.5			
Illinois		Siever	75.5					0.0			
Illinois		Siever	70.0					4.0			
Illinois		Siever	90.0					0.0			
Illinois		Siever	87.0					0.0			
Illinois		Siever	93.1					0.2			
Illinois		Siever	55.5					11.5			
Illinois		Siever	32.5					1.5			
Illinois		Siever	47.5					4.5			
Illinois		Siever	61.5					4.0			
Illinois		Siever	46.0					4.0			
Illinois		Siever	56.5					5.5			
Illinois		Siever	58.5					3.5			
Illinois		Siever	52.0					5.5			
Illinois		Siever	60.0					6.5			
Illinois		Siever	65.4					4.5			
Illinois		Siever	56.8					3.0			
Illinois		Siever	42.0					3.0			
Illinois		Siever	62.5					4.0			
Illinois		Siever	52.5					7.0			
Illinois		Siever	66.5					7.0			

Table C1 (cont'd)

Location	Fm	Author	Q	Qm	Qp	P	K	F	Lv	Lm	Ls
Illinois		Siever	64.0					5.5			
Illinois		Siever	70.0					2.0			
Illinois		Siever	78.0					2.0			
Illinois		Siever	89.0					2.5			
Illinois		Siever	68.0					3.0			
Illinois		Siever	77.5					2.0			
Illinois		Siever	63.5					3.5			
Illinois		Siever	94.0					0.2			
Indiana		Siever	74.5					6.5			
Indiana		Siever	67.0					6.0			
Indiana		Siever	68.0					5.5			
Indiana		Siever	59.0					6.0			
Indiana		Siever	69.5					2.0			
Indiana		Siever	63.5					5.5			
Indiana		Siever	59.5					7.5			
Indiana		Siever	66.0					5.0			
Indiana		Siever	74.5					4.5			
Indiana		Siever	62.0					5.5			
Indiana		Siever	71.0					3.0			
Indiana		Siever	60.0					5.5			
Indiana		Siever	69.0					6.5			
Indiana		Siever	86.0					2.0			
Indiana		Siever	89.5					1.5			
Indiana		Siever	87.3					2.3			
Missouri		Siever	50.0					6.5			
Missouri		Siever	34.0					3.5			
Missouri		Siever	42.5					3.5			
Missouri		Siever	25.0					0.0			
Missouri		Siever	74.5					6.5			
Missouri		Siever	58.0					4.5			
Missouri		Siever	44.0					0.5			
Missouri		Siever	58.0					4.0			
Missouri		Siever	37.5					2.0			
Missouri		Siever	84.0					1.0			
Missouri		Siever	63.0					2.5			
Missouri		Siever	57.5					1.0			
Missouri		Siever	93.5					3.5			
Missouri		Siever	81.5					1.5			

Table C1 (cont'd)

Location	*Fm*	*Author*	*Q*	*Qm*	*Qp*	*P*	*K*	*F*	*Lv*	*Lm*	*Ls*
Missouri		Siever	62.5					2.5			
Missouri		Siever	80.5					0.5			
Missouri		Siever	80.5					1.5			
Western Kentucky		Siever	66.5					4.0			
Western Kentucky		Siever	81.0					2.5			
Western Kentucky		Siever	62.0					2.5			
Western Kentucky		Siever	73.5					3.0			
Western Kentucky		Siever	74.5					4.5			
Western Kentucky		Siever	67.0					9.5			
Western Kentucky		Siever	82.5					2.0			
Western Kentucky		Siever	60.5					3.0			
Western Kentucky		Siever	56.5					2.0			
Western Kentucky		Siever	70.0					1.0			
Western Kentucky		Siever	69.5					0.0			
Western Kentucky		Siever	75.5					2.5			
Western Kentucky		Siever	79.5					0.5			
Western Kentucky		Siever	70.0					1.0			
Western Kentucky		Siever	94.0					0.5			
Western Kentucky		Siever	82.5					1.0			
Western Kentucky		Siever	89.0					0.5			
Western Kentucky		Siever	70.0					2.0			
Western Kentucky		Siever	86.0					0.0			
Western Kentucky		Siever	91.2					0.2			

APPENDIX D

U-Pb Detrital Zircon Isotope ratios and ages from Carboniferous Sandstones of the Michigan Basin

Table D1: Analytical results of U-Pb detrital zircon isotope ratios and age data from the Marshall Sandstone

Sample: MIB-062510-01						Isotope ratios					Apparent ages (Ma)								
Sample #	U (ppm)	206Pb 204Pb	U/Th	206Pb* 207Pb*	± (%)	207Pb* 235U*	± (%)	206Pb* 238U	± (%)	error corr.	206Pb* 238U*	± (Ma)	207Pb* 235U	± (Ma)	206Pb* 207Pb*	± (Ma)	Best age (Ma)	± (Ma)	Conc (%)
UK1	300	97070	3.3	13.7	0.5	1.74	1.9	0.17	1.8	0.96	1030.7	17.5	1024.5	12.4	1011.3	11.0	1011.3	11.0	101.9
UK2	117	36784	3.2	13.4	2.0	1.91	2.8	0.18	2.0	0.69	1093.1	19.6	1084.0	18.8	1065.8	40.8	1065.8	40.8	102.6
UK3	161	26686	1.6	17.6	5.2	0.58	6.2	0.07	3.3	0.54	463.2	14.9	465.8	23.1	478.6	115.3	463.2	14.9	NA
UK5	104	14212	0.4	17.4	7.0	0.62	8.0	0.08	3.8	0.48	485.4	18.0	489.8	31.1	510.3	154.7	485.4	18.0	NA
UK6	204	129766	2.8	13.0	1.8	1.96	2.4	0.19	1.7	0.69	1094.6	16.8	1101.9	16.3	1116.3	35.2	1116.3	35.2	98.1
UK7	111	73714	2.4	13.6	1.4	1.73	3.8	0.17	3.5	0.93	1018.3	33.1	1021.4	24.3	1028.0	27.3	1028.0	27.3	99.1
UK8	171	59503	4.1	13.9	1.2	1.68	2.5	0.17	2.1	0.86	1005.9	19.7	1001.2	15.6	990.9	25.1	990.9	25.1	101.5
UK9	174	60450	2.8	13.7	1.5	1.76	3.4	0.17	3.0	0.89	1036.9	28.7	1029.7	21.8	1014.4	30.8	1014.4	30.8	102.2
UK10	50	10642	3.4	13.6	3.3	1.80	5.3	0.18	4.2	0.79	1053.8	40.9	1047.2	34.8	1033.5	65.8	1033.5	65.8	102.0
UK11	71	48743	0.9	10.5	1.9	3.38	2.7	0.26	2.0	0.71	1480.0	25.8	1500.3	21.5	1529.2	36.3	1529.2	36.3	96.8
UK12	53	14247	2.7	12.7	3.9	2.20	4.5	0.20	2.3	0.50	1189.0	24.5	1179.9	31.7	1163.3	78.2	1163.3	78.2	102.2
UK14	81	32852	3.6	13.9	4.0	1.59	4.3	0.16	1.5	0.35	958.7	13.3	966.8	26.9	985.1	82.4	985.1	82.4	97.3
UK15	98	57402	1.3	13.6	2.0	1.71	2.2	0.17	1.0	0.46	1003.8	9.3	1012.4	14.1	1031.2	39.6	1031.2	39.6	97.3
UK16	260	78913	2.8	13.8	1.3	1.72	2.5	0.17	2.2	0.85	1021.1	20.4	1015.9	16.3	1004.7	27.3	1004.7	27.3	101.6
UK17	117	17694	1.9	18.0	4.8	0.57	5.4	0.07	2.5	0.46	464.8	11.2	459.8	20.0	435.1	107.2	464.8	11.2	NA
UK18	60	29352	2.8	12.6	1.8	2.12	3.0	0.19	2.3	0.78	1145.5	24.5	1156.9	20.5	1178.3	36.5	1178.3	36.5	97.2
UK19	197	151209	3.4	13.6	1.1	1.76	1.8	0.17	1.5	0.82	1031.3	14.2	1030.2	11.8	1027.8	21.3	1027.8	21.3	100.3
UK20	125	58091	2.3	11.9	1.3	2.45	1.5	0.21	0.9	0.57	1236.7	9.8	1257.8	11.0	1294.1	24.4	1294.1	24.4	95.6
UK21	107	101359	2.0	12.8	3.0	2.05	4.4	0.19	3.3	0.74	1123.7	34.1	1131.4	30.3	1146.2	58.8	1146.2	58.8	98.0
UK22	71	33812	15.6	13.3	3.7	1.87	4.4	0.18	2.4	0.54	1069.8	23.6	1072.1	29.3	1076.9	74.7	1076.9	74.7	99.3
UK23	107	94228	1.7	13.9	2.1	1.70	2.4	0.17	1.0	0.43	1017.4	9.6	1007.0	15.2	984.4	43.6	984.4	43.6	103.4
UK24	40	30224	2.0	12.7	4.4	2.14	5.2	0.20	2.8	0.53	1161.9	29.3	1162.3	35.8	1163.0	86.6	1163.0	86.6	99.9
UK25	132	34647	1.0	18.6	6.8	0.56	7.4	0.08	3.1	0.42	469.5	14.0	451.5	27.1	360.8	152.7	469.5	14.0	NA
UK26	68	39185	2.0	11.9	2.4	2.63	2.9	0.23	1.6	0.56	1319.1	19.3	1308.6	21.0	1291.5	45.9	1291.5	45.9	102.1
UK27	379	141805	3.0	12.5	0.4	2.27	1.5	0.21	1.5	0.96	1206.9	16.0	1202.4	10.7	1194.2	8.3	1194.2	8.3	101.1

Table D1 (cont'd)

