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U-Pb detrital zircon geochronology of Paleozoic Clastics of the Ozark Plateau: Implication for sea-level fluctuations and far-field tectonics

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U-PB DETRITAL ZIRCON GEOCHRONOLOGY OF PALEOZOIC CLASTICS OF THE OZARK PLATEAU: IMPLICATION FOR SEA-LEVEL FLUCTUATIONS AND FAR-FIELD TECTONICS

by

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ABSTRACT

The Ozark Plateau of south-central Missouri is underlain by Ordovician to Pennsylvanian carbonate and clastic strata. Enigmatic, presumably Pennsylvanian "filled sink" structures are common on the Ozark Plateau and remain a source of controversy. We present results for U-Pb ages of detrital zircons for 13 samples from the OP. We use U-Pb ages from other Paleozoic clastics and "filled sinks" on the OP, to suggest: 1) FSS record a period of Middle Ordovician erosion and sedimentation and 2) document significant shifts in sediment provenance that reflect regional tectonic events affecting the North American Craton.

The KDE plots of normalized detrital zircon ages indicate two major changes in the source of detrital zircons for Paleozoic clastics on the Ozark Plateau: (1) the provenance shifted from local the St. Francois Mountain to the Archean Province in the Late Cambrian-Early Ordovician. (2) In Mississippian through the Pennsylvanian time the source shifted from the Archean Province to the central/southern Appalachian Province, with variable contributions from the Grenville Province.

The similarity of the KDE of detrital zircon U-Pb age plots, combined with the MDS analyses, of samples from "Pennsylvanian FSS" and Ordovician sandstones indicates that these filled sink structures have a higher probability of being coeval with Ordovician clastic sediments. This is consistent with field relationships where the "Cave Hill" sandstone is correlative to the Ordovician Everton Formation. We suggest that many of these "sink structures" formed during the sub-Tippecanoe regression and were "filled" (e.g., Cave Hill) with clastics during the Tippecanoe transgression.

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1. INTRODUCTION

The Ozark Plateau (OP) in the midcontinent region of North America was a tectonically stable area in Early Paleozoic and rejuvenated as a foreland region by the Appalachian-Ouachita Orogeny in Late Paleozoic (Cox, 2008; Bunker et al. 1988). The sedimentary rocks of the OP consist of Cambrian through Pennsylvanian shallow-water clastic and marine carbonate rocks with several intervening unconformities. The widespread and thick carbonate strata have been investigated thoroughly (Overstreet et al., 2003; Lyle, 1977; Gregg, 1985). The widespread carbonate provides a good precondition for the karstification which formed the bottom unconformity in the filled sink structures. Generally, the filled sink structure is an erosional space in carbonate strata filled by following sediments.

The origin of "Filled Sink Structures" (FSS) remains controversial with regards to the formation and age of deposition. The definition of the FSS is solution cavities filled later by clastic or carbonate sediments in carbonate strata (Bretz, 1950). The cavities could be formed by underground rivers as closed cavities or by surface fluid as open cavities. FSSs are pervasive in the OP due to the widespread presence of carbonate rocks. The conformable relationship of flat-lying carbonate and clastic formations is easy to understand in the OP area as a long-term tectonic stable region (Gerdemann and Myers, 1972). However, several erosional periods in Paleozoic complicate the origin and deposition age of the FSS (Bunker et al. 1988). Bretz (1950) proposed that FSSs are isolated cavities filled during the Pennsylvanian by the roof-collapse and its overlying sandstones and mudstones. However, the FSS outcrops at the north flank of the OP containing shoreface features indicate a problem with the origin of FSS (Little, 2004). Little (2004) proposed that the FSS at the north flank of the OP could deposit in the Ordovician.

The high durability of zircon grains in sedimentary rocks and advanced laser ablation detrital zircon U-Pb dating improvements make U-Pb detrital zircon geochronology the primary technology in the study of provenance, deposition age, paleogeography, and sediments dispersal pathways (Gehrels et al., 2006). The main purpose of this paper is to constrain the age of the FSSs, understand the provenance of clastic sedimentary rocks in the region, and reconstruct the Paleozoic history of the Ozark Plateau. This paper reports 1296 detrital zircon U-Pb dates and sediment composition from Ordovician to Pennsylvanian formations in Southeast Missouri. Integration of the detrital zircon ages with regional Paleozoic history constrains the influence of sea-level fluctuation and far-field tectonics on the development of the Ozark Dome province of the mid-continent.

2. GEOLOGIC SETTING

The Paleozoic sedimentary rocks nonconformably overlie the Precambrian Granite-Rhyolite basement in the OP area.

The Precambrian basement rock under the Paleozoic sedimentary rock in OP region is the Mesoproterozoic Granite-Rhyolite province (Dickinson and Gehrels, 2009). The 1.35-1.55 Ga Granite-Rhyolite basement extends from Fennoscandia to southwest North America craton (Barners et al., 2002) (Fig. geologic Province). This large igneous complex was subdivided into two portions: the 1.35 Ga Southern Granite-Rhyolite and the 1.47 Ga Eastern Granite-Rhyolite (Lovell, 2013). The ~1.48Ga St. Francois Mountain, exposed in southeastern Missouri, is the representative of the Eastern Granite-Rhyolite, which consists of ~40,000 km^2 igneous rocks with ~900km^2 exposed on the surface (Barnes et al., 2002; Meert et al., 2002). This basement is nonconformably overlain by the Late Cambrian Lamotte Sandstone and later re-exposed during uplift of the OP (Wenner & Taylor, 1976; Thompson, 1995; Meert et al., 2002).

The deposition of the Cambrian sedimentary rocks started from the middle of the Middle Cambrian (Mulvany and Thompson, 2013). It thickens from the northwest corner of the OP to the southeastern part of the Illinois Basin (Bunker, 1988). The bottom Lamotte Sandstone directly deposited on the Precambrian basement. The rest formations of the Cambrian on top of the Lamotte Sandstone are dominated by carbonate rocks (Mulvany and Thompson, 2013). The Ordovician strata contact with the underlying Cambrian unconformably. It consists of three parts, Lower, Middle, and Upper Ordovician. The

Lower and Middle Ordovician dominated by dolomite and limestone and the Upper Ordovician dominated by shale and thin limestone (Thompson, 1991).

Because of the erosion event or non-deposition, the Silurian strata in Missouri is not pervasive (Thompson, 1993). Dolomite dominates the Silurian rock with limestone presence (Thompson, 1993). The Devonian strata are exposed at central and southeast of Missouri. Devonian strata were subdivided into three sections. Lower and Middle Devonian are dominated by limestone and dolomitic limestone. Upper Devonian is dominated by clastics, such as shale and sandstones (Thompson, 1993).

The Mississippian sediments conformably deposited on Devonian. It is dominated by limestone and shale. The same for the overlying Pennsylvanian strata which are dominated by shale and limestone with interbedded coal beds (Thompson, 1993). Permian strata in the OP are composed of shale, limestone, and evaporates (Bunker, 1988).

The strata from Cambrian to Pennsylvanian could be separated into four sequences: Sauk, Tippecanoe, Kaskaskia, and Absaroka. Each sequence starts with a great transgression event and ends with a regression event (Sloss, 1988). Therefore, the unconformities formed by the regression event separates the sequence with its overlying and underlying sequences. In Missouri, strata from Cambrian to Middle Ordovician were regarded as the Sauk Sequence. It thickens from the northwest corner of the OP to the southern part of the Illinois Basin (Bunker, 1988). The erosional event in Middle Ordovician separates the Sauk Sequence with its overlying Tippecanoe Sequence (Sloss, 1988). The strata from Middle Ordovician to Early Devonian were the Tippecanoe Sequence. The lower part of the Tippecanoe Sequence is represented by an extensive transgressive sandstone layer, typically the St. Peter Sandstone. Top layer of the

Tippecanoe Sequence were removed by the prolonged erosion event at the end of the transgression (Sloss, 1988). The Kaskaskia Sequence in the OP region range from Middle Devonian to the end of the Middle Mississippian (Bunker, 1988). The Absaroka Sequence was deposited from Middle Pennsylvanian to Late Permian.

3. METHOD

3.1. FSS SAMPLE COLLECTION

Approximately 10 kg of sample were collected from the filled sink structures in the OP. CZ-1 & CZ-2, 14MO6 (Li, 2016), and 14MO9 & 14MO10 (Meehan, 2016) were collected from the north flank of the OP (Figure 3.1).

CZ-1 & CZ-2 were collected from a ~ ten m-thick filled sink structure with an apparent truncation (Figure 3.2). The truncation marks an unconformity surface which separates the dolomitic country rock from clastic infill material. CZ-1 was collected from a truncated sandstone layer in the older chert-bearing Jefferson City-Cotter Dolomite (JCCD). CZ-2 was collected from a thick sandstone layer, associated with other sandstones unevenly interbedded with greenish/purple siltstone in the younger unit that overlies the unconformity. The sandstone is composed of fine to medium rounded quartz grains with scattered siltstone chips. At the top, the infilling material is conformably capped by a ~1.5 m-thick dolomite layer. These clastic and carbonate strata were previously interpreted as undifferentiated Pennsylvanian sandstones.

Sample14MO6 was collected from a ~ ten m-thick outcrop, where currently, only top ~1 m rock layers can be identified and the rest is concealed by slumping and vegetation (Figure 3.3). Green and purple siltstone are conformably sandwiched between two fine to medium grained, sandstone which contain fragments of siltstone and chert. Samples 14MO9 & 14MO10 were collected from sandstone exposed in a road cut near Hwy 63 north of Rolla, Phelps County.

Two samples, CZ-5 & CZ-6, were collected from Pennsylvanian Warner Formation in northeast Missouri, beyond the boundary of the OP. Sample, CZ-1 was collected in Jefferson City-Cotter Dolomite (Figure 3.1). Six samples of were collected from Lamotte Sandstone (14MO2 & 14MO1), Roubidoux Formation (13MO1), St. Peter Sandstone (13MO2), Bushberg Sandstone (14MO4), and Aux Vases Sandstone (14MO3) inside of the Ozark Plateau (Li Master Thesis, 2016).

3.2. U-PB ZIRCON GEOCHRONOLOGY

Mineral separation processes were completed at Macalester College, St Paul, Minnesota. Samples were hammered into chips and then pulverized into fine grain sand utilizing a jaw crusher and disk mill. Zircon grains were then separated from the samples by the standard mineral separation processes, including the Gemini shaking table, heavy liquid with methylene iodide (3.3g/cm^3), and magnetic separation by the Frantz magnetic separator. Finally, mineral grains other than zircon were manually removed under a binocular microscope. Pure zircon grains and standard reference zircons (R33 & Sri Lanka (SL)) were mounted in epoxy and imaged using a scanning electron microscope in backscattered and secondary electron mode. These images were used as location maps in to assist with the geochronological analyses.

The geochronology analyses of all the samples were done by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) in the LaserChron Lab at the University of Arizona. Approximately 100 random spots were analyzed for each sample. All data were collected in the same mode using the method described by Gehrels et al. (2008). Analysis of zircon standard R33 (419.3± 0.4Ma) was performed at the beginning, middle, and final spot analysis for corrections between each sample. Zircon standard SL (563.5±3.2Ma) was analyzed after five spot analyses in every unknown for use in corrections for every single sample (Gehrels et al., 2011 & 2008). Analyses that are greater than 10% discordant or greater than 5% reversely discordant are excluded from the interpretation data pool. The average systematic errors are 1.2% for $^{206}Pb/^{238}U$ ages and 1% for $^{206}Pb/^{207}Pb$ ages (with 2σ uncertainty) (shown in Appendix). Reported ages were calculated from $^{206}Pb/^{238}U$ ages for zircon dates less than 800Ma, whereas reported ages for zircons older than 800 Ma were calculated from $^{206}Pb/^{207}Pb$ ages. Further details are in the Appendix. The best zircon ages were plotted by the Kernel Density Estimation (KDE) (Vermeesch, 2012).

3.3. PETROLOGICAL ANALYSIS

In this study, we collected four samples from Ordovician Jefferson City-Cotter Dolomite (CZ-1), FSS (CZ-2), Pennsylvanian Graydon Formation (CZ-5), and Warner Formation (CZ-6) respectively. Rest samples and data are referenced from Li (2016) and Meehan (2016). Seven thin sections were treated with blue epoxy for point counting using the Gazzi-Dickinson method (Ingersoll et al., 1984 & Ingersoll, 1990). A total of 400 points point-counting per sample were applied for five FSS samples (CZ-1, CZ-2, 14MO6, 14MO9, 14MO10) and two Pennsylvanian samples (CZ-5 and CZ-6) (Shown in Appendix).