UK28	95	51131	1.1	13.9	3.2	1.61	3.7	0.16	1.8	0.50	969.4	16.6	975.3	23.2	988.7	65.3	988.7	65.3	98.0
UK30	450	212344	2.3	12.8	0.5	2.16	1.4	0.20	1.3	0.93	1173.3	14.1	1167.7	9.8	1157.4	10.2	1157.4	10.2	101.4
UK31	105	69960	3.9	12.3	1.5	2.39	1.9	0.21	1.2	0.63	1248.1	13.7	1240.0	13.7	1226.0	29.0	1226.0	29.0	101.8
UK32	281	128805	4.3	12.7	1.0	2.12	2.2	0.20	2.0	0.89	1154.1	20.7	1156.2	15.1	1160.2	19.6	1160.2	19.6	99.5
UK33	28	37663	1.5	11.0	4.0	3.17	4.5	0.25	2.1	0.47	1448.5	27.5	1449.9	34.9	1451.9	75.9	1451.9	75.9	99.8
UK34	95	18550	1.5	12.5	4.3	2.13	6.0	0.19	4.3	0.71	1139.6	44.6	1158.6	41.8	1194.2	84.5	1194.2	84.5	95.4
UK35	108	51923	3.0	13.9	2.6	1.67	3.0	0.17	1.4	0.46	1006.7	12.8	998.6	18.9	980.8	53.7	980.8	53.7	102.6
UK36	65	41224	2.3	13.7	3.4	1.61	4.4	0.16	2.7	0.61	955.3	23.7	974.3	27.3	1017.4	69.8	1017.4	69.8	93.9
UK37	43	35412	2.8	11.9	2.7	2.58	3.4	0.22	2.0	0.59	1296.5	23.7	1296.0	25.0	1295.2	53.4	1295.2	53.4	100.1
UK38	83	26760	3.2	14.3	3.3	1.48	3.4	0.15	0.9	0.26	920.3	7.7	921.4	20.7	924.0	67.6	924.0	67.6	99.6
UK39	200	29029	1.5	18.1	3.7	0.55	4.4	0.07	2.4	0.55	449.2	10.4	444.2	15.8	418.5	82.0	449.2	10.4	NA
UK40	64	47157	3.6	13.9	2.5	1.68	3.1	0.17	1.8	0.57	1006.3	16.4	1000.2	19.6	986.9	51.6	986.9	51.6	102.0
UK41	300	88300	2.9	14.0	1.3	1.55	1.9	0.16	1.3	0.69	943.8	11.2	952.1	11.4	971.4	27.4	971.4	27.4	97.2
UK42	123	72738	3.6	12.8	2.2	2.08	3.5	0.19	2.8	0.79	1138.5	29.1	1141.6	24.2	1147.6	42.7	1147.6	42.7	99.2
UK43	103	16577	1.2	17.9	5.1	0.55	7.2	0.07	5.0	0.70	442.3	21.6	442.8	25.8	445.2	114.3	442.3	21.6	NA
UK44	115	72080	2.5	12.4	1.8	2.37	2.8	0.21	2.1	0.76	1241.2	24.0	1233.2	20.1	1219.4	36.1	1219.4	36.1	101.8
UK46	129	67872	2.5	10.9	1.7	3.31	2.6	0.26	2.0	0.76	1495.0	26.6	1483.4	20.4	1466.8	32.1	1466.8	32.1	101.9
UK48	70	25609	2.4	13.8	3.0	1.66	3.4	0.17	1.6	0.47	989.0	14.7	993.6	21.8	1003.7	61.6	1003.7	61.6	98.5
UK49	47	33669	1.9	12.4	3.3	2.28	3.5	0.21	1.4	0.39	1202.3	15.2	1204.6	25.0	1208.7	64.2	1208.7	64.2	99.5
UK50	29	18510	2.5	14.3	4.4	1.55	4.7	0.16	1.8	0.38	962.4	15.9	951.6	29.3	926.7	90.2	926.7	90.2	103.9
UK51	75	38166	3.4	12.2	2.5	2.34	2.9	0.21	1.5	0.51	1210.4	16.5	1223.2	20.8	1245.8	49.3	1245.8	49.3	97.2
UK54	96	39087	3.8	13.9	2.2	1.72	2.8	0.17	1.8	0.62	1032.3	16.9	1017.5	18.3	985.7	45.4	985.7	45.4	104.7
UK55	164	60664	3.3	13.6	0.8	1.71	1.6	0.17	1.4	0.86	1005.2	12.7	1011.5	10.2	1025.1	16.7	1025.1	16.7	98.1
UK57	129	53011	2.2	13.5	1.9	1.80	4.1	0.18	3.6	0.88	1046.5	34.7	1045.7	26.6	1044.0	38.7	1044.0	38.7	100.2
UK58	234	184843	2.3	13.0	1.5	2.00	3.4	0.19	3.1	0.90	1115.8	31.5	1116.8	23.2	1118.9	30.1	1118.9	30.1	99.7
UK59	69	44364	3.2	13.9	2.9	1.60	3.6	0.16	2.2	0.61	964.1	19.9	970.6	22.8	985.5	58.7	985.5	58.7	97.8
UK60	69	19733	2.0	13.4	2.7	1.81	3.3	0.18	1.9	0.57	1045.7	18.5	1049.3	21.9	1056.9	55.1	1056.9	55.1	98.9
UK61	77	33910	2.7	12.6	2.3	2.16	2.8	0.20	1.7	0.59	1163.6	17.9	1167.5	19.6	1174.8	44.9	1174.8	44.9	99.0
UK62	36	17566	1.6	13.6	3.7	1.67	4.6	0.16	2.7	0.59	982.5	24.6	997.7	29.2	1031.5	75.4	1031.5	75.4	95.2

Table D1 (cont'd)

UK63	98	37945	3.1	11.0	2.1	3.21	2.6	0.26	1.5	0.58	1467.9	20.2	1460.7	20.4	1450.1	40.8	1450.1	40.8	101.2
UK64	497	355725	5.2	13.7	0.7	1.70	1.1	0.17	0.9	0.80	1005.1	8.2	1009.0	7.0	1017.6	13.3	1017.6	13.3	98.8
UK65	196	89946	5.0	13.9	1.4	1.69	1.7	0.17	1.0	0.58	1009.6	9.1	1003.6	10.8	990.7	28.2	990.7	28.2	101.9
UK66	121	46043	2.1	13.5	1.7	1.80	2.6	0.18	2.0	0.77	1047.1	19.2	1045.9	16.9	1043.5	33.4	1043.5	33.4	100.3
UK67	177	87768	6.8	13.6	1.5	1.76	2.8	0.17	2.3	0.83	1032.1	21.8	1029.2	17.8	1022.9	31.0	1022.9	31.0	100.9
UK68	254	121605	4.3	17.8	3.2	0.51	5.4	0.07	4.4	0.81	415.0	17.6	421.3	18.7	455.5	71.0	415.0	17.6	NA
UK70	132	47846	2.0	14.0	1.8	1.56	2.1	0.16	1.1	0.49	948.5	9.3	953.1	13.2	963.8	37.8	963.8	37.8	98.4
UK72	103	41121	2.0	14.0	3.5	1.63	4.0	0.17	1.9	0.48	986.1	17.8	980.4	25.4	967.8	72.4	967.8	72.4	101.9
UK73	195	109884	2.6	12.3	0.9	2.35	1.6	0.21	1.3	0.83	1222.4	14.5	1227.5	11.3	1236.4	17.5	1236.4	17.5	98.9
UK74	81	65037	1.4	10.8	1.6	3.27	1.9	0.25	0.9	0.51	1463.9	12.3	1473.9	14.5	1488.2	30.4	1488.2	30.4	98.4
UK75	172	16365	2.6	17.9	3.3	0.51	5.2	0.07	4.1	0.77	410.3	16.1	416.7	17.9	452.3	73.9	410.3	16.1	NA
UK76	62	27212	2.4	13.8	2.3	1.66	3.3	0.17	2.3	0.71	993.4	21.5	995.0	21.0	998.6	47.5	998.6	47.5	99.5
UK77	167	71778	1.5	13.0	0.6	2.00	1.6	0.19	1.5	0.92	1117.8	15.2	1115.8	10.9	1111.9	12.7	1111.9	12.7	100.5
UK78	85	38752	3.2	12.3	1.7	2.30	2.4	0.21	1.7	0.71	1203.4	18.7	1211.0	17.1	1224.5	33.6	1224.5	33.6	98.3
UK80	57	27843	4.5	10.9	2.4	3.22	2.7	0.25	1.4	0.50	1463.4	17.8	1462.5	21.3	1461.2	45.3	1461.2	45.3	100.2
UK81	131	53210	4.0	12.3	1.1	2.30	4.4	0.21	4.3	0.97	1207.9	47.0	1213.2	31.2	1222.6	21.9	1222.6	21.9	98.8
UK82	161	32136	1.9	17.4	4.0	0.59	4.4	0.07	1.9	0.43	466.1	8.4	472.8	16.7	505.4	87.8	466.1	8.4	NA
UK83	165	31113	111.8	18.4	4.7	0.59	6.0	0.08	3.7	0.62	487.4	17.5	469.1	22.6	380.4	105.7	487.4	17.5	NA
UK84	76	47365	2.3	10.8	2.7	3.29	3.0	0.26	1.3	0.42	1474.9	16.5	1477.9	23.3	1482.2	51.6	1482.2	51.6	99.5
UK85	54	29093	2.2	12.2	4.1	2.36	4.4	0.21	1.7	0.39	1218.9	19.0	1230.4	31.6	1250.5	79.9	1250.5	79.9	97.5
UK87	86	26278	1.6	14.1	3.8	1.55	4.1	0.16	1.5	0.37	949.7	13.3	950.4	25.0	952.1	77.1	952.1	77.1	99.7
UK88	141	34866	1.2	17.5	4.3	0.61	4.9	0.08	2.3	0.48	480.5	10.7	482.9	18.8	494.6	94.7	480.5	10.7	NA
UK89	41	8781	2.0	12.3	5.9	2.33	6.8	0.21	3.4	0.50	1218.0	38.0	1220.6	48.6	1225.2	116.3	1225.2	116.3	99.4
UK90	213	179687	3.2	14.3	1.7	1.54	3.4	0.16	2.9	0.86	956.5	25.8	947.7	20.7	927.4	34.7	927.4	34.7	103.1
UK91	350	76675	9.5	13.5	1.1	1.74	4.3	0.17	4.1	0.97	1017.2	38.7	1024.5	27.5	1040.2	22.5	1040.2	22.5	97.8
UK92	101	40351	2.1	14.1	2.4	1.57	3.5	0.16	2.5	0.73	958.3	22.7	957.6	21.7	956.0	48.8	956.0	48.8	100.2
UK93	284	29625	3.0	17.1	3.4	0.54	5.3	0.07	4.1	0.77	419.2	16.5	440.1	18.9	551.1	73.7	419.2	16.5	NA
UK94	131	121650	1.9	11.7	1.2	2.63	2.8	0.22	2.5	0.90	1298.8	29.9	1308.8	20.8	1325.2	24.1	1325.2	24.1	98.0
UK95	189	26527	1.5	17.8	3.4	0.56	6.6	0.07	5.7	0.86	447.6	24.6	449.8	24.2	460.8	76.5	447.6	24.6	NA

Table D1 (cont'd)

UK96	97	25362	1.8	18.1	8.8	0.57	9.8	0.07	4.4	0.45	462.8	19.7	455.6	36.0	419.3	195.7	462.8	19.7	NA
UK97	62	73264	2.3	12.5	3.9	2.26	4.9	0.20	2.9	0.59	1198.5	31.3	1199.5	34.3	1201.3	77.8	1201.3	77.8	99.8
UK98	83	25142	2.0	12.7	1.9	2.23	3.9	0.21	3.3	0.86	1209.0	36.9	1191.8	27.1	1160.7	38.6	1160.7	38.6	104.2
UK99	330	49908	1.6	17.6	2.3	0.58	3.2	0.07	2.3	0.70	461.8	10.2	466.1	12.1	487.5	51.0	461.8	10.2	NA
UK100	238	29255	4.9	11.8	3.7	2.44	9.0	0.21	8.2	0.91	1225.5	91.1	1255.8	64.7	1308.2	72.1	1308.2	72.1	93.7
UK101	410	341952	101.7	13.4	0.8	1.82	2.7	0.18	2.6	0.95	1050.3	25.0	1052.0	17.7	1055.6	16.3	1055.6	16.3	99.5
UK102	50	18530	2.9	13.6	4.1	1.76	4.6	0.17	2.1	0.45	1032.0	19.9	1032.3	29.9	1032.9	83.3	1032.9	83.3	99.9
UK103	113	76464	2.9	10.9	1.0	3.14	2.4	0.25	2.2	0.92	1435.1	28.5	1443.4	18.6	1455.5	18.1	1455.5	18.1	98.6
UK104	152	88977	5.4	14.0	2.0	1.59	2.2	0.16	0.9	0.43	966.8	8.5	967.1	13.6	967.8	40.2	967.8	40.2	99.9
UK105	321	209977	4.2	13.7	0.9	1.74	5.0	0.17	4.9	0.98	1028.5	46.8	1023.4	32.3	1012.6	18.2	1012.6	18.2	101.6

Table D2: Analytical results of U-Pb detrital zircon isotope ratios and age data from the Marshall Sandstone

Sample: MIB-062510-02						Isotope ratios					Apparent ages (Ma)								
Sample	U (ppm)	206Pb 204Pb	U/Th	206Pb* 207Pb*	± (%)	207Pb* 235U*	± (%)	206Pb* 238U	± (%)	error corr.	206Pb* 238U*	± (Ma)	207Pb* 235U	± (Ma)	206Pb* 207Pb*	± (Ma)	Best age (Ma)	± (Ma)	Conc (%)
UK1	47	26939	2.5	10.46	1.4	3.59	6.0	0.27	5.9	0.97	1552.0	81.0	1546.8	48.0	1539.6	26.9	1539.6	26.9	100.8
UK-2	653	61697	18.3	13.33	0.5	1.71	4.6	0.17	4.5	0.99	988.4	41.6	1013.5	29.3	1068.3	10.2	1068.3	10.2	92.5
UK-3	195	188632	3.5	10.19	0.6	3.73	1.8	0.28	1.7	0.94	1569.5	23.8	1577.9	14.6	1589.2	11.8	1589.2	11.8	98.8
UK4	186	79100	1.0	13.41	0.8	1.90	1.9	0.18	1.7	0.91	1091.7	17.2	1080.4	12.5	1057.7	15.8	1057.7	15.8	103.2
UK5	44	30388	1.4	13.89	3.5	1.66	3.9	0.17	1.8	0.46	994.0	16.3	991.6	24.6	986.3	70.4	986.3	70.4	100.8
UK6	168	48547	3.0	10.84	1.5	3.06	4.4	0.24	4.1	0.94	1391.5	51.5	1424.0	33.4	1472.9	27.6	1472.9	27.6	94.5
UK7	71	38607	3.8	13.59	3.1	1.72	3.8	0.17	2.1	0.55	1008.2	19.4	1015.2	24.2	1030.5	63.6	1030.5	63.6	97.8
UK8	63	26795	1.1	14.27	3.4	1.47	3.9	0.15	1.8	0.47	912.0	15.7	917.6	23.5	930.9	70.1	930.9	70.1	98.0
UK9	205	174491	1.9	10.57	1.1	3.28	2.8	0.25	2.5	0.91	1444.7	32.9	1475.8	21.7	1520.8	21.7	1520.8	21.7	95.0
UK10	217	220810	1.9	9.42	3.0	3.86	4.3	0.26	3.1	0.73	1508.9	42.3	1605.8	35.0	1735.4	54.8	1735.4	54.8	86.9
UK11	61	5372	1.7	16.60	12.2	0.63	13.1	0.08	4.7	0.36	470.0	21.3	495.0	51.3	612.5	264.6	470.0	21.3	76.7
UK12	57	24868	2.0	13.78	5.1	1.63	5.4	0.16	1.6	0.29	970.9	14.0	980.7	33.7	1002.5	104.1	1002.5	104.1	96.8
UK13	150	18153	3.5	12.62	1.0	2.15	1.8	0.20	1.5	0.83	1156.1	15.7	1164.0	12.4	1178.6	19.7	1178.6	19.7	98.1
UK14	193	74262	0.6	15.67	1.4	1.04	2.1	0.12	1.5	0.74	722.4	10.6	725.7	10.9	735.7	30.0	722.4	10.6	98.2
UK15	38	18114	4.0	12.25	3.1	2.35	4.4	0.21	3.1	0.71	1223.7	35.0	1228.4	31.7	1236.8	61.7	1236.8	61.7	98.9
UK16	187	84014	2.6	13.88	1.8	1.68	2.6	0.17	1.9	0.74	1006.0	18.0	1000.2	16.7	987.4	36.2	987.4	36.2	101.9
UK17	110	55574	1.4	14.20	3.5	1.47	3.9	0.15	1.7	0.44	911.0	14.8	919.8	23.9	940.8	72.6	940.8	72.6	96.8
UK18	51	35933	2.3	13.87	4.0	1.63	4.9	0.16	2.9	0.59	981.8	26.3	983.7	31.0	988.1	81.0	988.1	81.0	99.4
UK19	203	87643	2.6	13.68	1.2	1.70	1.9	0.17	1.5	0.78	1006.8	13.9	1009.7	12.2	1016.1	24.0	1016.1	24.0	99.1
UK20	375	209955	3.2	13.51	0.7	1.76	2.9	0.17	2.8	0.97	1025.3	26.7	1030.9	18.9	1042.7	15.0	1042.7	15.0	98.3
UK21	300	342785	6.9	10.72	0.4	3.36	1.8	0.26	1.7	0.98	1497.0	22.9	1495.5	13.7	1493.3	7.2	1493.3	7.2	100.2
UK22	126	64432	1.3	10.85	1.7	3.35	3.0	0.26	2.4	0.83	1509.9	32.8	1493.4	23.1	1469.9	31.7	1469.9	31.7	102.7
UK23	104	57070	1.9	13.86	1.8	1.66	2.4	0.17	1.7	0.68	993.5	15.3	992.3	15.4	989.4	36.3	989.4	36.3	100.4
UK24	115	80056	4.1	13.10	1.6	2.01	2.3	0.19	1.7	0.73	1125.9	17.6	1118.4	15.8	1103.8	31.8	1103.8	31.8	102.0
UK26	73	41160	2.9	12.57	3.4	2.16	3.8	0.20	1.8	0.47	1157.4	19.1	1167.5	26.5	1186.4	66.3	1186.4	66.3	97.6

Table D2 (cont'd)

UK27	40	22318	1.2	13.78	8.6	1.64	8.7	0.16	1.3	0.15	980.6	12.1	987.0	55.1	1001.3	175.2	1001.3	175.2	97.9
UK28	69	78005	1.4	13.66	1.9	1.79	2.4	0.18	1.4	0.60	1055.1	13.9	1043.5	15.5	1019.4	38.5	1019.4	38.5	103.5
UK29	54	29582	2.3	12.22	2.4	2.40	3.5	0.21	2.6	0.73	1244.7	29.2	1243.8	25.4	1242.1	47.5	1242.1	47.5	100.2
UK30	505	62356	1.5	18.02	0.9	0.55	1.8	0.07	1.5	0.86	446.5	6.5	444.3	6.4	432.7	20.4	446.5	6.5	NA
UK31	55	30174	2.6	14.39	5.0	1.52	5.5	0.16	2.2	0.39	950.3	19.1	939.1	33.7	912.9	103.9	912.9	103.9	104.1
UK32	144	107848	0.9	10.58	0.5	3.49	3.4	0.27	3.4	0.99	1529.4	46.4	1524.8	27.2	1518.5	9.2	1518.5	9.2	100.7
UK33	455	230496	1.9	12.50	0.6	2.28	3.3	0.21	3.2	0.99	1213.3	35.7	1207.6	23.1	1197.2	11.0	1197.2	11.0	101.3
UK34	188	53176	3.6	13.78	1.5	1.68	3.0	0.17	2.6	0.86	1001.6	23.7	1001.9	19.0	1002.7	31.4	1002.7	31.4	99.9
UK35	104	68478	3.1	12.72	2.2	2.03	4.0	0.19	3.3	0.84	1105.7	33.9	1124.9	27.1	1162.3	43.1	1162.3	43.1	95.1
UK36	59	21381	1.5	14.33	4.1	1.55	5.0	0.16	2.8	0.56	963.2	24.7	950.9	30.6	922.5	84.7	922.5	84.7	104.4
UK37	104	75376	1.5	9.23	0.8	4.42	1.5	0.30	1.3	0.85	1669.7	18.7	1715.5	12.3	1772.0	14.2	1772.0	14.2	94.2
UK38	130	14053	2.2	12.67	2.2	2.00	3.4	0.18	2.5	0.75	1085.4	25.4	1114.3	22.9	1171.0	44.3	1171.0	44.3	92.7
UK39	117	58430	3.1	13.76	1.5	1.72	1.9	0.17	1.2	0.61	1022.0	11.0	1016.4	12.3	1004.4	31.0	1004.4	31.0	101.7
UK40	103	78767	1.9	13.87	2.6	1.71	2.8	0.17	0.9	0.34	1023.9	8.8	1012.9	17.6	989.3	52.7	989.3	52.7	103.5
UK41	127	34676	1.5	18.64	8.3	0.44	8.7	0.06	2.5	0.29	373.3	9.1	371.0	26.9	356.8	187.5	373.3	9.1	NA
UK42	190	157702	2.8	13.81	1.0	1.64	1.4	0.16	0.9	0.66	981.0	8.2	986.1	8.7	997.3	21.0	997.3	21.0	98.4
UK43	126	52418	2.2	13.72	1.2	1.74	1.5	0.17	1.0	0.65	1028.1	9.5	1022.6	9.9	1010.7	23.6	1010.7	23.6	101.7
UK45	49	20201	2.6	13.09	2.1	2.04	3.6	0.19	2.9	0.81	1141.9	30.5	1129.3	24.7	1105.3	42.8	1105.3	42.8	103.3
UK47	177	32801	2.4	19.27	4.4	0.40	5.0	0.06	2.3	0.46	351.4	7.7	342.2	14.4	280.6	101.1	351.4	7.7	NA
UK48	190	84675	5.0	14.02	1.4	1.64	2.4	0.17	1.9	0.80	992.9	17.5	984.8	15.0	966.8	28.9	966.8	28.9	102.7
UK49	28	14919	1.9	13.98	5.1	1.64	5.7	0.17	2.6	0.46	992.7	24.2	986.5	36.2	972.7	103.9	972.7	103.9	102.1
UK50	248	132704	4.9	13.68	1.0	1.71	1.9	0.17	1.7	0.86	1010.0	15.6	1011.9	12.5	1016.0	20.2	1016.0	20.2	99.4
UK51	63	43640	0.9	12.81	2.6	2.02	4.8	0.19	4.0	0.84	1107.2	40.7	1121.3	32.3	1148.5	50.8	1148.5	50.8	96.4
UK52	77	25719	3.1	14.41	4.2	1.45	4.4	0.15	1.1	0.25	908.0	9.1	908.9	26.2	911.2	87.1	911.2	87.1	99.6
UK53	236	177557	4.2	12.82	0.8	2.08	1.9	0.19	1.7	0.90	1137.4	17.7	1140.7	13.0	1146.9	16.5	1146.9	16.5	99.2
UK55	133	16164	2.1	17.81	7.2	0.55	7.7	0.07	2.7	0.35	442.2	11.4	444.9	27.8	458.8	160.6	442.2	11.4	NA
UK56	279	292432	4.5	6.01	7.0	7.57	7.9	0.33	3.6	0.46	1838.2	58.3	2181.0	70.8	2521.1	117.6	2521.1	117.6	72.9
UK57	88	56047	1.0	13.34	2.4	1.83	2.9	0.18	1.6	0.54	1048.9	15.2	1054.8	19.0	1067.1	49.0	1067.1	49.0	98.3
UK58	276	163955	1.7	11.42	0.5	2.79	1.2	0.23	1.1	0.90	1340.0	13.3	1352.5	9.2	1372.2	10.5	1372.2	10.5	97.7

Table D2 (cont'd)