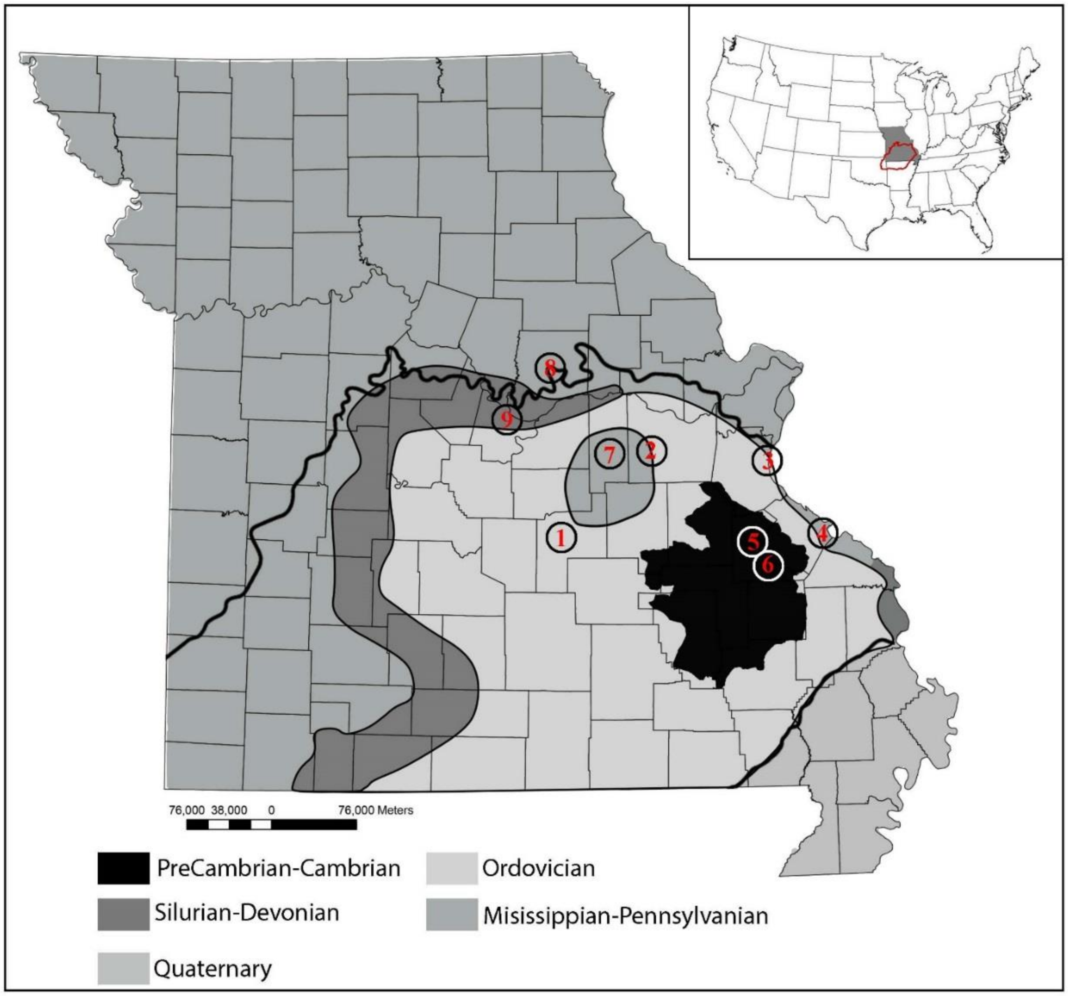

Figure 3.1. Simplified geologic map of Missouri with sample locations. The red line in the United State of America map at top right corner is the outline of the integrated Ozark Plateau. The black thick line is the part of the outline of the Ozark Plateau in Missouri.**1**, 13MO1, 14MO9, 14MO10; **2**, 14MO6; **3**, 14MO4; **4**, 14MO3; **5**, 14MO1; **6**, 14MO2; **7**, CZ-1, CZ-2; **8**, CZ-5, CZ-6; **9**, Little, 2004. Modified after Starbuck, E.A., (2017). Geologic Map of Missouri. Missouri Department of Natural Resources, Missouri Geological Survey. Scale 1:500,000.

Figure 3.2. The “Cave Hill” road-cut on U.S. Highway 50 Missouri. Location of CZ-1 a well indurated sandstone in the older Cotter Dolomite and CZ-2 a more friable sandstone in the overlying Everton Formation is shown.

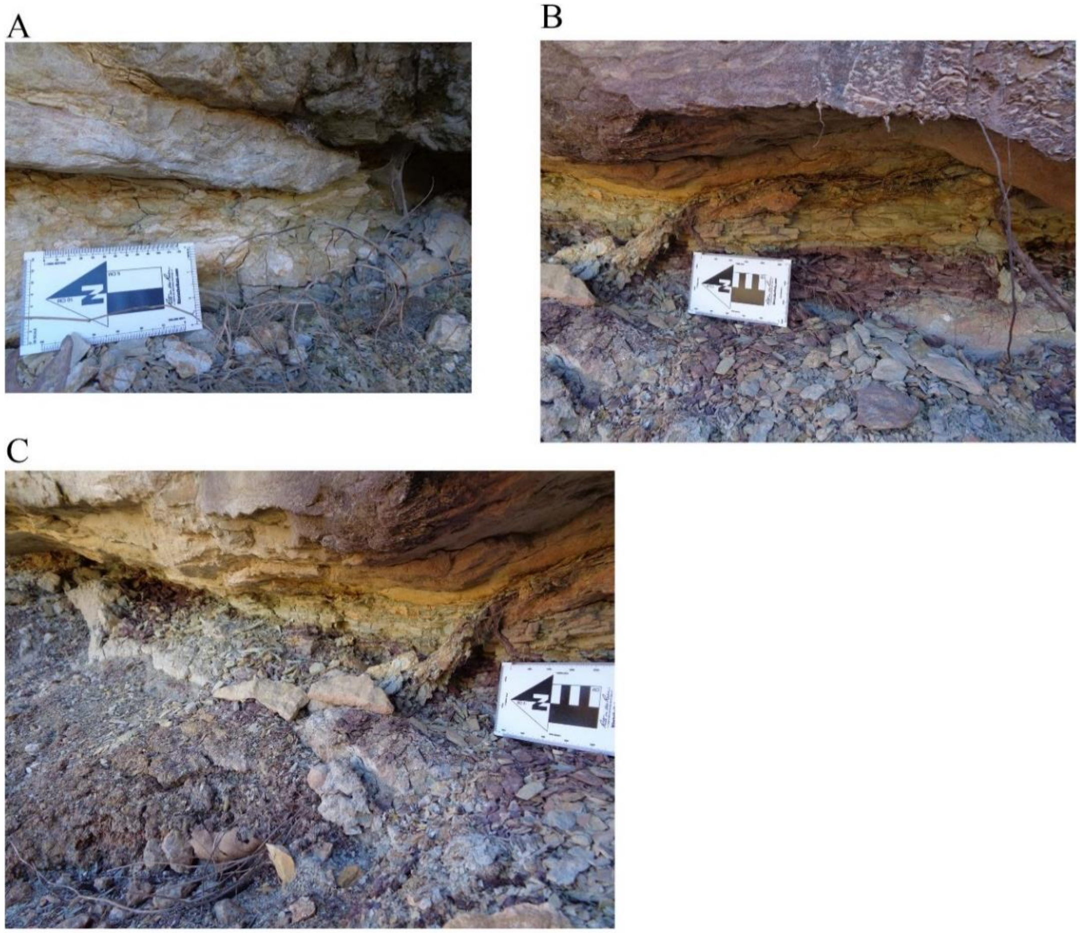

Figure 3.3. Outcrop figures of 14MO6 at the east of the Cave Hill on Hwy 50.

4. RESULTS

1199 out of 1365 detrital zircon grains, from 13 samples from OP Paleozoic clastic rocks yield less than 10% discordance, and 5% reverse discordance. The age of these detrital zircons is plotted in KDE with age population classifications and lithologic positions (Figure 4.1). Five distinct populations are recognized based on the North American Geologic Province (Figure 4.2), and the proportion of each population was summarized in Tables.

4.1. LATE CAMBRIAN LAMOTTE SANDSTONE

The Late Cambrian Lamotte Sandstone rests unconformably on the Precambrian granite basement in southeastern Missouri. It is predominately a medium grain, moderate to well sorted, orthoquartzite sandstone (Ojakangas, 1961; Houseknecht & Ethridge, 1978). The two detrital zircon age datasets are from the lower and upper Lamotte Sandstone. Detrital zircons from the lower sandstone (14MO2) define an age population from ~1.3 Ga to ~1.76 Ga (Figure 4.1). This includes peaks in detrital zircon ages corresponding to source in the Granite-Rhyolite terrane (81%) with peaks at ~1.38 Ga, ~1.47 Ga, and a minor peak at ~1.65 Ga. The upper sample (14MO1) yields a wider range in detrital zircon ages from ~1.1 Ga to ~3 Ga. It is dominated by two dominant age groups; one corresponding to the Granite-Rhyolite terrane (41%) with two peaks at ~1.38 Ga and ~1.46 Ga, and the other corresponding to an Archean source (35%) with a peak at ~2.7 Ga. Detrital zircons with Grenville ages (15%) and PYM (9%) represent the rest of the data (Figure 4.1, Table 4.1)

4.2. ORDOVICIAN ROUBIDOUX FORMATION

The Ordovician Roubidoux Formation consists of medium to coarse sandstone layers, locally interbedded with lens shape dolomite and chert layers (Thompson, 1991; Cordry, 1929). The Roubidoux (13MO1) detrital zircon ages define a population that spans from ~1.04 Ga to ~3.16 Ga. The Archean population with a peak at ~2.7 Ga accounts for 80% of the total. Grenville age zircons account for (17%) of the population and are define two minor peaks at ~1.13 Ga and ~1.2 Ga. The remaining zircon dates are represented by data is Granite-Rhyolite terrane (2%) and the PYM (1%) (Figure 4.1, Table 4.1).

4.3. ORDOVICIAN JEFFERSON CITY-COTTER DOLOMITE

The Jefferson City Dolomite is a heterogeneous formation comprised dominantly of crystallized and argillaceous dolomite. These two dolomites are locally interbedded with sandstone, chert, conglomerate, and shale lenses. The conformably overlaying Cotter Dolomite is similar in lithology with the Jefferson City Dolomite. Argillaceous and medium-grained dolomite are interbedded with sandstone (with ripple marks), chert, and shale. Because of the similarity of the lithologic compositions and the blurred boundary with the overlaying Cotter Dolomite, we combined the Jefferson City Dolomite and Cotter Dolomite as one formation (CZ-1) in this study. The sandstone where the sample collected from is a well indurated, fine grained, moderately sorted, quartz-arenite. Grains are sub-rounded to rounded with scarce overgrowths. Detrital zircon ages range from ~0.9 Ga to ~2.78 Ga with a primary peak at ~2.7 Ga in Archean (90%). The remaining detrital zircon ages consist of Grenville (5%), Granite-Rhyolite (2%), and PYM (3%) (Figure 4.1, Table 4.1).

4.4. CZ-2

CZ-2 is collected from a sandstone layer within the sedimentary strata deposited just above the unconformity in the Jefferson City-Cotter Dolomite in FSS-1 at the road cut of Hwy-50 (Fig. 3.1). This formation is comprised of interbedded clay, mudstone, and sandstone and has previously been interpreted as undifferentiated Pennsylvanian clastics filling in collapsed sink-hole (i.e., karst) features. The sandstone where CZ-2 was collected composed of weakly indurated, fine-grain, moderately sorted, quartz grains. The grains are sub-angular to sub-rounded with scarce silica overgrowths. Detrital zircons from sample CZ-2 define an age population that spans from 0.97 Ga to 2.7 Ga with a prominent peak at ~2.7 Ga in the Archean population (48%). Grenville age detrital zircon comprises 30% of the total population with minor peaks at ~1 Ga, ~ 1.16 Ga, and ~1.27 Ga. The remaining detrital zircons consist of Granite-Rhyolite affinity (19%) and PYM (3%) with peaks at ~ 1.4 Ga and ~1.6 Ga (Figure 4.1, Table 4.1)

4.5. 14MO6

14MO6 was collected from a sandstone layer within the sedimentary strata previously been interpreted as undifferentiated Pennsylvanian clastics filling in collapsed sink-hole (i.e., karst) features in a road cut east of the CZ-2 (Figure 3.1). Similar to CZ-2 the sandstone layer was interbedded with clay, and mudrock surrounded by the Jefferson City-Cotter Dolomite. 14MO6 is a fine-grained, moderately well sorted, quartz-arenite (Table 2). The grains are sub-angular to sub-rounded. Ages of detrital zircon grains span from ~0.1 Ga to ~3.3 Ga with a major peak at ~2.7 Ga in Archean population (63%). The subordinate peaks include Grenville (24%) with two peaks at ~1.06 Ga and ~1.2 Ga;

Granite-Rhyolite (11%) also with two peaks at ~1.37 Ga and ~1.45 Ga; and a minor peak at ~1.67 Ga in PYM (2%) (Figure 4.1, Table 4.1)

4.6. 14MO9 AND 14MO10

Sample 14MO9 and the overlying "rim sandstone" (RS) 14MO10 were collected from outcrops just north of Rolla, MO (Figure 3.1). FSS 14MO9 is a medium-grained, moderately well sorted, quartz-arenite comprised of sub-angular to sub-rounded quartz grains. RS 14MO10 is a fine-grained, well sorted, quartz-arenite comprised of sub-angular to sub-rounded quartz grains with scared silica overgrowths (Figure 4.3). Detrital zircon from FSS 14MO9 defines an age population that spans from ~0.98 Ga to ~2.9 Ga with a major peak at ~2.7 Ga in Archean population (42%). Subordinate peaks in the age population are associated with the Grenville (37%), which has two peaks one at 1.06 Ga and 1.2 Ga; at ~1.38 Ga in Granite-Rhyolite (12%), and ~1.6 Ga in PYM (9%). The detrital zircon age population from the overlying "rim sandstone" RS 14MO10 exhibits a similar pattern with an age range from ~1 Ga to ~3.2 Ga. The dominant age populations are associated with the Archean (41%) with a peak at ~2.7 Ga and the Grenville (42%) with a peak at ~1.07 Ga, and a slight shoulder at ~1.2 Ga. Minor contributions from detrital zircons from the Granite-Rhyolite (11%), with a peak at ~1.38 Ga, and PYM (6%) are also present (Figure 4.1, Table 4.1)

4.7. ORDOVICIAN ST. PETER SANDSTONE

Sample 13MO2 is from the transgressive St. Peter Sandstone, a massive quartz arenite belonging to the Tippecanoe Sequence and covering a vast area of the interior craton in Arkansas, Missouri, Illinois, Iowa, Wisconsin, and Minnesota (Thiel, 1935). It is a weakly indurated, fine to medium grained, well sorted, sandstone containing shale and limestone locally (Ibrahim, 2016). The detrital zircon grain age population spans from ~1 Ga to ~3.1 Ga. Archean (70%) detrital zircons are the most abundant population with a peak at ~2.7 Ga. Grenville (23%) detrital zircons are also common and define a single peak at ~1.07 Ga. Detrital zircon ages from the PYM (6%) are minor with a peak at ~1.8 Ga (Figure 4.1, Table 4.1).