UK59	289	153616	3.3	12.79	0.8	2.16	2.5	0.20	2.4	0.94	1176.9	25.3	1168.0	17.3	1151.5	16.7	1151.5	16.7	102.2
UK61	210	87761	1.1	13.77	2.0	1.70	2.3	0.17	1.1	0.46	1008.9	9.8	1007.4	14.7	1004.0	41.4	1004.0	41.4	100.5
UK62	64	124598	1.7	7.82	0.7	6.70	1.1	0.38	0.9	0.79	2076.5	15.1	2072.5	9.5	2068.5	11.5	2068.5	11.5	100.4
UK64	138	27908	1.5	18.41	5.2	0.48	5.4	0.06	1.5	0.27	401.8	5.7	399.3	17.7	384.7	115.8	401.8	5.7	NA
UK65	67	11108	1.7	19.72	9.7	0.51	10.2	0.07	3.1	0.30	454.3	13.5	418.8	35.1	227.7	225.7	454.3	13.5	NA
UK66	44	56613	2.9	5.11	0.8	15.05	2.5	0.56	2.3	0.94	2859.5	53.3	2818.5	23.4	2789.3	13.8	2789.3	13.8	102.5
UK67	122	50861	3.8	14.06	2.6	1.64	3.4	0.17	2.2	0.64	994.1	20.3	984.0	21.7	961.4	53.9	961.4	53.9	103.4
UK68	50	56697	2.4	10.82	2.5	3.19	3.0	0.25	1.7	0.57	1439.4	22.4	1454.6	23.4	1476.9	47.0	1476.9	47.0	97.5
UK69	98	22470	3.4	17.82	6.1	0.56	7.3	0.07	4.0	0.55	451.5	17.3	452.4	26.5	457.0	135.2	451.5	17.3	NA
UK70	258	74378	14.8	13.57	1.0	1.71	1.5	0.17	1.1	0.72	1002.3	10.0	1011.9	9.6	1032.7	21.2	1032.7	21.2	97.1
UK71	59	23787	2.4	14.01	3.7	1.66	4.1	0.17	1.7	0.43	1003.5	16.2	992.6	25.8	968.4	75.3	968.4	75.3	103.6
UK72	69	42224	4.1	12.65	3.5	2.11	3.6	0.19	0.8	0.21	1141.1	8.1	1152.1	24.9	1172.9	70.0	1172.9	70.0	97.3
UK73	122	148904	1.8	9.90	1.3	4.03	1.6	0.29	1.0	0.63	1637.9	14.6	1639.9	13.1	1642.5	23.2	1642.5	23.2	99.7
UK74	61	44989	3.5	12.96	3.6	2.13	3.9	0.20	1.6	0.40	1175.7	16.7	1158.2	27.0	1125.5	71.4	1125.5	71.4	104.5
UK76	384	107835	1.4	17.35	1.6	0.64	3.9	0.08	3.5	0.91	502.7	17.0	505.1	15.4	516.3	34.6	502.7	17.0	97.4
UK79	138	71453	1.6	14.20	3.2	1.47	3.6	0.15	1.6	0.44	908.2	13.4	917.7	21.8	940.8	66.4	940.8	66.4	96.5
UK81	30	22256	1.3	13.35	6.8	1.65	7.5	0.16	3.0	0.40	954.1	26.7	988.5	47.2	1065.8	137.6	1065.8	137.6	89.5
UK82	134	23183	5.4	15.99	4.2	0.88	4.5	0.10	1.4	0.32	628.8	8.7	642.7	21.3	692.1	90.1	628.8	8.7	90.9
UK83	139	82077	1.5	13.82	1.2	1.64	2.6	0.16	2.3	0.89	983.0	21.2	987.1	16.5	996.3	24.2	996.3	24.2	98.7
UK84	181	88100	6.2	13.62	1.5	1.71	1.9	0.17	1.2	0.63	1008.1	11.1	1013.4	12.2	1024.9	29.8	1024.9	29.8	98.4
UK85	72	34961	2.9	13.82	3.9	1.62	4.4	0.16	2.0	0.45	968.4	17.6	977.1	27.3	996.6	79.1	996.6	79.1	97.2
UK86	129	59856	2.5	14.07	2.7	1.53	3.2	0.16	1.8	0.55	933.0	15.2	940.8	19.7	959.0	55.0	959.0	55.0	97.3
UK87	131	38633	4.2	13.61	2.2	1.74	3.5	0.17	2.7	0.78	1019.4	25.6	1021.7	22.5	1026.6	44.5	1026.6	44.5	99.3
UK88	194	142153	2.2	11.66	0.5	2.73	3.1	0.23	3.0	0.99	1338.3	36.7	1336.3	22.9	1333.1	9.6	1333.1	9.6	100.4
UK89	76	34882	2.4	13.68	2.6	1.67	3.2	0.17	1.9	0.58	990.9	17.3	999.1	20.5	1017.0	53.0	1017.0	53.0	97.4
UK90	356	103226	2.2	17.70	2.5	0.58	3.6	0.07	2.6	0.73	463.7	11.7	465.2	13.4	472.4	54.3	463.7	11.7	NA
UK91	28	23922	2.9	13.23	6.6	1.75	7.0	0.17	2.2	0.31	999.1	19.9	1026.1	45.1	1083.9	133.3	1083.9	133.3	92.2
UK92	534	125178	7.5	18.10	2.7	0.47	3.5	0.06	2.2	0.63	384.5	8.2	390.0	11.3	422.8	60.6	384.5	8.2	NA

Table D2 (cont'd)

UK93	72	29311	0.7	13.15	4.5	1.97	6.2	0.19	4.2	0.69	1112.7	43.3	1107.0	41.7	1095.8	90.3	1095.8	90.3	101.5
UK94	147	34289	1.2	17.31	5.9	0.63	7.6	0.08	4.8	0.63	487.0	22.7	493.0	29.7	520.7	129.2	487.0	22.7	93.5
UK96	57	46371	4.3	11.82	1.8	2.43	2.1	0.21	1.1	0.51	1218.5	11.8	1250.5	14.9	1305.9	34.5	1305.9	34.5	93.3
UK97	81	26062	2.0	13.67	3.5	1.59	4.0	0.16	1.8	0.45	945.1	15.6	967.1	24.7	1017.5	71.7	1017.5	71.7	92.9
UK98	70	28331	55.4	13.69	1.8	1.69	2.4	0.17	1.6	0.66	1001.3	14.8	1005.6	15.4	1014.8	36.7	1014.8	36.7	98.7
UK99	97	31714	4.3	10.92	1.5	3.20	1.9	0.25	1.1	0.61	1454.5	14.8	1456.4	14.3	1459.0	27.9	1459.0	27.9	99.7
UK100	279	235782	34.2	13.52	1.3	1.81	2.1	0.18	1.7	0.80	1055.8	16.6	1050.7	13.9	1040.3	25.7	1040.3	25.7	101.5
UK101	53	20358	1.6	14.01	5.2	1.62	7.2	0.17	5.0	0.70	985.0	45.8	979.7	45.3	967.8	105.5	967.8	105.5	101.8
UK102	155	7817	1.0	17.69	8.6	0.58	9.8	0.07	4.8	0.49	461.9	21.4	463.8	36.6	473.3	190.3	461.9	21.4	NA
UK103	157	83293	2.0	15.38	2.0	1.17	6.9	0.13	6.6	0.96	789.9	49.1	785.9	37.8	774.7	42.5	789.9	49.1	102.0
UK104	106	47627	3.0	13.91	2.0	1.64	3.1	0.17	2.4	0.78	989.1	22.2	987.2	19.6	983.1	39.7	983.1	39.7	100.6
UK105	42	16731	1.5	13.43	5.9	1.76	6.7	0.17	3.4	0.50	1020.4	31.8	1031.3	43.7	1054.7	118.0	1054.7	118.0	96.7

Table D3: Analytical results of U-Pb detrital zircon isotope ratios and age data from the Parma Sandstone

Sample MIB-070810-01						Isotope ratios					Apparent ages (Ma)									
Sample	U (ppm)	206Pb 204Pb	U/Th	206Pb* 207Pb*	± (%)	207Pb* 235U*	± (%)	206Pb* 238U	± (%)	error corr.	206Pb* 238U*	± (Ma)	207Pb* 235U	± (Ma)	206Pb* 207Pb*	± (Ma)	Best age (Ma)	± (Ma)	Conc (%)
UK1	176	80290	1.1	9.89	0.6	4.11	1.1	0.30	0.9	0.85	1667.4	13.9	1657.1	9.0	1644.0	10.7	1644.0	10.7	101.4
UK2	81	46252	2.9	12.80	2.9	2.00	3.0	0.19	0.9	0.30	1099.6	9.4	1116.8	20.6	1150.4	57.6	1150.4	57.6	95.6
UK3	228	182509	4.4	13.01	1.1	2.03	2.2	0.19	1.9	0.86	1128.9	19.4	1125.0	14.9	1117.4	22.5	1117.4	22.5	101.0
UK4	262	41590	1.4	10.65	1.0	3.43	1.9	0.26	1.7	0.86	1515.2	22.7	1511.6	15.3	1506.6	18.7	1506.6	18.7	100.6
UK5	49	21579	0.7	11.22	2.6	2.97	3.6	0.24	2.5	0.70	1395.8	32.0	1400.4	27.5	1407.4	49.3	1407.4	49.3	99.2
UK6	22	24444	1.3	4.96	1.2	15.02	2.1	0.54	1.7	0.81	2786.1	38.1	2816.4	19.8	2838.1	19.9	2838.1	19.9	98.2
UK8	52	22797	2.2	14.03	3.4	1.63	3.8	0.17	1.7	0.44	989.6	15.3	981.9	23.9	964.8	69.5	964.8	69.5	102.6
UK9	29	20992	1.2	13.03	8.8	1.85	9.7	0.17	4.1	0.43	1037.8	39.5	1063.0	63.9	1115.2	175.2	1115.2	175.2	93.1
UK10	170	86138	2.1	8.95	0.8	5.21	1.9	0.34	1.8	0.91	1879.4	28.8	1854.6	16.5	1826.8	14.2	1826.8	14.2	102.9
UK11	88	80588	2.9	9.96	1.9	3.95	2.3	0.28	1.4	0.60	1616.3	20.1	1623.0	19.0	1631.6	34.9	1631.6	34.9	99.1
UK12	20	10030	1.4	12.21	8.7	2.39	9.9	0.21	4.8	0.49	1238.8	54.2	1240.3	71.0	1242.8	169.9	1242.8	169.9	99.7
UK14	161	24091	2.1	9.72	0.8	4.26	1.1	0.30	0.8	0.72	1692.2	11.8	1685.0	9.0	1676.1	14.0	1676.1	14.0	101.0
UK15	313	224717	1.2	9.07	0.4	5.01	1.1	0.33	1.0	0.94	1835.9	16.1	1820.6	9.1	1803.0	6.9	1803.0	6.9	101.8
UK16	73	59541	2.0	10.55	1.6	3.43	2.4	0.26	1.8	0.74	1501.7	23.9	1510.7	19.1	1523.3	30.9	1523.3	30.9	98.6
UK17	155	110475	3.1	11.23	0.7	2.90	1.3	0.24	1.1	0.84	1366.9	13.8	1381.8	10.1	1404.8	13.9	1404.8	13.9	97.3
UK18	80	37651	3.5	13.38	3.6	1.93	4.9	0.19	3.3	0.68	1105.9	33.9	1091.0	32.8	1061.5	72.5	1061.5	72.5	104.2
UK19	172	46762	3.2	12.66	1.5	2.13	1.8	0.20	1.1	0.58	1152.8	11.4	1159.3	12.8	1171.6	29.7	1171.6	29.7	98.4
UK20	53	21479	1.8	13.23	5.2	1.92	5.5	0.18	1.8	0.32	1088.1	17.6	1086.9	36.5	1084.6	103.9	1084.6	103.9	100.3
UK21	275	121950	4.0	13.48	1.4	1.85	2.2	0.18	1.6	0.75	1072.8	16.2	1064.4	14.3	1047.2	28.9	1047.2	28.9	102.4
UK22	420	119723	9.3	12.97	0.7	2.02	1.2	0.19	1.0	0.81	1120.6	9.8	1121.4	8.0	1123.1	14.0	1123.1	14.0	99.8
UK23	89	40539	1.7	8.84	0.8	5.26	1.8	0.34	1.6	0.90	1874.7	26.1	1863.0	15.3	1850.0	14.2	1850.0	14.2	101.3
UK24	187	157456	3.0	13.45	1.7	1.87	2.7	0.18	2.1	0.79	1079.2	21.3	1070.0	18.0	1051.5	33.9	1051.5	33.9	102.6
UK25	37	16095	1.5	13.29	4.4	1.89	4.9	0.18	2.0	0.41	1080.3	19.7	1078.7	32.3	1075.6	89.0	1075.6	89.0	100.4
UK27	185	213921	2.4	9.42	0.5	4.47	1.4	0.31	1.3	0.92	1718.4	20.0	1725.2	11.9	1733.5	10.1	1733.5	10.1	99.1
UK28	108	117707	1.7	5.25	0.5	13.79	2.3	0.53	2.3	0.98	2722.5	50.1	2735.3	21.9	2744.8	8.4	2744.8	8.4	99.2

Table D3 (cont'd)

UK29	264	186113	3.0	12.91	1.1	2.06	2.4	0.19	2.1	0.90	1137.9	22.3	1136.4	16.4	1133.5	21.2	1133.5	21.2	100.4
UK30	25	11039	2.5	11.34	5.1	2.93	5.2	0.24	1.2	0.23	1392.1	15.3	1389.9	39.5	1386.6	97.3	1386.6	97.3	100.4
UK31	75	15646	1.0	9.78	1.6	3.86	2.2	0.27	1.6	0.72	1559.9	22.4	1605.1	18.1	1664.8	28.8	1664.8	28.8	93.7
UK32	53	18116	1.5	9.91	2.1	3.93	2.8	0.28	1.9	0.66	1603.5	26.6	1619.9	23.0	1641.2	39.6	1641.2	39.6	97.7
UK33	107	30009	3.1	13.81	2.4	1.72	3.1	0.17	2.1	0.66	1022.3	19.5	1014.2	20.2	996.8	48.2	996.8	48.2	102.6
UK34	169	42808	2.4	18.15	4.3	0.53	4.6	0.07	1.7	0.37	434.3	7.1	431.5	16.2	416.6	95.8	434.3	7.1	NA
UK36	90	24666	0.7	13.25	2.2	1.92	5.5	0.18	5.1	0.91	1092.9	50.8	1088.9	37.0	1081.1	45.0	1081.1	45.0	101.1
UK37	127	17038	1.7	5.33	0.5	12.53	2.1	0.48	2.0	0.97	2547.2	43.0	2644.8	19.8	2720.3	8.2	2720.3	8.2	93.6
UK38	153	66148	1.6	9.81	1.2	4.16	3.1	0.30	2.8	0.92	1670.4	41.9	1665.9	25.3	1660.1	22.3	1660.1	22.3	100.6
UK39	51	28229	1.1	8.79	1.7	5.31	3.0	0.34	2.4	0.82	1880.0	39.5	1871.0	25.4	1861.0	31.0	1861.0	31.0	101.0
UK40	338	85830	1.3	18.11	2.3	0.53	2.7	0.07	1.6	0.57	430.6	6.5	429.1	9.6	421.3	50.4	430.6	6.5	NA
UK41	100	20031	1.5	18.81	5.9	0.55	6.9	0.07	3.6	0.52	465.9	16.2	444.6	24.8	335.8	132.8	465.9	16.2	NA
UK43	95	79729	2.9	13.70	3.0	1.74	3.3	0.17	1.3	0.39	1025.6	12.4	1021.8	21.4	1013.7	61.8	1013.7	61.8	101.2
UK44	60	31795	2.0	13.56	2.2	1.84	4.5	0.18	3.9	0.88	1073.3	39.1	1060.8	29.6	1035.1	43.6	1035.1	43.6	103.7
UK45	252	150455	7.0	9.18	0.4	4.64	1.1	0.31	1.1	0.94	1733.6	16.2	1755.8	9.4	1782.3	6.7	1782.3	6.7	97.3
UK46	67	48735	1.3	13.75	3.9	1.71	4.5	0.17	2.1	0.48	1017.0	20.1	1013.4	28.7	1005.6	79.7	1005.6	79.7	101.1
UK47	272	190140	4.1	9.31	0.3	4.67	1.3	0.32	1.2	0.97	1767.6	18.9	1762.3	10.5	1756.0	5.9	1756.0	5.9	100.7
UK48	138	41420	3.3	13.76	2.2	1.71	3.0	0.17	2.1	0.69	1013.2	19.6	1010.8	19.3	1005.6	44.0	1005.6	44.0	100.8
UK49	146	21603	1.9	17.23	4.8	0.56	5.2	0.07	1.9	0.37	433.3	8.1	449.2	18.8	531.6	105.1	433.3	8.1	NA
UK50	178	74848	2.9	13.73	1.9	1.73	3.8	0.17	3.3	0.87	1022.9	31.6	1018.5	24.7	1009.0	38.7	1009.0	38.7	101.4
UK51	71	47392	1.1	9.84	1.5	4.24	2.0	0.30	1.4	0.69	1704.9	21.1	1682.5	16.7	1654.6	27.3	1654.6	27.3	103.0
UK53	276	189280	1.8	12.79	0.6	2.14	2.2	0.20	2.1	0.96	1168.3	22.4	1162.7	15.1	1152.3	12.4	1152.3	12.4	101.4
UK54	144	51973	3.1	13.69	1.2	1.76	2.5	0.17	2.2	0.88	1036.3	21.1	1029.4	16.2	1014.8	24.5	1014.8	24.5	102.1
UK55	46	13123	1.5	13.78	5.7	1.70	6.3	0.17	2.6	0.41	1009.0	23.8	1007.0	40.2	1002.5	116.8	1002.5	116.8	100.7
UK57	106	27626	1.6	18.04	11.4	0.56	11.7	0.07	2.4	0.20	456.2	10.4	451.9	42.6	430.2	255.3	456.2	10.4	NA
UK58	98	46055	1.5	10.96	1.6	3.12	2.3	0.25	1.6	0.70	1428.4	20.3	1438.0	17.4	1452.3	30.9	1452.3	30.9	98.4
UK59	71	119559	0.8	4.46	0.4	18.71	2.9	0.61	2.9	0.99	3052.0	70.4	3027.0	28.2	3010.5	6.3	3010.5	6.3	101.4
UK60	51	34401	0.8	13.75	5.8	1.74	6.2	0.17	2.2	0.36	1032.2	21.4	1024.1	40.0	1006.8	117.4	1006.8	117.4	102.5
UK61	296	179191	6.8	13.27	1.9	1.99	10.1	0.19	9.9	0.98	1128.2	102.7	1111.3	68.4	1078.4	38.7	1078.4	38.7	104.6

Table D3 (cont'd)

UK62	76	37918	0.9	13.12	4.6	1.78	4.8	0.17	1.3	0.27	1010.0	12.0	1039.0	31.0	1100.6	92.0	1100.6	92.0	91.8
UK63	112	132384	0.7	4.70	0.5	17.10	2.9	0.58	2.8	0.98	2959.0	67.4	2940.6	27.7	2928.0	8.3	2928.0	8.3	101.1
UK64	35	36700	1.2	9.92	3.7	4.03	4.5	0.29	2.6	0.58	1643.2	37.7	1641.0	36.6	1638.2	68.3	1638.2	68.3	100.3
UK65	126	49492	1.0	13.85	1.5	1.71	2.9	0.17	2.4	0.85	1023.8	23.1	1013.7	18.4	991.9	30.9	991.9	30.9	103.2
UK66	344	117396	3.5	13.42	0.7	1.85	2.6	0.18	2.5	0.97	1068.4	24.5	1064.3	17.0	1056.0	13.6	1056.0	13.6	101.2
UK67	82	32540	1.6	12.91	2.1	2.04	4.7	0.19	4.2	0.89	1127.8	43.0	1129.3	31.8	1132.3	42.5	1132.3	42.5	99.6
UK68	282	400801	0.9	8.72	0.4	5.37	1.4	0.34	1.3	0.96	1884.1	21.7	1879.5	11.8	1874.4	6.5	1874.4	6.5	100.5
UK69	99	35306	2.7	11.07	1.5	3.24	2.5	0.26	2.0	0.81	1491.1	26.3	1467.3	19.1	1433.0	27.8	1433.0	27.8	104.1
UK70	92	46022	2.7	12.83	2.8	2.10	3.3	0.20	1.8	0.55	1148.5	19.0	1147.5	22.7	1145.5	54.9	1145.5	54.9	100.3
UK71	32	13781	3.0	13.24	4.3	1.85	7.2	0.18	5.7	0.80	1052.1	55.5	1062.0	47.2	1082.3	86.6	1082.3	86.6	97.2
UK72	217	117005	1.2	10.61	0.8	3.40	1.9	0.26	1.8	0.91	1498.8	23.5	1505.1	15.2	1514.0	15.6	1514.0	15.6	99.0
UK73	234	85129	3.9	12.95	1.1	2.05	2.9	0.19	2.7	0.93	1134.6	27.9	1132.1	19.7	1127.4	21.3	1127.4	21.3	100.6
UK74	353	215202	5.7	13.81	0.9	1.66	3.7	0.17	3.6	0.97	991.3	33.2	993.4	23.5	998.1	17.3	998.1	17.3	99.3
UK75	325	295545	2.8	11.17	0.6	3.05	2.8	0.25	2.8	0.98	1424.5	35.2	1420.6	21.5	1414.9	10.8	1414.9	10.8	100.7
UK76	150	8465	1.4	12.90	2.6	2.01	5.8	0.19	5.2	0.90	1110.8	53.5	1119.1	39.6	1135.2	51.2	1135.2	51.2	97.9
UK77	86	25722	1.4	10.84	2.1	3.24	3.7	0.25	3.0	0.83	1461.2	39.6	1466.1	28.4	1473.1	39.1	1473.1	39.1	99.2
UK78	176	107728	2.1	10.91	0.6	3.20	2.5	0.25	2.4	0.97	1456.5	31.6	1458.3	19.4	1461.0	11.9	1461.0	11.9	99.7
UK80	94	152144	1.6	9.13	1.1	4.86	2.0	0.32	1.7	0.84	1799.7	26.3	1795.9	16.8	1791.6	19.9	1791.6	19.9	100.5
UK81	74	26139	1.3	13.49	2.9	1.77	3.1	0.17	1.1	0.36	1028.6	10.8	1033.8	20.4	1044.8	59.2	1044.8	59.2	98.4
UK82	321	143483	3.1	11.02	0.2	3.19	2.5	0.25	2.5	1.00	1463.2	33.0	1454.2	19.6	1440.9	4.3	1440.9	4.3	101.5
UK83	153	44680	3.6	13.76	2.0	1.72	2.5	0.17	1.5	0.60	1018.3	14.5	1014.2	16.3	1005.2	41.1	1005.2	41.1	101.3
UK84	115	59065	2.8	14.26	1.9	1.50	4.6	0.16	4.2	0.91	929.6	36.6	930.1	28.2	931.4	39.2	931.4	39.2	99.8
UK85	102	97990	3.7	8.89	1.7	5.00	3.6	0.32	3.2	0.88	1799.9	50.1	1818.9	30.6	1840.6	30.7	1840.6	30.7	97.8
UK86	109	59783	3.5	12.94	2.2	2.06	2.8	0.19	1.8	0.65	1137.8	19.2	1134.6	19.5	1128.6	43.3	1128.6	43.3	100.8
UK87	35	87824	0.9	5.78	1.3	11.65	2.4	0.49	2.0	0.85	2564.3	43.3	2576.8	22.4	2586.6	20.9	2586.6	20.9	99.1
UK89	552	411859	4.4	10.09	0.5	3.77	3.8	0.28	3.8	0.99	1571.7	53.2	1586.9	30.9	1607.0	9.4	1607.0	9.4	97.8
UK90	464	251064	1.1	17.97	3.1	0.56	3.8	0.07	2.2	0.57	452.6	9.4	450.2	13.8	437.9	69.6	452.6	9.4	NA
UK91	134	49263	2.3	13.51	1.9	1.81	2.7	0.18	1.9	0.70	1054.0	18.3	1050.2	17.7	1042.2	39.2	1042.2	39.2	101.1