4.8. DEVONIAN BUSHBERG SANDSTONE

Detrital zircons from the Late Devonian Bushberg Sandstone (14MO4) define an age population that spans from ~1.0 Ga to ~2.75 Ga. Grenville (54%) detrital zircons, with a primary peak at ~1.07 Ga and a minor peak at ~1.1 Ga represents the largest group. Detrital zircons from the Archean (22%) with a peak at ~2.7 Ga and the Granite-Rhyolite (17%) with a peak at ~1.35 are common. Detrital zircons from the PYM (7%) are less abundant (Figure 4.1, Table 4.1).

4.9. MISSISSIPPIAN AUX VASES SANDSTONE

Sample 14MO3 is from the Late Mississippian Aux Vases Sandstone which is part of the Kaskaskia Sequence that crops out along the east edge of the OP near the Missouri River (Thompson, 1986). Detrital zircon ages from the Aux Vases Sandstone define an age population that spans from ~0.4 Ga to ~2.7 Ga. Grenville (44%) detrital zircons are the most abundant and display a single, rather than double, peak, at ~1.04 Ga. Detrital zircons from the Appalachian (24%) are common with a peak at ~0.44 Ga. Detrital zircons from the remaining provinces define minor peaks at Granite-Rhyolite (9%) at ~1.4 Ga, PYM (17%) at ~1.7 Ga, and Archean (5%) ~2.6 Ga (Figure 4.1, Table 4.1)

4.10. PENNSYLVANIAN GRAYDON FORMATION

Sample CZ-5 was collected from the Graydon Formation, the basal unit of the Pennsylvanian system in Missouri (Figure 4.1). It is poorly-sorted and locally matrix supported chert and limestone cobbles conglomerate set in the iron-oxide cemented matrix (Gentile and Thompson, 2004). Detrital zircons from the matrix sandstone of CZ-5 define an age population that spans from ~0.37 Ga to ~2.7 Ga. Grenville (74%) detrital zircons are very abundant and define a solitary peak at ~1.07 Ga. Detrital zircons from the Appalachian (12%) define a subordinate peak at ~0.44 Ga. Minor to rare detrital zircon ages are consistent with derivation from the Granite-Rhyolite (3%), PYM (8%), and Archean (3%) provenance (Figure 4.1, Table 4.1)

4.11. PENNSYLVANIAN WARNER FORMATION

Sample CZ-6 was collected from sandstones of the Middle Pennsylvanian Warner Formation that deposited conformably overlying sample CZ-5 of the Graydon Conglomerate. It is fine-grained, moderately well sorted, quartz-arenite with well develop cross-bedding (Table 4.2, Figure 4.3). Detrital zircons ages from CZ-6 span from ~0.3 Ga to ~3.2 Ga. The dominant source of detrital zircons is Grenville (40%) which has several discrete peaks, the highest peak is at ~1.06 Ga and the secondary peak at 1.35 Ga. There is a substantial contribution of detrital zircons from the Appalachian (31%) with a primary peak at ~0.3 Ga and a minor peak at ~0.4. The rest of the detrital zircons are sourced from multiple age provinces including Granite-Rhyolite (6%), PYM (15%), and Archean (8%) with peaks at ~2.7 Ga and ~3.2 Ga (Figure 4.1, Table 4.1). Comparing with the underlying CZ-5 (Graydon Formation), CZ-6 has more PYM and Archean grains and covers much wider zircon age range.

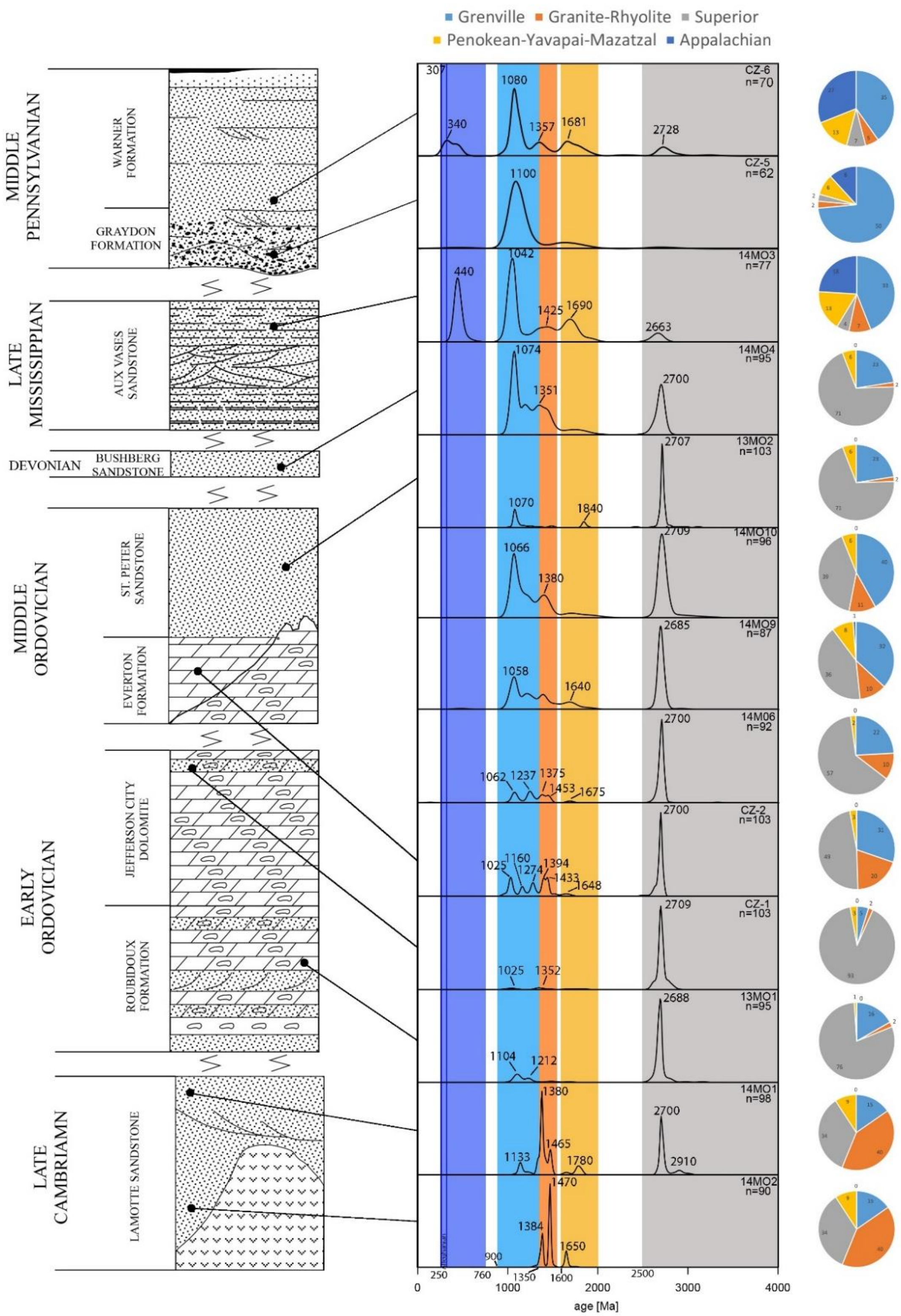

Figure 4.1. The Kernel Density Estimation of all samples collected from the OP.

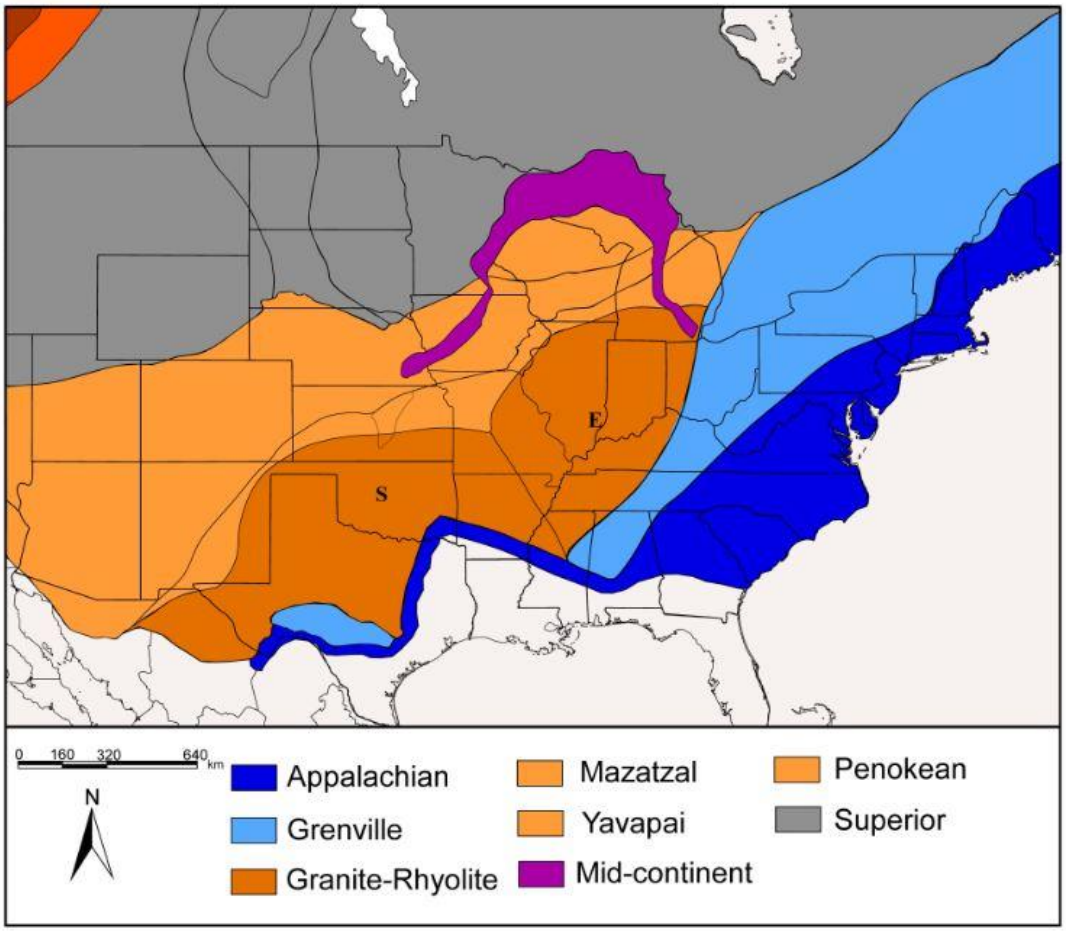

Figure 4.2. North American geologic province map. Modified after Dickenson and Gehrels et al., 2009; Meert and Stuckey, 2002.

Table 4.1. The proportions of each population of all samples from OP.

			0.25-0.76 Ga	0.9-1.35Ga	1.55-1.35 Ga	1.6-2Ga	>2.5 Ga
Time	Formation Name	Label	Appalachian	Grenville	Granite-Rhyolite	PYM	Archean
Penn	Warner Formation	CZ-6	16%	49%	7%	18%	10%
Penn	Graydon Conglomerate	CZ-5	3%	82%	3%	8%	3%
Miss	Aux Vases Sandstone	14MO3	24%	44%	9%	17%	5%
Devonian	Bushberg Sandstone	14MO4	0%	54%	17%	7%	22%
Ordovician	Sr. Peter Sandstone	13MO2	0%	23%	2%	6%	70%
Ordovician	FSS Rim Rock	14MO10	0%	42%	11%	6%	41%
Ordovician	FSS-3	14MO9	0%	37%	12%	9%	42%
Ordovician	FSS-2	14MO6	0%	24%	11%	2%	63%
Ordovician	Everton Formation (FSS-1)	cz-2	0%	30%	19%	3%	48%
Ordovician	Jefferson City-Cotter Dolomite	cz-1	0%	5%	2%	3%	90%
Ordovician	Roubidoux Formation	13MO1	0%	17%	2%	1%	80%
Cambrian	Upper Lamotte Sandstone	14MO1	0%	15%	41%	9%	35%
Cambrian	Lower Lamotte Sandstone	14MO2	0%	3%	81%	16%	0%

Table 4.2. Results of sorting and mean from point counting.

	σ1 (Φ)	Sorting	Mean (Φ)	Mean (mm)
14MO6	0.63	moderately well sorted	2.61	0.16
CZ-2	0.75	moderately sorted	2.14	0.23
14MO9	0.59	moderately well sorted	1.53	0.35
CZ-1	0.78	moderately sorted	2.37	0.19
14MO10	0.46	well sorted	2.5	0.18
CZ-5	0.58	moderately well sorted	1.24	0.42
CZ-6	0.55	moderately well sorted	1.9	0.27

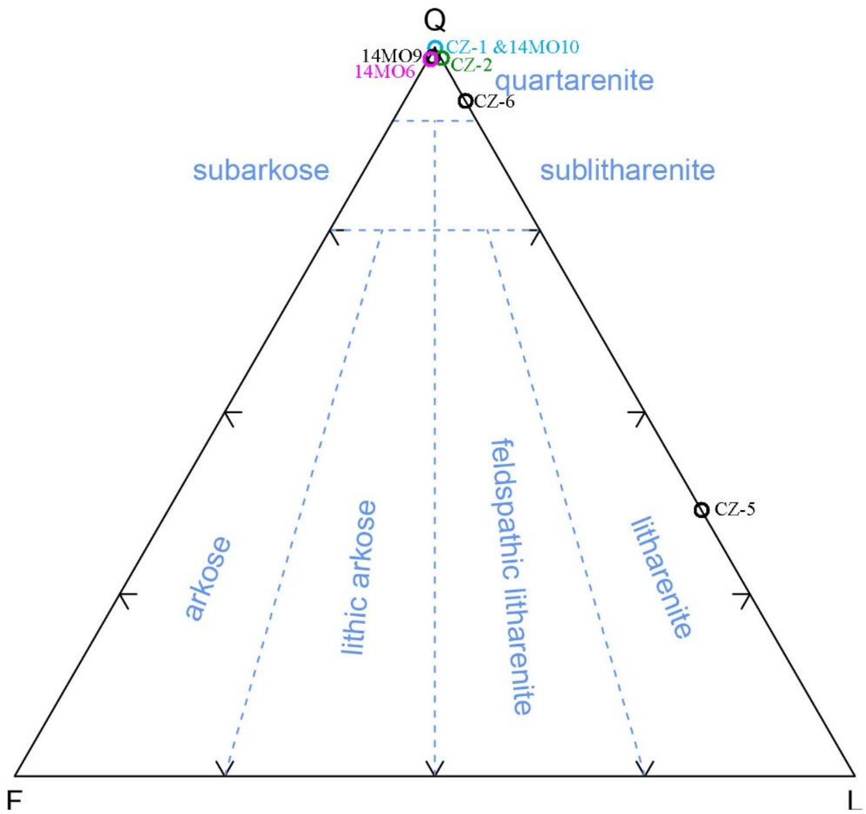

Figure 4.3. The Quartz-Feldspar-Lithic ternary plot with Folk's background. The Pennsylvanian CZ-5 falls into litharenite. The Pennsylvanian CZ-6 and Ordovician CZ-1 and FSS 14MO6, CZ-2, 14MO9, 14MO10 fall into quartzarenite.

5. DISCUSSION

5.1. PROVENANCE OF "FILLED-SINK" STRUCTURES

The age and origin FSS of in Missouri has been the subject of considerable debate. Previous researchers investigating these rocks concluded that they represent collapsed epeirogenic karst structures that developed, and were subsequently infilled by clastic sediments, during the Pennsylvanian (Bretz, 1950). More recently, Little (2004) based on stratigraphic relationships with overlying Mississippian strata, and primary structures, suggested these units were not Pennsylvanian in age, nor were they filling collapsed caves or sink-holes, but represented an earlier period of clastic sedimentation in channels developed in the great Ordovician carbonate bank. We compare and contrast the characteristics of the detrital zircon age populations of clastic rocks from the FSS with other Paleozoic clastics from Missouri as a means of constraining the answer to this controversy.

The KDE plots of Ordovician clastic rocks, including Roubidoux Formation (13MO1), Jefferson City-Cotter Dolomite (CZ-1), and St. Peter Sandstone (13MO2), share commonalities with the FSS including CZ-2, 14MO6, and 14MO9 (Figure 4.1). Detrital zircons populations from all of these samples are characterized by a distribution of ages spanning from ~0.9 Ga to 2.8 Ga. Detrital zircons derived from Archean provenance are the most abundant, typically representing over 70% of the zircon population from major Ordovician clastic units (Table. 4.1, e.g., St. Peter Sandstone) and noticeably less, but still over 40% or more of the zircon population, from sandstones that have been associated with the FSS. All samples have a prominent peak at ~2.7 Ga. Detrital zircons derived from

Grenville provenance are the next most abundant. They typically represent ~5% to ~20% of the detrital zircons found in major Ordovician clastic units (e.g., Roubidoux Formation) and ~20% to 40% of the detrital zircon population from sandstones that have been associated with the FSS. Grenville detrital zircons from lower Ordovician clastics and from the FSS typically exhibit more complex age patterns with multiple minor peaks. Detrital zircons with Paleozoic ages that were derived from Appalachian sources (Eriksson et al., 2004; Ettensohn, 2008; Xie et al., 2018) are noticeably absent. The marked similarity of the detrital zircon age populations of clastics that fill the FSS and detrital zircon populations from known Ordovician age clastics rocks in Missouri is consistent with an older Ordovician depositional age for FSS.

The characteristics of the detrital zircon age population from the FSS are in marked contrast to those of well-established Pennsylvanian clastics from Missouri. A major shift in the provenance of clastics on the Ozark Dome in Missouri occurs after deposition of the Devonian Bushberg Sandstone (14MO4) and before, or concomitant with, deposition of the late Mississippian Aux Vases sandstone (14MO3) as marked by the appearance of abundant detrital zircons with Paleozoic ages indicating deviation from Appalachians sources (Figure 4.1). In addition, the character of the detrital zircons in Grenville population displays a subtle change from a provenance with a diverse range of "Grenville" ages in Devonian and Ordovician clastics, to a large single peak in the late Mississippian (Aux Vases Sandstone, 14MO3) and early Pennsylvanian (Graydon Formation, CZ-5) clastics. The marked dissimilarity of the zircon age populations of clastics that fill the FSS with detrital zircon populations from known Pennsylvanian age clastics rocks in Missouri is inconsistent with a Pennsylvanian depositional age for these rocks without requiring unique circumstances.

The similarities, as well as dissimilarities, of the detrital zircon age characteristics of Paleozoic clastics rocks of Missouri observed in KDE plots can be more rigorously evaluated using multivariate statistics (Figure 5.1, Table 5.1). Application of K-S tests (Gehrels et al., 2006; Ludwig, 2003) examining the similarity of detrital zircon age populations between FSS and Mississippian-Pennsylvanian samples return P-values equal to 0.00-0.01 which is below the minimum limit (0.05) (Table 5.1). This is consistent with the deviation of detrital zircons of the FSS and Pennsylvanian clastic from distinct sources (Table 5.1). In contrast, K-S tests of detrital zircon age populations between FSS and Ordovician clastics return P-values of 0.089 that are above the limit (0.05). This is consistent with the deviation of detrital zircons of the FSS and Ordovician/Devonian clastics from similar source regions and with the deposition of the FSS during the Ordovician/Devonian.

The similarity, or dissimilarity, of individual detrital zircon age populations between samples using multi-variate statistics, can be readily visualized using MDS maps (Figure 5.1A and 5.1B). In these maps, detrital zircon populations that share similarities are indicated by solid lines connecting the samples; the shorter the line, the greater statistical probability that the two samples are similar, and therefore derived from similar sources. Statistically weaker connections are shown by dash lines also of varying length. Samples that are statistically dissimilar are indicated by the absence of solid or dashed lines connecting the samples. The further apart samples plot the greater the statistical certainty that the samples are unrelated and therefore derived from distinct sources. MDS maps of the detrital zircon age populations from Ordovician to Pennsylvanian clastics of the OP are shown in Figure 5.1. Immediately obvious is the strong connection between the Late Mississippian Aux Vases sandstone (14MO3) and the Pennsylvanian Graydon Formation (CZ-5) and Warner Formations (CZ-6). These samples define a cluster that plots at the right side of the diagram. Detrital zircons recovered from these late Paleozoic clastic rocks contain abundant detrital zircons with Late Paleozoic ages establishing their derivation from a provenance with Appalachian affinities (Xie et al., 2018; Eriksson et al., 2004). In addition, these samples plot away from detrital zircon populations that characterize Ordovician clastic rocks (Figure 5.1B). The absence of any connection (either solid or dash lines) to these clusters indicates for the OP, Mississippian and Pennsylvanian clastics rocks were derived from very distinct sources than the Devonian Bushberg Sandstone (14MO4) and older rocks (Figure 5.1A).

The extent of similarity among detrital zircon age populations of the Devonian Bushberg Sandstone (14MO4) and older Ordovician clastic rocks is also shown by the MDS map (Figure 5.1). Detrital zircon populations from the Ordovician clastics rocks define a cluster, with solid-line and dash-line connections, in the left side of the diagram demonstrating their derivation from similar source rocks (Figure 5.1B). Detrital zircon populations from FSS define a tight cluster, with short, solid-line connections, in the center of the diagram without direct Mississippian-Pennsylvanian connections (Figure 5.1A & 5.1B). This also demonstrates their derivation from similar source rocks and is consistent with deposition of clastics of the FSS in the Ordovician/Devonian and not during the Pennsylvanian.

In Fig. 5.1A & B, the cluster defined by the detrital zircon population from FSS plots between the field for the known Ordovician clastics (i.e., Roubidoux, Jefferson-City-Cotter Dolomite, and St. Peter) and the Devonian Bushberg Sandstone. FSS cluster forms a “bridge” between the older Ordovician clastics and the younger Devonian clastics. These three “sub-clusters” (OP Ordovician, FSS, and OP-Devonian) being linked together by a combination of both short, solid lines, and short, dashed lines to form one, statistically significant, cluster (Figure 5.1A). This indicates that the detrital zircon populations of these samples were derived from similar sources. Stratigraphically, these FSS clastics define a well observed unconformable relationship to underlying Ordovician rocks (see Fig3. 2 and Little (2004)) and are overlain locally by Devonian (Spreng and Proctor, 1993; Spreng et al., 2000) and Mississippian age rocks. In the OP of Missouri, the stratigraphic relationships and the strong affinity of the detrital zircon characteristics with other Ordovician clastics suggest the FSS are more consistent with being remnants of the Middle Ordovician Everton Formation. The Everton Formation was deposited on the Sub-Tippecanoe erosional surface below the widespread, transgressive St. Peter Sandstone (Figure 5.2). The possibility exists, that other sandstones classified as “undifferentiated Pennsylvanian sandstones” in Missouri (Figure 3.2) are also correlative with the Middle Ordovician Everton Formation or are possibly Devonian in age (see discussion below) if unconformable relationships correspond to Pre-Kaskaskia erosional surface.

The position of Ordovician and Devonian sub-cluster in Figure.7B which changing across the diagram tracks transitions in the sediments provenance. The influence of Grenville and PYM populations decreases from the Roubidoux to the Jefferson City-Cotter Dolomite (CZ1) but reappears as a significant component in the Devonian Bushberg

Sandstone (Figure 4.1 & Table 4.1.) The same sources that contributed to the Devonian Bushberg Sandstone also contributed to the clastics forming the FSS. This is shown by the complexity of the Grenville and PYM populations of the FSS (Figure 4.1, Table 5.2) and the close connection of the FSS sub-group to the Devonian Bushberg Sandstone (14MO3) (Figure 5.1). The close outcrop spatial association of sandstone sample from the Jefferson City-Cotter Dolomite (CZ-1) with the unconformably overlying sandstone (CZ-2) is consistent with an important shift in provenance which may have come about with the reorganization of major river drainages in response to tectonism associated with Paleozoic tectonism along the eastern margin of Laurentia. If the FSS are correlative with the Middle Ordovician Everton Formation then an additional shift in provenance is required as the detrital zircon population for the St. Peter Sandstone (13MO2) shows the limited influence of sources containing Grenville and PYM populations (Figure 4). Compared with the zircon data from St. Peter Sandstone and its overlaying strata in KDE plots and MDS map (Ibrahim, 2016; Figure 5.3), the Devonian Bushberg Sandstone (14MO4) is similar with the KDE plots of the Iowa Upper Ordovician samples and has better connection in MDS map with the Upper Ordovician data (B1, J1, and UHS). The FSS (14MO9 & 14MO10) also have solid-line connections with Iowa Upper Ordovician samples which could younger than the FSS CZ-2 & 14MO6 (Figure 5.3). The detrital zircon populations of the clastics associated with the FSS also display a close affinity to the Devonian Bushberg Sandstone (14MO4) (Figure 5.1). The possibility arises that these rocks may have been deposited unconformably on a Pre-Kaskaskia erosional surface in the Devonian prior to the major shift to Appalachian provenance as documented by the Mississippian Aux Vases Sandstone (14MO3) (Figure 4.1). This is consistent with stratigraphic relationships observed in many localities where clastics of the FSS are overlain by Mississippian strata (Little, 2004).

The proximity of CZ-2, 14MO6, and Little (2004) outcrops and their similar lithologies constrain them to the same depositional regime (Figure 3.1). Sandstone and shale interbedded stratigraphic features, the bottom unconformity, and the locations at the north flank of the OP highly overlap with the descriptions of the Ordovician Everton Formation (Thompson, 1991; Ethington et al., 2012). With the solid support of the zircon analyses, the FSSs including CZ-2 and 14MO6, are re-defined as the Ordovician Everton Formation. The Everton Formation in Oklahoma and Arkansas reported by Ethington et al., (2012) was interpreted as near-shore, tidal flat, and subtidal deposit. The Everton Formation represented by the FSS could mark the initiation of the Tippecanoe transgression in Missouri in Middle Ordovician.

The southern FSS 14MO9 and its rim sandstone 14MO10 (Figure 3.1) have more connections with the St. Peter Sandstone data from Iowa in MDS map (Ibrahim, 2016; Figure 5.3). It is worth notice that the FSS CZ-2 also has connections with the inland FSS 14MO9 and the St. Peter Sandstone from Iowa. In south Missouri, the Everton Formation finally grades into the overlying St. Peter Sandstone (Cordry, 1929). Additionally, the Everton Formation and the St. Peter Sandstone are hard to differentiate in north Arkansas, the south flank of the OP (Suhm, 1974). Thus, Everton Formation and St. Peter Sandstone could derive from the same source in Ordovician within the Tippecanoe Transgression.

The Sub-Tippecanoe regression assistance with the OP uplifting event enlarged the Sauk carbonate strata exposure area in the OP (Cox, 2009; Sloss, 1963; Thacker and Anderson, 1977) (Figure 5.4). The karstification by the surface and subsurface fluid and other subaerial erosions made small depositional spaces in the carbonate strata. With the sea-level raising in Tippecanoe transgression, these open accommodation spaces at flanks were filled first by shoreface sediments (the Everton Formation). With the sea-level kept raising, the whole plateau covered by the Tippecanoe Sequence at the end of Silurian before the Pre-Kaskaskia erosion (Figure 5.4).