Table D3 (cont'd)

UK92	289	137554	2.6	12.72	0.8	2.18	2.4	0.20	2.2	0.93	1178.9	24.0	1173.1	16.6	1162.5	16.8	1162.5	16.8	101.4
UK93	37	4142	2.8	22.60	27.8	0.40	28.3	0.06	4.8	0.17	405.6	18.9	338.8	81.6	-97.4	695.2	405.6	18.9	NA
UK94	29	9522	1.2	13.28	5.5	1.88	5.9	0.18	2.1	0.36	1070.7	20.6	1072.8	38.9	1077.2	110.3	1077.2	110.3	99.4
UK95	91	22957	3.1	12.96	1.9	2.08	3.4	0.20	2.8	0.82	1152.1	29.6	1143.0	23.4	1125.8	38.8	1125.8	38.8	102.3
UK96	209	193318	1.7	8.36	0.5	5.73	2.3	0.35	2.2	0.98	1922.8	37.0	1935.7	19.7	1949.5	8.7	1949.5	8.7	98.6
UK97	143	69208	1.7	12.46	1.3	2.29	1.9	0.21	1.4	0.74	1214.6	15.9	1210.7	13.7	1203.8	25.5	1203.8	25.5	100.9
UK98	61	19066	1.0	13.72	4.0	1.66	5.0	0.16	3.0	0.61	983.0	27.5	991.8	31.5	1011.3	80.4	1011.3	80.4	97.2
UK99	136	104364	2.9	13.54	2.2	1.83	3.1	0.18	2.1	0.69	1065.6	20.8	1056.3	20.2	1037.0	44.9	1037.0	44.9	102.8
UK100	281	12735	1.3	18.05	4.8	0.47	5.7	0.06	3.0	0.53	382.8	11.3	389.4	18.3	428.9	107.0	382.8	11.3	NA
UK101	125	29832	4.5	13.69	1.4	1.75	3.9	0.17	3.6	0.93	1032.2	34.6	1026.9	25.2	1015.4	29.0	1015.4	29.0	101.7
UK102	82	33056	3.4	13.88	3.8	1.67	4.5	0.17	2.4	0.53	998.8	21.9	995.4	28.3	987.7	76.8	987.7	76.8	101.1
UK103	24	22223	2.2	13.10	9.0	1.85	9.9	0.18	4.1	0.41	1045.5	39.3	1064.6	65.3	1103.8	180.3	1103.8	180.3	94.7
UK104	65	29533	2.0	13.12	4.2	1.77	5.2	0.17	3.1	0.60	1001.2	29.0	1033.0	33.9	1100.9	83.7	1100.9	83.7	90.9
UK105	93	52173	1.8	13.42	4.2	1.80	5.3	0.17	3.3	0.62	1038.6	31.6	1044.2	34.8	1055.9	84.6	1055.9	84.6	98.4

Table D4: Analytical results of U-Pb detrital zircon isotope ratios and age data from the Saginaw Formation

Sample MIB-072510-01						Isotope ratios					Apparent ages (Ma)									
Sample	U (ppm)	206Pb 204Pb	U/Th	206Pb* 207Pb*	± (%)	207Pb* 235U*	± (%)	206Pb* 238U	± (%)	error corr.	206Pb* 238U*	± (Ma)	207Pb* 235U	± (Ma)	206Pb* 207Pb*	± (Ma)	Best age (Ma)	± (Ma)	Conc (%)
UK1	39	18951	1.3	12.88	4.6	2.08	5.4	0.19	2.8	0.52	1142.4	29.7	1140.8	37.2	1137.7	92.2	1137.7	92.2	100.4
UK4	368	197060	5.0	12.61	0.5	2.23	1.4	0.20	1.3	0.93	1198.4	14.1	1191.8	9.7	1179.9	9.7	1179.9	9.7	101.6
UK5	110	28788	1.9	17.73	6.2	0.55	7.9	0.07	4.8	0.61	444.3	20.7	448.2	28.6	468.2	138.5	444.3	20.7	NA
UK6	106	52510	1.1	9.91	1.0	4.12	2.1	0.30	1.8	0.87	1671.2	26.5	1657.9	17.0	1641.1	19.1	1641.1	19.1	101.8
UK7	368	192207	2.5	12.85	0.6	2.11	2.5	0.20	2.4	0.97	1158.1	25.4	1152.6	17.0	1142.2	11.6	1142.2	11.6	101.4
UK8	167	96479	3.1	12.78	0.8	2.20	1.8	0.20	1.6	0.90	1193.9	17.6	1179.7	12.5	1153.8	15.1	1153.8	15.1	103.5
UK10	103	67600	2.7	11.46	1.7	2.76	2.4	0.23	1.6	0.69	1330.3	19.5	1344.3	17.6	1366.6	33.0	1366.6	33.0	97.3
UK11	107	115673	2.9	8.94	0.8	5.03	0.9	0.33	0.4	0.50	1819.4	7.0	1824.5	7.5	1830.4	13.9	1830.4	13.9	99.4
UK12	27	16471	2.3	12.60	5.4	2.31	5.7	0.21	1.7	0.30	1234.7	19.1	1215.2	40.5	1180.8	107.8	1180.8	107.8	104.6
UK13	142	145554	1.6	9.20	1.2	4.75	4.2	0.32	4.0	0.96	1776.2	62.8	1776.5	35.4	1776.9	21.5	1776.9	21.5	100.0
UK14	81	46374	2.7	12.68	3.4	2.08	3.7	0.19	1.5	0.41	1130.3	15.8	1143.7	25.6	1169.3	67.4	1169.3	67.4	96.7
UK15	111	31089	3.3	13.81	1.2	1.66	3.6	0.17	3.4	0.94	991.7	30.8	993.5	22.7	997.3	25.1	997.3	25.1	99.4
UK16	80	25138	0.6	13.71	3.7	1.73	5.1	0.17	3.5	0.69	1025.0	33.4	1020.8	33.1	1011.6	75.9	1011.6	75.9	101.3
UK17	122	43003	2.0	12.87	1.1	2.09	2.4	0.20	2.1	0.87	1149.2	21.7	1145.7	16.2	1138.9	22.7	1138.9	22.7	100.9
UK18	135	50123	4.2	13.47	1.0	1.90	3.4	0.19	3.3	0.96	1097.8	33.0	1081.3	22.7	1048.4	19.3	1048.4	19.3	104.7
UK19	76	84123	3.7	13.29	2.7	1.85	3.4	0.18	2.1	0.62	1060.5	20.9	1065.2	22.7	1074.6	54.1	1074.6	54.1	98.7
UK20	185	46342	4.7	13.78	1.6	1.73	2.1	0.17	1.3	0.62	1026.1	12.2	1018.3	13.4	1001.4	33.4	1001.4	33.4	102.5
UK21	115	68229	4.2	13.98	2.9	1.62	3.3	0.16	1.5	0.47	981.3	14.0	978.5	20.8	972.2	59.7	972.2	59.7	100.9
UK23	157	128515	1.2	12.86	2.3	2.09	3.3	0.19	2.4	0.72	1146.9	24.9	1144.7	22.7	1140.7	45.7	1140.7	45.7	100.5
UK25	52	17490	2.1	13.43	4.0	1.76	4.3	0.17	1.7	0.39	1018.3	15.9	1029.5	27.8	1053.5	79.7	1053.5	79.7	96.7
UK26	311	153595	9.0	11.64	0.4	2.62	2.3	0.22	2.2	0.98	1287.8	26.1	1306.3	16.7	1336.9	7.7	1336.9	7.7	96.3
UK28	83	36381	2.6	13.44	6.1	1.81	6.4	0.18	1.7	0.26	1045.6	16.2	1047.7	41.5	1052.0	123.6	1052.0	123.6	99.4
UK29	217	128198	3.7	10.89	0.6	3.22	1.4	0.25	1.3	0.90	1461.6	16.6	1462.8	11.0	1464.5	12.0	1464.5	12.0	99.8
UK31	57	18445	2.4	19.66	18.0	0.51	19.4	0.07	7.3	0.38	453.2	32.0	419.0	66.6	235.0	417.1	453.2	32.0	NA
UK32	153	119544	2.7	13.33	1.5	1.89	1.8	0.18	1.1	0.59	1083.9	10.6	1079.2	12.0	1069.7	29.5	1069.7	29.5	101.3

Table D4 (cont'd)