5.2. PROVENANCE SHIFTING IN PALEOZOIC

5.2.1. Provenance of Late Cambrian. Detrital zircon age populations of the clastics from the Late Cambrian Lamotte sandstone are dominated by zircons derived from the Granite-Rhyolite terrane (80%) for the stratigraphically lower sample (14MO2). Additional contributions are derived from the PYM sources and noticeably absent are zircons from an Archean provenance (Figure 4.1). Clastics from the stratigraphically higher in the Lamotte sandstone (14MO1) show a shift in sources contributing to these sediments. Detrital zircons derived locally from the Granite-Rhyolite terrane decrease to a little more than 40%; and contributions from both Archean (35%), PYM (9%), and Grenville age sources increase (Figure 4.1, Table 4.1). The ~1.47 Ga and ~1.38 Ga peak in the lower Lamotte Sandstone (14MO2) is coeval with well-documented two periods of igneous activity in the St. Francois Mountain in SE Missouri (Rohs and Schmus, 2006) which is part of the Eastern Granite-Rhyolite terrane. The absence of Archean age zircons suggests the bulk of the sediments which formed the lower portions of the Lamotte Sandstone were locally derived (see also Wenner & Taylor, 1976; Thompson, 1995; Meert et al., 2002). With time and prior to the end of the Cambrian, additional sediment was being delivered from rivers that were transporting material from erosion of Archean, as well as the PYM, sources to the north (see Figure 4.2), southward to the Mid-continent.

5.2.2. Provenance of Ordovician. Detrital zircon populations for the Ordovician clastic rocks sampled display both important similarities and differences with the Late Cambrian Lamotte Sandstone. The KDE plots of Ordovician clastic rocks, including Roubidoux Formation and Jefferson City-Cotter Dolomite, and the St. Peter Sandstone show detrital zircons populations from all of these samples are characterized by a distribution of ages spanning from ~0.9 Ga to 2.8 Ga (Figure 4.1, Table 4.1). Detrital zircons derived from Archean provenance are the most abundant, typically representing over 70% of the zircon population from major Ordovician clastic units (e.g., St. Peter Sandstone). All samples have a prominent peak at ~2.7 Ga. Detrital zircons derived from Grenville province are the next most abundant. They typically represent ~5 to ~20% of the detrital zircons found in major Ordovician clastic units (e.g., Roubidoux Formation). Grenville detrital zircons from lower Ordovician clastics may have more than one age peak, but discerning a consistent pattern is beyond the resolution of the data set. Detrital zircons with Paleozoic ages that were derived from Appalachian sources (Eriksson et al., 2004) are noticeably absent from all Ordovician clastics.

The Midcontinent Rift System (MCR) at the southern margin of the Canadian Shield is a potential provenance that could provide all the detrital zircon age populations recorded in the Ordovician samples (Figure 5.5). The MCR (1.1 Ga) is a large bowed structure in the central North American craton that extends from Kansas to the center of Lake Superior and from Lake Superior to southeastern Michigan (Figure 4.2). It is composed of a lower volcanic section and an upper clastic sedimentary section (Ojakangas, 2001). The exposed MCR in the Ordovician lead to the erosion of the upper clastic sedimentary section (Konstantinous et al., 2013). The upper sedimentary rocks mainly consist of Late Cambrian sandstones and Mesoproterozoic clastics which are subdivided into the Bayfield Group, Oronto Group, and North Shore Volcanics (Ojakongas, 2001; Craddock, 2013).

The Late Cambrian section and the Bayfield Group from MCR (Craddock, 2013) and its adjacent Huron Basin (Konstantious, 2013) were selected for potential source comparison with the OP Ordovician samples. The composite KDE plot of three OP Ordovician samples (13MO1, CZ-1, and 13MO2) dominated by the Archean population (80%) with a peak at ~2.7 Ga. The remaining populations are 15% Grenville, 2% Granite-Rhyolite, and 3% PYM (Table 5.2). From the KDE plots, the composite OP Ordovician is much similar to the composite MCR Late Cambrian sample (Figure 5.5). However, in MDS map the composite OP Ordovician has a solid-line connection with composite Huron Basin and a dash-line connection with the composite MCR Late Cambrian (Figure 5.6). The relationships in the MDS map indicate that the OP Ordovician had a mixed source with the domination of the Huron Basin and the exposed MCR Late Cambrian as the secondary source that introduced the PYM and Grenville population (Konstantinous et al., 2013). These two populations could also gain on its way to the OP. In this MDS map, the FSS, as a bridge, linking the MCR Late Cambrian with a solid-line and the Devonian (14MO4) with dash-line points to the same interpretation with section 5.1 that the FSS has both the features of Ordovician (dominated) and Devonian (Figure 5.6).

Compared with the MCR Late Cambrian data, the MCR Bayfield Group and the Huron Basin zircon plots have fewer commonalities with the composite OP Ordovician data (Figure 5.5 &5.6, Table 5.2). The composite OP Ordovician detrital zircon KDE plot matches well with the composite MCR Late Cambrian plot. Both of the two datasets are dominated by the Archean population (OP: 28%, MCR LC: 26%) with a major peak at ~2.7 Ga and no Appalachian population. The proportions of the rest populations including Grenville, Granite-Rhyolite, and PYM are also similar (Table 5.2). In the MDS map, the composite OP Ordovician spot is much closer to the MCR Late Cambrian spot and has no connection with the MCR Bayfield Group (Figure 5.6). Thus, the MCR Late Cambrian sedimentary rock was the sediment source for the Ordovician OP. However, the Huron Basin could contribute to a small number of grains because of its unique Archean peak (Figure 5.7).

5.2.3. Provenance of Late Paleozoic. Three Mississippian-Pennsylvanian zircon plots (14MO3, CZ-5, CZ-6) yield a bimodal distribution pattern that characterized by a major peak at ~1.06 Ga in the Grenville population (51%) and two secondary peaks at ~0.3 Ga and ~0.44 Ga in Appalachian population (23%) (Figure 5.8, Table 5.3). The zircon age of~0.3 Ga is coeval with the Alleghanian orogeny and ~0.44 Ga is coeval with the Acadian at the east margin of Laurentia in Mississippian to Pennsylvanian, which supporting a provenance east of the OP. The good sorting and rounded grain shape indicate that the detritus deposited in the OP region should be recycled for at least twice. Thus, the Appalachian Foreland Basin (AFB) is the preferred potential source for Late Paleozoic clastic sediments in the OP (Craddock, 2013; Eriksson et al., 2004; Park et al., 2010). MCR was also involved for potential source comparison to test if any grains derived from the north.

All three samples show a primary peak in Grenville at ~1.1 Ga. However, the OP Mississippian-Pennsylvanian (OP-MP) sample has more commons with the AFB than the MCR (Figure 5.8, Table 5.3). The OP-MP and AFB yield a subordinate peak at ~0.4 Ga in Appalachian, while the MCR yields a subordinate peak at ~1.86 Ga in Granite-Rhyolite with no Appalachian component.

In the MDS map, the nearest spot to OP-MP is the AFB and the second nearest spot is the MCR Bayfield Group which is the reference data for Ordovician potential provenance (Figure 12). The MCR Bayfield Group also has a relationship with the Appalachian Foreland Basin, but it does not match with the OP-MP. Therefore, the AFB is the preferred provenance of the OP in Mississippian-Pennsylvanian. The MCR Bayfield Group could be the subordinate source for the OP (Figure 5.9).

5.2.4. Provenance Shifting. Two provenance shifting events are recognized in Late Cambrian and Mississippian from the discussion above. The first appearance of Archean grains at the top of the Late Cambrian Lamotte sandstone marks the first provenance shift. A later Archean provenance dominates successive Ordovician clastic sedimentary rocks in the OP area. The second provenance shifting event is marked by the presence of an Appalachian population and a sharp decrease in the Archean population. Compared with Archean-dominated Ordovician samples and Grenville and Appalachian dominated Mississippian-Pennsylvanian samples, the bimodal distribution of the Devonian sample shows conspicuous transitional features. The 54% Grenville population of the total with 1074Ma peak, the 22% Superior population of the total with 2700Ma peak, and the absence of Appalachian contributions indicate the onset of the second shifting event which the source is migrating from northern Archean area to eastern AFB.

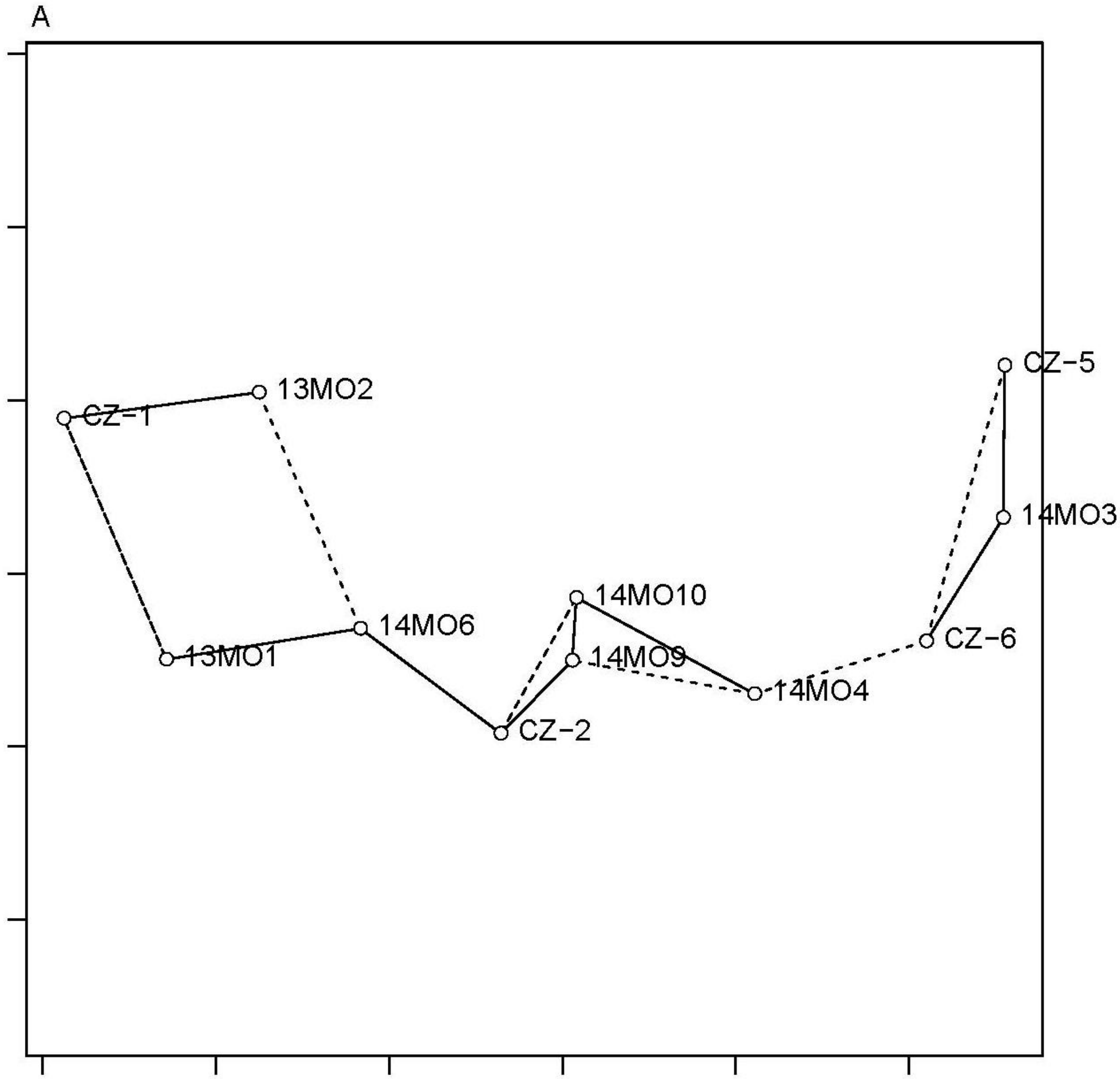

Figure 5.1. MDS map of samples from the OP without Cambrian. A. The original MDS map. The FSS is closer to the Archean dominated area and FSS CZ-2, 14MO9, and 14MO10 are at the middle of the Archean dominated and the Grenville dominated. Solid lines represent the nearest neighbors and dashed lines represent the second nearest neighbors. B. The same MDS map grouped samples into different fields based on the deposition ages.

B

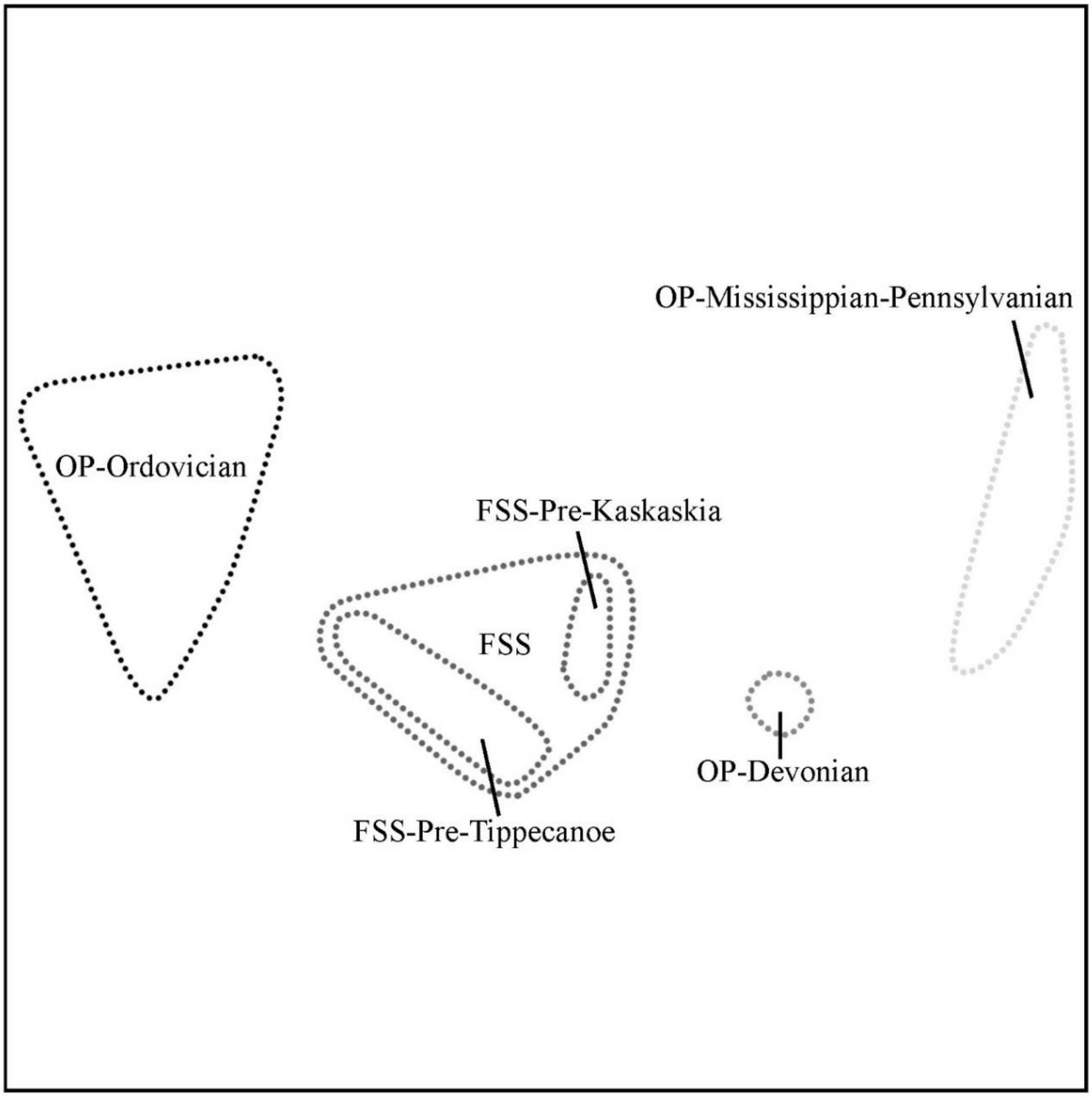

Figure 5.1. MDS map of samples from the OP without Cambrian. A. The original MDS map. The FSS is closer to the Archean dominated area and FSS CZ-2, 14MO9, and 14MO10 are at the middle of the Archean dominated and the Grenville dominated. Solid lines represent the nearest neighbors and dashed lines represent the second nearest neighbors. B. The same MDS map grouped samples into different fields based on the deposition ages (cont.).

Table 5.1. The K-S P-values of all samples from the OP. Yellow color marked values that the two samples are not statistically different.

K-S P-values using error in the CDF

	14MO2	14MO1	14MO6	CZ-1	CZ-2	14MO9	14MO10	13MO1	13MO2	14MO4	14MO3	CZ-5	CZ-6
14MO2		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14MO1	0.000		0.001	0.000	**0.208**	0.019	0.002	0.000	0.000	0.000	0.000	0.000	0.000
14MO6	0.000	0.001		0.000	**0.206**	0.034	0.028	**0.089**	0.004	0.000	0.000	0.000	0.000
CZ-1	0.000	0.000	0.000		0.000	0.000	0.000	0.011	0.020	0.000	0.000	0.000	0.000
CZ-2	0.000	**0.208**	**0.206**	0.000		**0.736**	**0.268**	0.000	0.000	0.003	0.000	0.000	0.000
14MO9	0.000	0.019	0.034	0.000	**0.736**		**0.913**	0.000	0.000	0.024	0.000	0.000	0.001
14MO10	0.000	0.002	0.028	0.000	**0.268**	**0.913**		0.000	0.000	**0.053**	0.000	0.000	0.001
13MO1	0.000	0.000	**0.089**	0.011	0.000	0.000	0.000		0.003	0.000	0.000	0.000	0.000
13MO2	0.000	0.000	0.004	0.020	0.000	0.000	0.000	0.003		0.000	0.000	0.000	0.000
14MO4	0.000	0.000	0.000	0.000	0.003	0.024	**0.053**	0.000	0.000		0.000	0.001	**0.132**
14MO3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		**0.116**	**0.399**
CZ-5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	**0.116**		**0.105**
CZ-6	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	**0.132**	**0.399**	**0.105**	

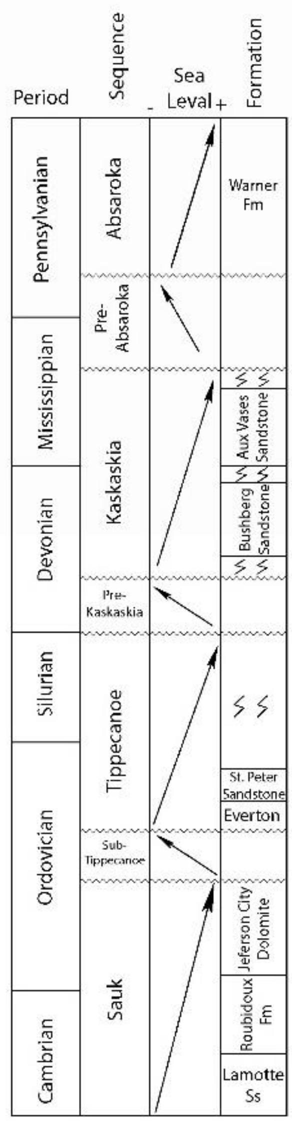

Figure 5.2. Sea-Level fluctuation history of the North American Craton. Modified after Bunker et al., 1988.

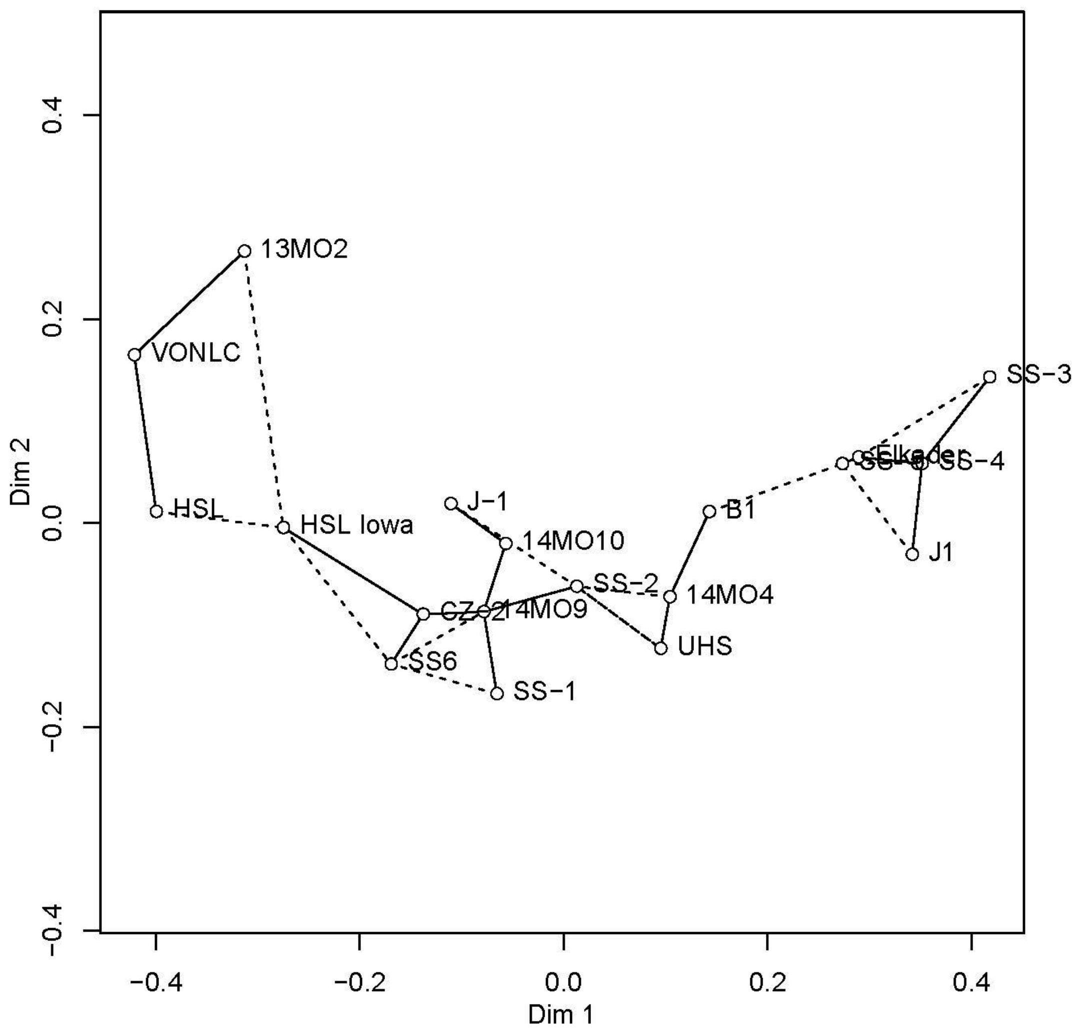

Figure 5.3. The MDS map of St. Peter Sandstone from Iowa and FSS 14MO9 and 14MO10.

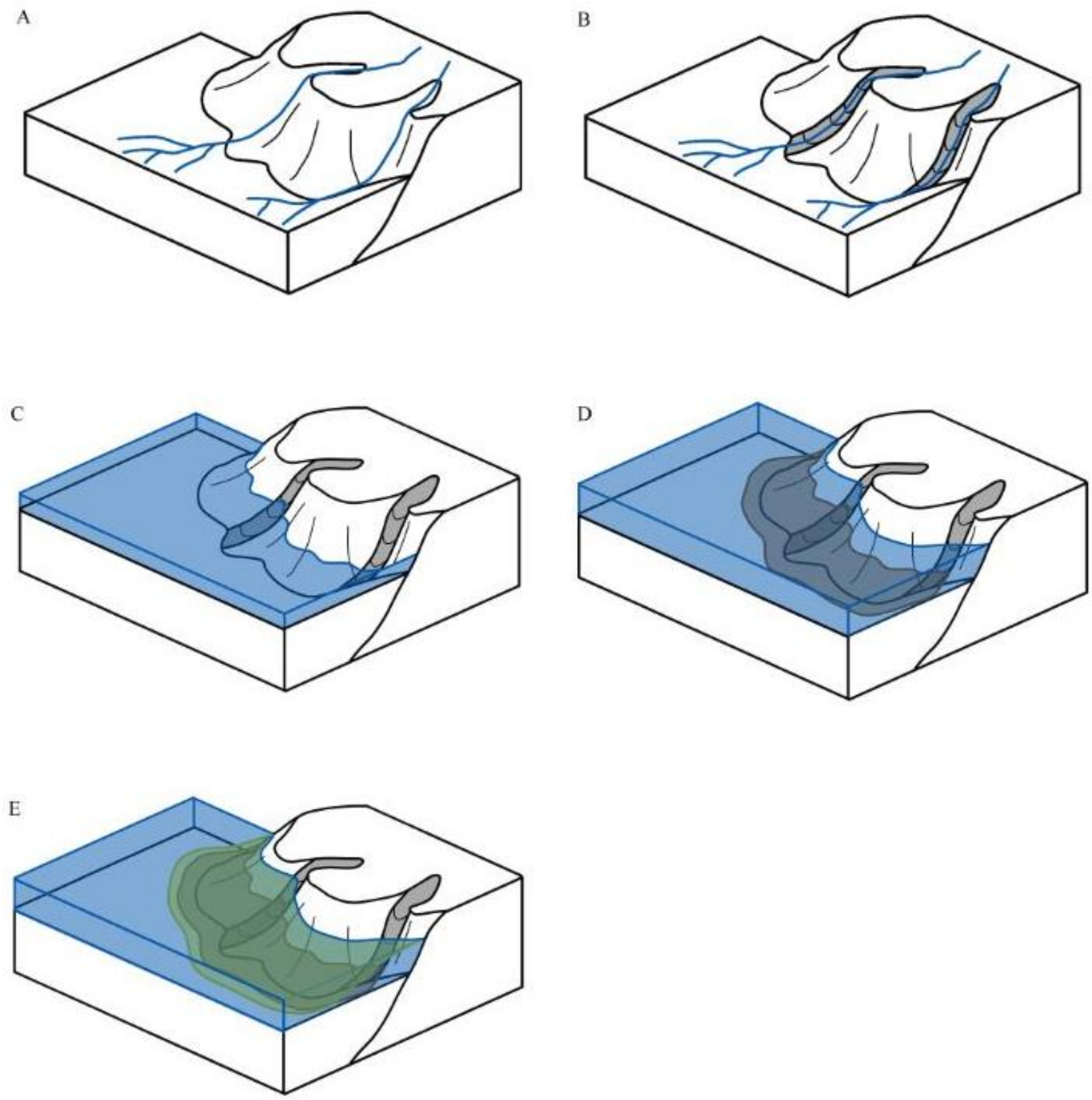

Figure 5.4. The depositional model of FSS in the OP with sea-level fluctuation. A. The OP uplifted and exposed in Sub-Tippecanoe regression. B. Surface fluids eroded the subaerial carbonate strata. C. Sea-level raised in Tippecanoe transgression. D. Shoreface sediments deposition. E. Shallow marine sediments deposited.