UK33	63	39668	2.7	10.89	2.6	3.04	3.6	0.24	2.5	0.69	1389.1	31.1	1418.9	27.8	1463.9	50.2	1463.9	50.2	94.9
UK34	112	82082	1.3	11.49	0.7	2.84	1.3	0.24	1.1	0.82	1369.9	13.2	1366.8	9.8	1361.9	14.2	1361.9	14.2	100.6
UK35	201	53599	3.2	12.00	1.1	2.46	2.2	0.21	2.0	0.88	1250.4	22.2	1260.1	16.1	1276.6	20.7	1276.6	20.7	98.0
UK36	130	60404	1.6	13.58	1.6	1.74	2.1	0.17	1.4	0.66	1017.6	12.8	1022.3	13.4	1032.2	31.6	1032.2	31.6	98.6
UK37	523	124077	19.6	12.67	0.8	2.04	7.8	0.19	7.8	1.00	1110.1	79.2	1130.4	53.3	1169.7	15.5	1169.7	15.5	94.9
UK38	77	22017	1.3	11.19	1.4	2.82	2.8	0.23	2.4	0.85	1329.3	28.5	1361.4	20.8	1412.1	27.7	1412.1	27.7	94.1
UK39	163	31390	1.7	16.84	2.9	0.81	3.1	0.10	0.9	0.29	604.6	5.2	599.7	13.8	581.3	63.4	604.6	5.2	104.0
UK40	21	14760	2.1	12.37	5.5	2.18	8.7	0.20	6.7	0.77	1149.8	70.5	1173.4	60.4	1217.2	108.4	1217.2	108.4	94.5
UK41	53	24724	2.4	12.15	1.7	2.38	2.1	0.21	1.2	0.58	1225.1	13.5	1235.4	14.9	1253.4	33.2	1253.4	33.2	97.7
UK42	181	81981	2.8	13.60	1.8	1.75	4.0	0.17	3.5	0.89	1024.2	33.5	1025.8	25.8	1029.2	37.3	1029.2	37.3	99.5
UK43	98	38084	3.0	13.31	1.4	1.71	2.3	0.17	1.9	0.80	984.5	17.0	1011.9	15.0	1071.7	28.5	1071.7	28.5	91.9
UK44	157	47678	3.4	9.19	0.9	4.59	2.0	0.31	1.7	0.88	1721.4	26.3	1748.2	16.4	1780.4	16.9	1780.4	16.9	96.7
UK45	91	67881	4.9	13.23	2.2	1.83	2.5	0.18	1.2	0.47	1045.1	11.3	1057.7	16.3	1083.7	44.0	1083.7	44.0	96.4
UK46	48	13651	2.0	12.63	3.7	2.13	4.9	0.19	3.1	0.64	1146.7	32.7	1157.0	33.5	1176.5	73.8	1176.5	73.8	97.5
UK47	181	26017	0.7	18.70	5.8	0.41	6.2	0.06	2.2	0.36	349.9	7.5	349.8	18.3	349.0	130.3	349.9	7.5	NA
UK48	194	14441	1.2	17.38	6.9	0.58	7.8	0.07	3.6	0.46	451.3	15.8	461.5	29.0	512.6	152.5	451.3	15.8	NA
UK49	85	46837	4.0	13.03	3.3	1.98	4.1	0.19	2.4	0.59	1107.8	24.5	1110.1	27.5	1114.6	65.7	1114.6	65.7	99.4
UK50	229	114512	6.2	13.58	0.8	1.74	2.4	0.17	2.3	0.94	1021.7	21.4	1025.0	15.5	1032.0	16.6	1032.0	16.6	99.0
UK51	354	166523	12.1	13.37	1.1	1.80	1.7	0.17	1.3	0.77	1036.8	12.7	1045.2	11.3	1062.7	22.2	1062.7	22.2	97.6
UK52	206	118335	6.6	12.60	0.8	2.20	2.6	0.20	2.5	0.95	1180.4	27.0	1180.5	18.3	1180.6	16.0	1180.6	16.0	100.0
UK53	203	69269	3.2	10.62	2.5	3.47	3.2	0.27	2.0	0.62	1525.6	27.2	1519.9	25.3	1511.9	47.4	1511.9	47.4	100.9
UK54	31	21501	3.1	11.13	3.2	3.07	4.0	0.25	2.5	0.61	1425.3	31.8	1424.4	31.0	1423.0	61.0	1423.0	61.0	100.2
UK55	27	12486	3.5	11.28	4.5	2.89	6.6	0.24	4.8	0.73	1368.2	59.6	1379.3	50.0	1396.5	86.6	1396.5	86.6	98.0
UK56	130	16521	0.7	12.78	1.8	1.89	3.8	0.17	3.3	0.88	1038.4	31.9	1076.0	25.2	1153.0	36.3	1153.0	36.3	90.1
UK57	345	125113	1.7	13.56	0.8	1.82	3.1	0.18	3.0	0.97	1061.5	29.6	1052.7	20.5	1034.5	15.9	1034.5	15.9	102.6
UK58	398	136655	2.6	12.82	0.9	2.09	2.1	0.19	1.9	0.91	1143.5	19.9	1144.5	14.3	1146.5	16.9	1146.5	16.9	99.7
UK59	274	42408	1.9	17.79	2.3	0.57	3.0	0.07	1.9	0.63	460.0	8.4	460.1	11.1	460.5	51.7	460.0	8.4	NA
UK61	199	66493	2.5	14.24	1.7	1.47	2.5	0.15	1.9	0.75	913.1	16.0	919.7	15.2	935.6	34.3	935.6	34.3	97.6
UK62	292	67189	4.4	13.39	1.4	1.85	3.1	0.18	2.8	0.90	1067.5	27.8	1065.0	20.7	1059.8	27.3	1059.8	27.3	100.7

Table D4 (cont'd)

UK63	402	141848	1.2	17.65	1.7	0.55	2.4	0.07	1.7	0.71	440.4	7.4	446.6	8.8	478.2	38.0	440.4	7.4	NA
UK64	87	90685	1.0	10.05	1.4	3.90	1.8	0.28	1.2	0.64	1614.4	16.5	1614.3	14.7	1614.2	26.2	1614.2	26.2	100.0
UK67	190	28033	1.9	9.16	0.5	4.82	2.0	0.32	1.9	0.96	1791.9	29.7	1789.1	16.6	1785.9	9.5	1785.9	9.5	100.3
UK68	412	199156	2.4	13.61	0.5	1.73	1.7	0.17	1.6	0.95	1016.8	14.9	1019.9	10.7	1026.6	10.6	1026.6	10.6	99.1
UK69	258	164377	27.8	12.73	1.8	2.05	3.0	0.19	2.4	0.79	1115.9	24.4	1131.4	20.5	1161.2	36.3	1161.2	36.3	96.1
UK70	183	104783	3.5	9.38	0.6	4.57	2.1	0.31	2.0	0.96	1746.6	30.2	1744.4	17.1	1741.8	10.5	1741.8	10.5	100.3
UK71	329	85567	0.8	17.77	2.3	0.56	3.6	0.07	2.7	0.76	447.3	11.7	450.0	12.9	463.7	51.0	447.3	11.7	NA
UK74	256	63239	1.5	17.71	2.4	0.57	2.8	0.07	1.4	0.49	458.8	6.0	460.9	10.3	471.0	53.5	458.8	6.0	NA
UK75	540	274736	83.6	13.10	1.1	1.99	2.0	0.19	1.7	0.85	1119.1	17.6	1113.7	13.6	1103.3	21.2	1103.3	21.2	101.4
UK76	467	22714	2.4	17.74	3.5	0.53	4.6	0.07	3.0	0.65	422.8	12.1	429.8	16.0	467.5	77.2	422.8	12.1	NA

Table D5: Analytical results of U-Pb detrital zircon isotope ratios and age data from the Eaton Sandstone

Sample MIB-072010-01						Isotope ratios					Apparent ages (Ma)									
Sample	U (ppm)	206Pb 204Pb	U/Th	206Pb* 207Pb*	± (%)	207Pb* 235U*	± (%)	206Pb* 238U	± (%)	error corr.	206Pb* 238U*	± (Ma)	207Pb* 235U	± (Ma)	206Pb* 207Pb*	± (Ma)	Best age (Ma)	± (Ma)	Conc (%)
UK1	103	69204	1.8	9.02	0.9	4.88	1.9	0.32	1.7	0.88	1785.5	26.5	1798.5	16.2	1813.7	16.4	1813.7	16.4	98.4
UK2	102	39288	2.3	13.08	1.9	1.79	3.2	0.17	2.7	0.82	1013.4	24.9	1043.4	21.2	1106.9	37.3	1106.9	37.3	91.6
UK3	340	435832	2.4	9.06	0.5	4.88	2.2	0.32	2.1	0.98	1793.2	33.4	1798.7	18.4	1805.1	8.4	1805.1	8.4	99.3
UK4	94	223100	0.9	5.77	0.3	11.73	4.8	0.49	4.8	1.00	2573.3	101.1	2583.2	44.7	2591.1	5.6	2591.1	5.6	99.3
UK5	188	309892	1.5	9.77	0.5	4.20	2.2	0.30	2.1	0.97	1678.3	31.6	1673.4	18.0	1667.2	9.4	1667.2	9.4	100.7
UK6	129	32626	2.2	13.38	2.4	1.94	4.2	0.19	3.5	0.83	1110.5	35.8	1094.1	28.4	1061.6	48.1	1061.6	48.1	104.6
UK7	390	27793	1.6	17.72	3.7	0.59	4.7	0.08	2.9	0.61	471.2	13.0	471.0	17.5	469.7	81.6	471.2	13.0	NA
UK9	49	76382	1.1	5.04	1.1	15.12	2.9	0.55	2.7	0.93	2838.2	61.0	2822.9	27.2	2812.0	17.2	2812.0	17.2	100.9
UK10	142	93938	3.2	12.44	2.0	2.35	3.3	0.21	2.7	0.81	1239.2	30.5	1227.3	23.8	1206.5	38.7	1206.5	38.7	102.7
UK11	408	34115	0.8	13.42	0.9	1.73	1.5	0.17	1.2	0.78	1001.8	10.8	1018.6	9.6	1054.8	18.6	1054.8	18.6	95.0
UK12	155	91735	2.0	12.91	1.5	2.12	4.5	0.20	4.2	0.94	1168.6	45.2	1155.9	31.0	1132.3	30.2	1132.3	30.2	103.2
UK13	132	88139	1.6	13.39	2.9	1.81	3.4	0.18	1.8	0.52	1043.3	16.9	1048.8	22.2	1060.4	58.3	1060.4	58.3	98.4
UK14	116	89747	1.8	9.76	1.0	4.30	1.7	0.30	1.4	0.81	1713.4	20.5	1693.7	13.9	1669.3	18.3	1669.3	18.3	102.6
UK15	168	92166	2.2	10.77	1.3	3.30	1.6	0.26	1.0	0.58	1479.7	12.6	1481.6	12.8	1484.3	25.4	1484.3	25.4	99.7
UK16	63	15391	2.2	13.74	5.9	1.61	8.0	0.16	5.4	0.68	962.0	48.3	975.9	50.1	1007.4	119.2	1007.4	119.2	95.5
UK17	288	6470	0.9	16.67	9.3	0.60	10.9	0.07	5.7	0.52	452.3	25.0	478.1	41.7	603.5	201.9	452.3	25.0	75.0
UK18	208	117337	1.0	8.91	0.5	5.13	2.3	0.33	2.3	0.97	1845.6	36.2	1840.7	19.7	1835.1	9.6	1835.1	9.6	100.6
UK19	237	189671	3.0	9.42	0.7	4.55	2.6	0.31	2.4	0.96	1746.6	37.5	1741.0	21.2	1734.2	13.0	1734.2	13.0	100.7
UK20	117	39963	1.7	10.76	1.2	3.36	2.9	0.26	2.7	0.92	1500.5	36.0	1494.9	22.9	1486.8	21.9	1486.8	21.9	100.9
UK21	992	24223	3.7	8.03	0.3	4.59	9.0	0.27	9.0	1.00	1527.1	122.2	1747.0	75.1	2021.4	5.9	2021.4	5.9	75.5
UK22	254	176018	1.1	9.94	0.5	4.05	2.3	0.29	2.2	0.97	1650.4	32.1	1643.8	18.4	1635.4	9.8	1635.4	9.8	100.9
UK23	432	157999	1.7	12.42	0.5	2.24	1.9	0.20	1.8	0.96	1185.0	19.4	1193.9	13.1	1210.1	10.6	1210.1	10.6	97.9
UK24	68	34932	2.4	12.67	2.6	2.27	3.0	0.21	1.7	0.54	1219.8	18.3	1201.9	21.4	1169.8	50.6	1169.8	50.6	104.3
UK25	144	29771	1.0	4.97	0.5	15.26	5.7	0.55	5.7	1.00	2826.4	130.1	2831.7	54.4	2835.5	7.7	2835.5	7.7	99.7
UK26	243	56936	2.5	10.70	1.0	3.12	3.2	0.24	3.1	0.95	1397.7	38.3	1437.4	24.6	1496.6	18.2	1496.6	18.2	93.4

Table D5 (cont'd)