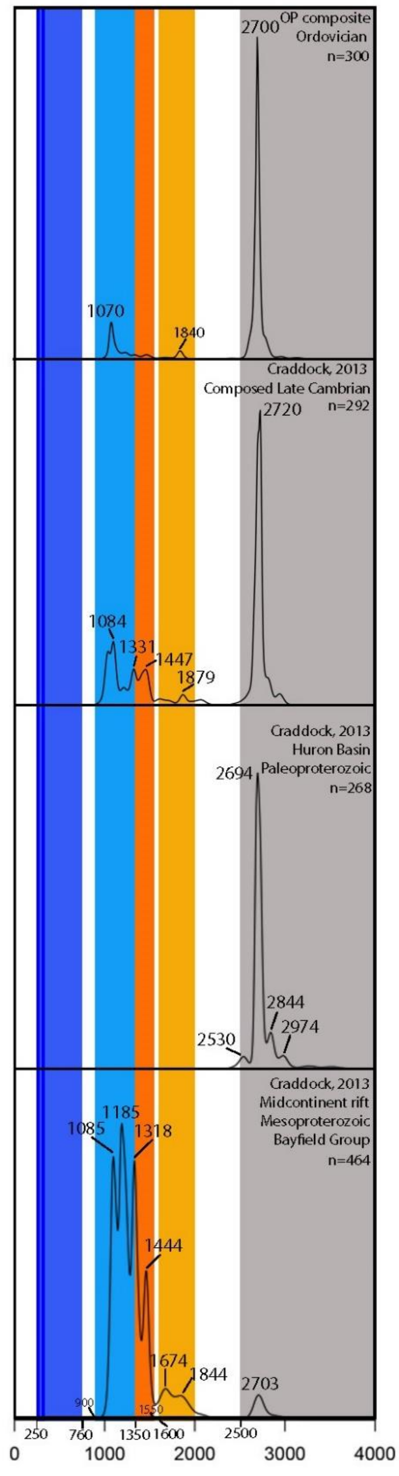

Figure 5.5. Potential sources comparison for Ordovician OP samples.

Table 5.2. Proportion of each population of composite OP Ordovician samples and composite MCR Late Cambrian samples.

	0.9-1.35 Ga	1.55-1.35 Ga	>2.5 Ga	1.6-2 Ga	0.25-0.76 Ga
	Grenville	Granite-Rhyolite	Archean	PYM	Appalachian
Composite OP True Ordovician	15%	2%	80%	3%	0%
Composite MCR-LC	26%	11%	59%	5%	0%
Composite HB	0%	0%	100%	0%	0%

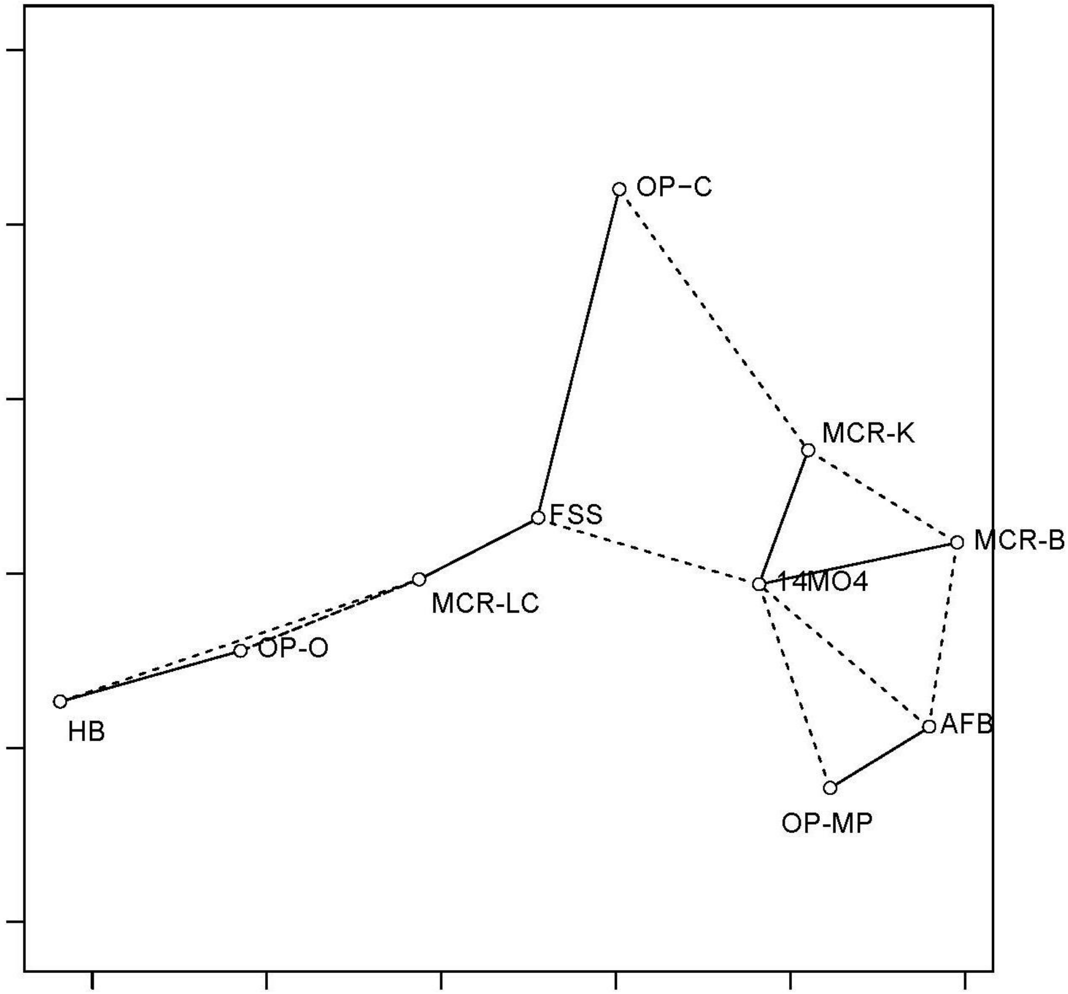

Figure 5.6. MDS map of OP samples and potential sources. Ordovician potential sources are all colored in blue. OP-C, composite OP Cambrian samples; OP-O, composite OP Ordovician samples; HB, Huron Basin; OP-MP, composite OP Mississippian and Pennsylvanian samples.; MCR-LC, composite MCR Late Cambrian samples; MCR-K, composite MCR Keweenaw Supergroup; MCR-B, composite MCR Bayfield Group; AFB, composite Appalachian Foreland Basin samples. The closer the circles, the higher possibility that they came from the same provenance. The composed OP Cambrian-Ordovician and MCR Late Cambrian overlap with each other. AFB is the closest sample to the composed OP Mississippian-Pennsylvanian.

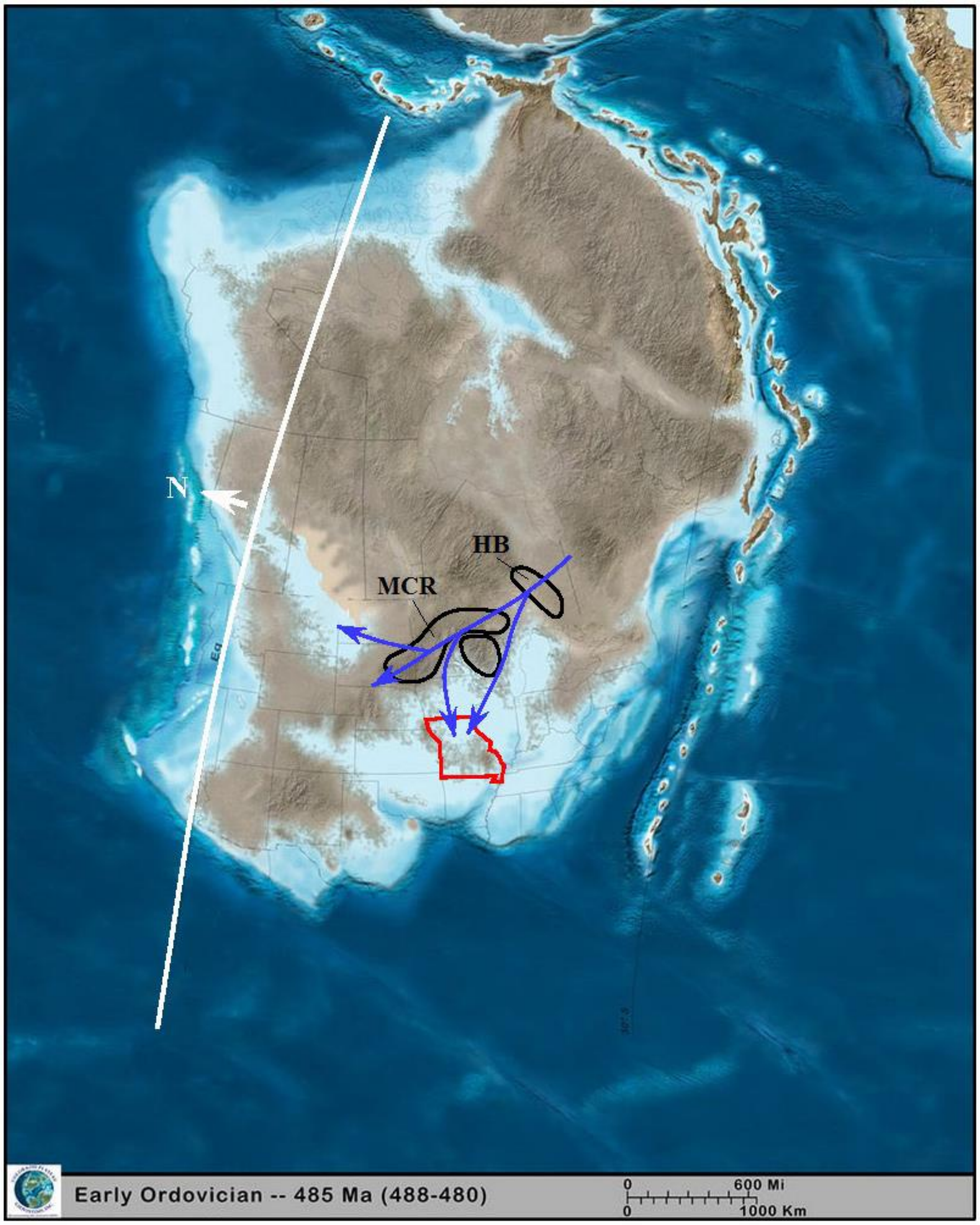

Figure 5.7. Schematic map of sediments dispersal path in Ordovician. MCR, Midcontinent Rift System; HB, Huron Basin.

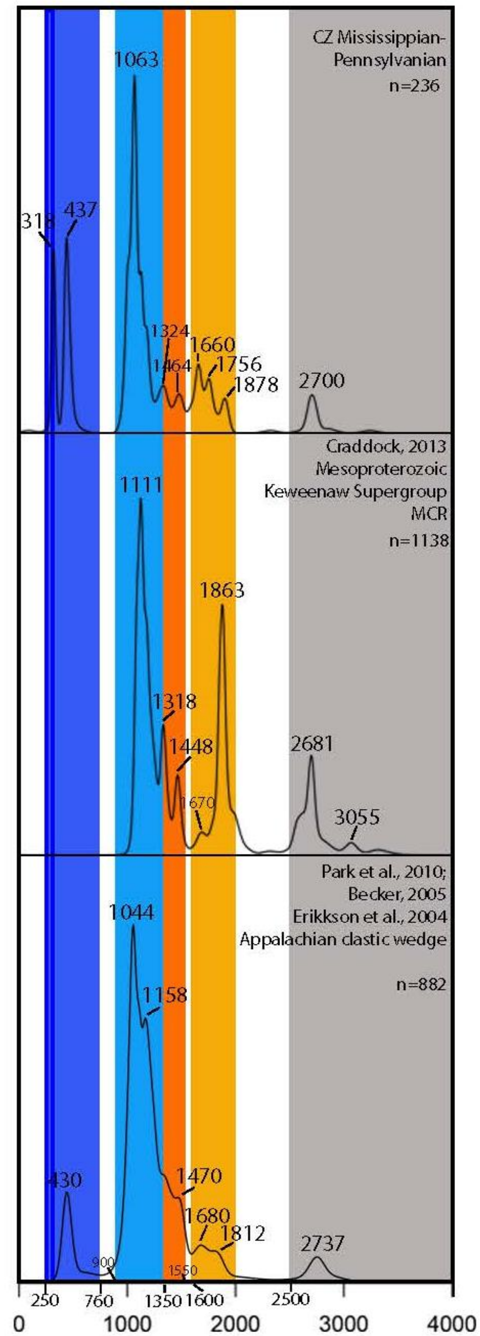

Figure 5.8. Potential sources for OP Mississippian-Pennsylvanian samples.

Table 5.3. Proportion of each population of composite OP Mississippian-Pennsylvanian (OP MP), composite Appalachian Foreland Basin (AFB), and composite MCR Keweenaw Supergroup (MCR-K).