UK27	347	73023	7.4	13.52	0.8	1.74	2.2	0.17	2.1	0.93	1016.9	19.5	1024.5	14.4	1040.7	16.7	1040.7	16.7	97.7
UK28	135	20135	0.9	5.41	0.4	11.70	5.3	0.46	5.2	1.00	2436.8	106.3	2580.8	49.2	2695.9	6.9	2695.9	6.9	90.4
UK29	71	55848	1.5	9.13	1.6	4.74	2.3	0.31	1.7	0.74	1759.3	26.4	1774.5	19.5	1792.4	28.4	1792.4	28.4	98.2
UK30	151	60822	0.9	9.87	1.1	4.02	2.0	0.29	1.6	0.83	1629.3	23.3	1637.6	15.9	1648.3	20.3	1648.3	20.3	98.8
UK31	95	144802	2.4	7.54	1.1	7.17	3.9	0.39	3.8	0.96	2133.1	68.2	2132.5	35.0	2131.9	19.8	2131.9	19.8	100.1
UK32	240	106007	0.9	5.32	0.2	13.39	2.2	0.52	2.2	1.00	2687.0	48.2	2707.6	20.8	2722.9	3.1	2722.9	3.1	98.7
UK35	274	628408	1.3	5.53	1.1	10.03	3.0	0.40	2.8	0.93	2177.8	51.7	2437.3	27.9	2661.6	19.0	2661.6	19.0	81.8
UK36	77	38971	4.5	10.91	1.1	3.16	1.9	0.25	1.5	0.82	1439.1	19.8	1447.5	14.5	1459.8	20.6	1459.8	20.6	98.6
UK37	265	106953	1.3	9.84	0.8	4.11	3.2	0.29	3.1	0.96	1658.6	45.4	1656.8	26.3	1654.5	15.6	1654.5	15.6	100.2
UK38	172	21413	3.2	11.28	1.8	2.93	2.5	0.24	1.7	0.67	1386.9	20.7	1390.7	18.8	1396.6	35.5	1396.6	35.5	99.3
UK39	102	128692	1.0	5.04	0.8	15.22	2.8	0.56	2.7	0.96	2850.0	61.2	2828.9	26.4	2813.8	12.9	2813.8	12.9	101.3
UK40	177	68112	2.0	10.70	0.8	3.55	3.7	0.28	3.6	0.98	1567.3	50.5	1537.4	29.5	1496.6	15.5	1496.6	15.5	104.7
UK41	475	134408	2.2	9.89	0.4	3.93	2.7	0.28	2.6	0.99	1600.3	37.2	1619.4	21.5	1644.4	8.3	1644.4	8.3	97.3
UK43	111	62097	1.8	13.70	2.5	1.75	3.2	0.17	2.1	0.65	1033.6	20.0	1027.5	21.0	1014.4	50.2	1014.4	50.2	101.9
UK45	210	119477	3.2	13.03	1.8	2.07	2.1	0.20	0.9	0.46	1151.9	9.9	1139.1	14.1	1114.7	36.5	1114.7	36.5	103.3
UK46	439	38438	1.8	10.96	0.5	3.06	4.8	0.24	4.8	0.99	1403.6	60.5	1422.7	36.9	1451.2	9.4	1451.2	9.4	96.7
UK47	119	12623	1.0	17.52	8.4	0.56	9.6	0.07	4.8	0.50	442.4	20.5	450.9	35.1	494.4	184.8	442.4	20.5	NA
UK48	139	56357	3.1	12.82	1.9	2.21	3.1	0.21	2.5	0.79	1203.6	27.2	1183.7	21.9	1147.5	38.0	1147.5	38.0	104.9
UK49	112	14802	1.0	9.82	2.9	4.05	3.5	0.29	1.9	0.55	1634.8	27.8	1645.1	28.6	1658.3	54.5	1658.3	54.5	98.6
UK50	50	54652	1.2	6.06	0.7	10.66	1.6	0.47	1.5	0.90	2477.7	30.0	2494.2	15.0	2507.7	11.8	2507.7	11.8	98.8
UK51	271	46022	1.9	12.66	0.8	2.26	3.1	0.21	3.0	0.97	1212.8	33.1	1198.4	21.8	1172.5	16.1	1172.5	16.1	103.4
UK54	170	12567	0.7	13.72	3.8	1.57	4.3	0.16	2.0	0.47	934.4	17.5	957.6	26.4	1011.1	76.1	1011.1	76.1	92.4
UK59	83	41595	1.6	12.69	2.0	2.14	4.7	0.20	4.3	0.91	1158.4	45.3	1161.4	32.6	1167.1	39.4	1167.1	39.4	99.3
UK61	148	87714	1.7	10.66	1.0	3.46	3.5	0.27	3.3	0.96	1526.9	45.5	1517.4	27.4	1504.1	18.4	1504.1	18.4	101.5
UK63	230	58035	4.9	13.53	1.3	1.79	2.0	0.18	1.6	0.78	1041.0	15.2	1040.3	13.2	1038.7	25.5	1038.7	25.5	100.2
UK64	206	107823	2.7	10.43	0.9	3.58	6.0	0.27	5.9	0.99	1543.4	81.2	1544.5	47.5	1546.0	17.2	1546.0	17.2	99.8
UK65	378	62668	1.1	17.77	2.1	0.52	2.7	0.07	1.7	0.62	419.3	6.9	426.1	9.5	463.0	47.4	419.3	6.9	NA
UK66	94	38207	1.4	13.28	3.6	1.98	4.0	0.19	1.9	0.47	1125.4	19.5	1108.8	27.3	1076.3	71.7	1076.3	71.7	104.6
UK67	263	113208	1.2	9.74	0.6	4.18	3.7	0.30	3.6	0.99	1668.9	53.3	1670.7	30.0	1673.0	10.2	1673.0	10.2	99.8

Table D5 (cont'd)

UK68	136	53042	1.4	13.22	1.5	1.87	2.4	0.18	1.9	0.79	1062.6	18.5	1070.0	15.8	1085.1	29.4	1085.1	29.4	97.9
UK69	129	76733	2.0	11.69	1.4	2.57	2.5	0.22	2.0	0.83	1268.7	23.5	1291.1	18.1	1328.5	27.1	1328.5	27.1	95.5
UK70	87	56481	0.8	8.67	1.0	5.44	2.1	0.34	1.8	0.88	1896.7	30.1	1891.2	17.9	1885.1	18.2	1885.1	18.2	100.6
UK71	371	143687	4.7	13.37	0.6	1.75	3.0	0.17	3.0	0.98	1008.5	27.8	1026.0	19.7	1063.4	13.1	1063.4	13.1	94.8
UK72	274	67366	1.7	5.04	0.4	14.27	8.5	0.52	8.5	1.00	2708.5	187.2	2768.1	80.6	2811.8	6.8	2811.8	6.8	96.3
UK73	115	44748	1.8	11.50	1.2	2.73	3.8	0.23	3.6	0.95	1320.6	43.3	1335.8	28.5	1360.1	24.1	1360.1	24.1	97.1
UK74	57	14933	0.9	13.14	4.4	1.79	7.4	0.17	6.0	0.81	1014.3	55.9	1041.3	48.1	1098.2	87.2	1098.2	87.2	92.4
UK75	325	110928	3.1	10.82	0.7	3.23	1.9	0.25	1.8	0.93	1456.7	23.2	1464.4	14.7	1475.6	12.8	1475.6	12.8	98.7
UK76	329	145016	0.5	9.23	2.7	3.85	3.9	0.26	2.8	0.72	1478.3	36.9	1603.2	31.5	1771.4	49.7	1771.4	49.7	83.5
UK77	103	79505	1.6	9.81	1.1	4.34	3.6	0.31	3.4	0.95	1734.5	51.6	1701.0	29.5	1659.9	20.6	1659.9	20.6	104.5
UK78	39	18308	1.5	13.91	7.9	1.70	8.7	0.17	3.6	0.42	1020.6	34.4	1008.6	55.9	982.9	162.0	982.9	162.0	103.8
UK79	245	133409	2.7	9.81	0.5	3.91	2.4	0.28	2.4	0.98	1583.4	33.6	1616.6	19.7	1660.0	8.3	1660.0	8.3	95.4
UK80	181	93371	0.9	13.20	2.3	1.81	2.7	0.17	1.4	0.50	1029.9	13.0	1049.0	17.7	1088.9	47.0	1088.9	47.0	94.6
UK81	209	67409	1.5	13.61	1.6	1.65	3.9	0.16	3.6	0.92	974.0	32.7	990.6	25.0	1027.4	32.0	1027.4	32.0	94.8
UK82	282	191621	5.0	9.32	0.4	4.58	2.5	0.31	2.5	0.99	1738.2	38.3	1745.7	21.2	1754.6	7.3	1754.6	7.3	99.1
UK83	475	39797	2.1	13.45	1.2	1.60	3.3	0.16	3.1	0.93	932.9	27.0	968.9	20.9	1051.3	24.9	1051.3	24.9	88.7
UK84	185	66410	3.5	13.59	1.4	1.78	2.6	0.18	2.2	0.84	1043.6	20.9	1039.0	16.8	1029.4	28.5	1029.4	28.5	101.4
UK85	147	1275	1.0	17.51	12.7	0.53	13.3	0.07	3.7	0.28	420.0	15.2	431.9	46.7	495.4	281.8	420.0	15.2	NA
UK86	95	63988	1.5	16.92	9.8	0.59	10.2	0.07	2.9	0.28	448.9	12.4	469.4	38.3	571.1	213.2	448.9	12.4	78.6
UK87	198	30668	0.9	17.68	4.5	0.60	4.9	0.08	2.0	0.41	477.8	9.3	477.2	18.6	474.3	98.7	477.8	9.3	NA
UK88	594	56744	3.5	9.99	0.4	3.59	5.8	0.26	5.8	1.00	1491.3	77.7	1547.6	46.5	1625.3	7.3	1625.3	7.3	91.8
UK89	821	16095	2.0	9.87	0.3	3.78	2.6	0.27	2.6	0.99	1544.0	36.1	1588.9	21.3	1649.0	6.4	1649.0	6.4	93.6
UK90	592	14902	1.0	9.70	0.4	3.75	9.2	0.26	9.2	1.00	1511.6	124.4	1583.1	74.2	1679.6	7.5	1679.6	7.5	90.0
UK91	439	9984	0.8	12.31	0.7	2.10	1.3	0.19	1.1	0.86	1106.1	11.7	1147.9	9.1	1227.7	13.1	1227.7	13.1	90.1
UK92	176	79126	2.5	11.88	1.4	2.62	3.9	0.23	3.7	0.93	1311.2	43.7	1305.7	29.0	1296.7	27.7	1296.7	27.7	101.1
UK94	318	19561	1.5	10.32	0.7	3.22	2.4	0.24	2.3	0.96	1393.1	29.2	1462.5	18.8	1564.7	12.8	1564.7	12.8	89.0
UK97	527	225470	4.6	12.88	0.7	2.01	3.3	0.19	3.2	0.98	1108.8	32.6	1118.3	22.1	1137.0	13.0	1137.0	13.0	97.5
UK98	165	156355	2.9	8.55	0.8	5.58	2.6	0.35	2.5	0.95	1913.9	41.4	1912.6	22.6	1911.2	14.2	1911.2	14.2	100.1
UK100	414	7939	0.6	12.63	1.5	2.13	3.0	0.19	2.6	0.87	1147.2	26.9	1157.2	20.4	1176.0	29.2	1176.0	29.2	97.5
UK102	194	13920	1.2	10.68	0.9	3.11	3.7	0.24	3.6	0.97	1390.8	45.0	1434.6	28.4	1500.1	16.1	1500.1	16.1	92.7