	0.9-1.35 Ga	1.55-1.35 Ga	>2.5 Ga	1.6-2 Ga	0.25-0.76 Ga
	Grenville	Granite-Rhyolite	Archean	PYM	Appalachian
Composite OP MP	51%	6%	6%	14%	23%
Composite AFB	66%	12%	5%	8%	9%
Composite MCR-K	51%	8%	16%	25%	0%

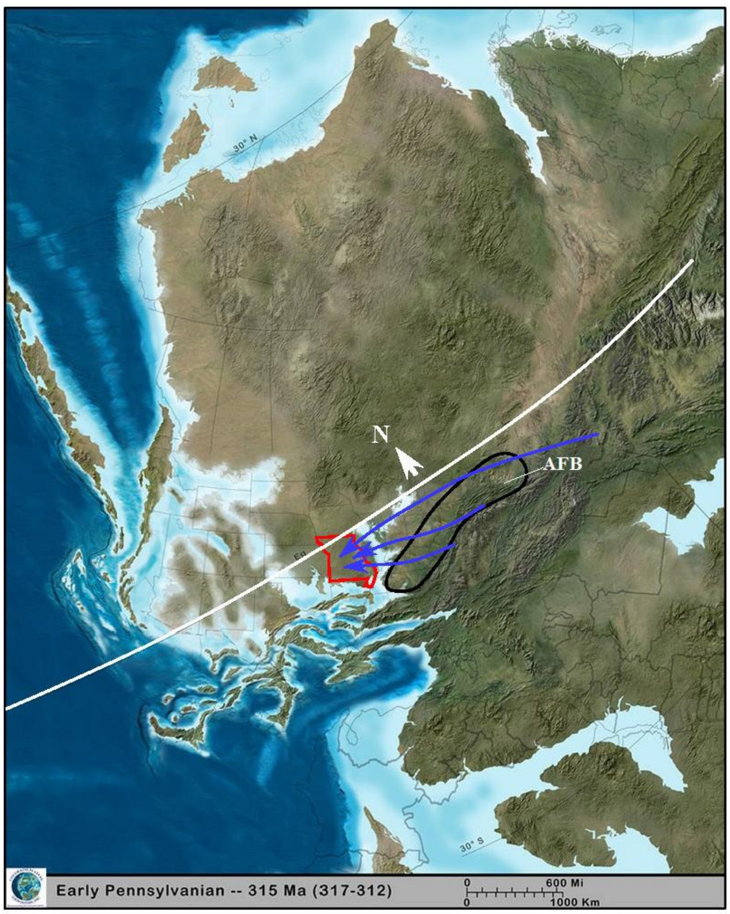

Figure 5.9. Early Pennsylvanian detritus dispersal path. AFB, Appalachian Foreland Basin.

6. CONCLUSION

6.1. FSS AND PROVENANCE SHIFTING

The zircon data, lithologic analyses, and field observations prove that the Type I filled sink structure in the Ozark Plateau is coeval with the Middle Ordovician Everton Formation. The Type I filled sink structures were deposited in the shoreface environment at the flanks of the Ozark Plateau in the Sub-Tippecanoe regression and Tippecanoe transgression cycle.

The Paleozoic clastic sedimentary rocks in the Ozark Plateau experience two major provenance shifting events. Due to the burial of the St. Francois Mtn, the first provenance shifted from the local to the northern Midcontinent Rift System. The second shifting event was caused by the Appalachian orogeny. The uplifted fold-thrust-belt and paleonorthwest slope by the Appalachian orogeny made more clastics derived from east of Laurentia. Consequently, the source rock for Late Paleozoic sedimentary rocks in the Ozark Plateau shifted from north MCR to the east Appalachian area.

6.2. IMPLICATION OF SEA-LEVEL FLUCTUATION AND FAR-FIELD TECTONISM

In short-term, the detritus source was controlled by the sea-level fluctuations such as the first provenance shifting in Late Cambrian. In the long-term, the onset orogeny would take the lead. The exhumed sedimentary rocks and fresh igneous rock by the ongoing orogeny, such as the Taconic Orogeny and Acadian Orogeny, would become the dominated clastic sources in the next deposition. Meanwhile, the remodified topography by the orogeny would help to transport the clastics to the basins. The second provenance shifting in the Ozark Plateau was the best example of the effect of far-field tectonism and the provenance shifting in St. Peter sandstone in Iowa was the result of the coaction of sea-level fluctuation and far-field tectonism.

APPENDIX

Table 1. CZ-1 U-Pb Geochronological analysis.

Table _____. U-Pb geochronologic analyses.									
			Apparent ages (Ma)						
Analysis	206Pb* 238U*	± (Ma)	207Pb* 235U	± (Ma)	206Pb* 207Pb*	± (Ma)	Best age (Ma)	± (Ma)	Conc (%)
ACHAPMAN_CZ1-52 <>	1028.3	10.1	1017.1	30.8	993.0	95.2	993.0	95.2	103.6
ACHAPMAN_CZ1-89 <>	1067.0	11.0	1059.2	43.7	1043.1	132.3	1043.1	132.3	102.3
ACHAPMAN_CZ1-36 <>	1054.6	5.0	1061.0	21.6	1074.1	65.2	1074.1	65.2	98.2
ACHAPMAN_CZ1-50 <>	1357.1	14.0	1349.3	43.6	1337.1	110.8	1337.1	110.8	101.5
ACHAPMAN_CZ1-8 <>	1343.7	56.3	1341.6	46.8	1338.3	81.8	1338.3	81.8	100.4
ACHAPMAN_CZ1-66 <>	1404.2	39.4	1398.7	58.7	1390.4	135.7	1390.4	135.7	101.0
ACHAPMAN_CZ1-57 <>	1460.8	8.1	1460.1	17.2	1459.1	40.6	1459.1	40.6	100.1
ACHAPMAN_CZ1-74 <>	1606.3	16.7	1626.1	34.8	1651.8	76.6	1651.8	76.6	97.2
ACHAPMAN_CZ1-73 <>	1752.6	10.2	1764.3	13.2	1778.1	26.1	1778.1	26.1	98.6
ACHAPMAN_CZ1-41 <>	1737.4	92.2	1790.0	54.8	1851.8	43.3	1851.8	43.3	93.8
ACHAPMAN_CZ1-33 <>	2570.4	11.3	2580.0	10.1	2587.6	15.6	2587.6	15.6	99.3
ACHAPMAN_CZ1-77 <>	2578.6	18.4	2595.1	34.8	2608.0	60.1	2608.0	60.1	98.9
ACHAPMAN_CZ1-53 <>	2622.3	18.1	2615.8	20.6	2610.7	33.8	2610.7	33.8	100.4
ACHAPMAN_CZ1-59 <>	2677.4	28.9	2639.7	85.8	2611.0	150.4	2611.0	150.4	102.5
ACHAPMAN_CZ1-44 <>	2608.3	14.5	2615.6	13.5	2621.2	21.2	2621.2	21.2	99.5
ACHAPMAN_CZ1-78 <>	2601.7	13.9	2614.3	15.6	2624.0	25.4	2624.0	25.4	99.1
ACHAPMAN_CZ1-12 <>	2589.6	17.9	2618.4	10.2	2640.8	11.5	2640.8	11.5	98.1
ACHAPMAN_CZ1-11 <>	2586.6	19.9	2617.8	12.7	2642.1	16.2	2642.1	16.2	97.9
ACHAPMAN_CZ1-4 <>	2608.1	9.9	2627.8	12.0	2642.9	19.8	2642.9	19.8	98.7
ACHAPMAN_CZ1-72 <>	2631.4	15.0	2646.2	11.2	2657.4	16.0	2657.4	16.0	99.0
ACHAPMAN_CZ1-30 <>	2658.1	19.3	2661.1	13.6	2663.5	18.8	2663.5	18.8	99.8
ACHAPMAN_CZ1-21 <>	2509.0	18.2	2596.1	14.8	2664.8	21.8	2664.8	21.8	94.2
ACHAPMAN_CZ1-18 <>	2633.9	16.3	2652.5	13.2	2666.7	19.6	2666.7	19.6	98.8
ACHAPMAN_CZ1-31 <>	2594.6	34.4	2637.6	24.1	2670.7	33.0	2670.7	33.0	97.2
ACHAPMAN_CZ1-45 <>	2676.5	24.1	2674.8	73.2	2673.6	127.2	2673.6	127.2	100.1
ACHAPMAN_CZ1-61 <>	2544.4	53.8	2617.3	27.4	2674.2	23.1	2674.2	23.1	95.1
ACHAPMAN_CZ1-3 <>	2625.6	30.0	2654.3	28.4	2676.3	44.2	2676.3	44.2	98.1
ACHAPMAN_CZ1-105 <>	2683.7	18.4	2681.0	16.1	2679.0	24.5	2679.0	24.5	100.2
ACHAPMAN_CZ1-47 <>	2680.2	14.7	2680.2	9.6	2680.1	12.7	2680.1	12.7	100.0
ACHAPMAN_CZ1-42 <>	2687.9	11.6	2684.9	20.0	2682.6	34.0	2682.6	34.0	100.2
ACHAPMAN_CZ1-15 <>	2686.1	17.2	2684.7	27.9	2683.7	47.2	2683.7	47.2	100.1
ACHAPMAN_CZ1-24 <>	2674.9	13.5	2680.1	11.3	2684.1	16.9	2684.1	16.9	99.7
ACHAPMAN_CZ1-9 <>	2659.4	18.8	2673.9	11.0	2684.9	12.9	2684.9	12.9	99.1
ACHAPMAN_CZ1-29 <>	2688.9	13.9	2688.1	27.9	2687.5	47.8	2687.5	47.8	100.1
ACHAPMAN_CZ1-69 <>	2756.0	28.9	2717.2	43.7	2688.4	73.3	2688.4	73.3	102.5
ACHAPMAN_CZ1-82 <>	2666.7	15.3	2679.3	18.6	2688.8	30.5	2688.8	30.5	99.2
ACHAPMAN_CZ1-34 <>	2717.3	52.6	2701.2	22.8	2689.1	7.3	2689.1	7.3	101.0
ACHAPMAN_CZ1-80 <>	2678.2	23.5	2684.7	34.6	2689.6	57.9	2689.6	57.9	99.6
ACHAPMAN_CZ1-40 <>	2611.0	35.4	2656.2	22.2	2690.7	27.8	2690.7	27.8	97.0
ACHAPMAN_CZ1-81 <>	2635.5	10.6	2667.2	9.7	2691.2	15.1	2691.2	15.1	97.9
ACHAPMAN_CZ1-1 <>	2687.7	17.3	2690.2	20.8	2692.1	34.0	2692.1	34.0	99.8
ACHAPMAN_CZ1-5 <>	2663.6	26.1	2680.6	28.4	2693.4	45.8	2693.4	45.8	98.9
ACHAPMAN_CZ1-63 <>	2683.3	42.7	2689.2	35.6	2693.6	53.4	2693.6	53.4	99.6
ACHAPMAN_CZ1-95 <>	2664.8	12.7	2681.4	11.6	2693.9	17.8	2693.9	17.8	98.9
ACHAPMAN_CZ1-35 <>	2675.1	16.1	2686.5	16.7	2695.0	26.6	2695.0	26.6	99.3
ACHAPMAN_CZ1-54 <>	2686.2	28.3	2691.5	22.2	2695.4	32.6	2695.4	32.6	99.7
ACHAPMAN_CZ1-39 <>	2713.9	19.4	2703.5	43.8	2695.8	75.2	2695.8	75.2	100.7
ACHAPMAN_CZ1-2 <>	2686.3	19.2	2692.4	14.8	2697.1	21.6	2697.1	21.6	99.6
ACHAPMAN_CZ1-101 <>	2651.4	20.6	2677.6	24.3	2697.5	39.5	2697.5	39.5	98.3
ACHAPMAN_CZ1-51 <>	2664.1	10.5	2683.3	11.1	2697.8	17.7	2697.8	17.7	98.7
ACHAPMAN_CZ1-103 <>	2566.1	24.8	2641.0	16.4	2698.9	21.3	2698.9	21.3	95.1
ACHAPMAN_CZ1-64 <>	2681.8	14.6	2691.8	12.3	2699.4	18.6	2699.4	18.6	99.3
ACHAPMAN_CZ1-13 <>	2629.3	11.9	2669.6	34.4	2700.2	59.6	2700.2	59.6	97.4
ACHAPMAN_CZ1-23 <>	2659.0	18.3	2682.5	20.3	2700.2	32.7	2700.2	32.7	98.5
ACHAPMAN_CZ1-67 <>	2685.5	11.1	2695.4	14.0	2702.8	23.0	2702.8	23.0	99.4
ACHAPMAN_CZ1-56 <>	2674.9	14.7	2691.3	12.5	2703.6	18.9	2703.6	18.9	98.9
ACHAPMAN_CZ1-71 <>	2617.6	26.4	2666.7	15.5	2704.1	18.2	2704.1	18.2	96.8
ACHAPMAN_CZ1-65 <>	2715.3	15.9	2709.0	8.1	2704.4	7.7	2704.4	7.7	100.4
ACHAPMAN_CZ1-38 <>	2710.6	11.0	2707.1	20.6	2704.5	35.0	2704.5	35.0	100.2
ACHAPMAN_CZ1-104 <>	2670.0	20.9	2689.9	14.4	2704.9	19.7	2704.9	19.7	98.7
ACHAPMAN_CZ1-19 <>	2662.7	27.0	2686.8	74.1	2705.0	127.9	2705.0	127.9	98.4
ACHAPMAN_CZ1-20 <>	2657.8	19.6	2684.9	10.4	2705.5	10.6	2705.5	10.6	98.2
ACHAPMAN_CZ1-17 <>	2647.7	15.1	2681.6	15.3	2707.3	24.2	2707.3	24.2	97.8
ACHAPMAN_CZ1-46 <>	2669.7	17.9	2691.5	13.3	2707.9	18.9	2707.9	18.9	98.6
ACHAPMAN_CZ1-37 <>	2699.6	10.4	2705.5	7.6	2709.8	10.7	2709.8	10.7	99.6
ACHAPMAN_CZ1-28 <>	2662.3	62.9	2689.8	33.4	2710.5	33.8	2710.5	33.8	98.2
ACHAPMAN_CZ1-68 <>	2712.3	21.5	2712.2	15.1	2712.2	21.0	2712.2	21.0	100.0
ACHAPMAN_CZ1-6 <>	2663.0	13.2	2692.4	25.0	2714.5	42.5	2714.5	42.5	98.1
ACHAPMAN_CZ1-16 <>	2647.3	17.2	2685.7	16.4	2714.8	25.6	2714.8	25.6	97.5

Table 1. CZ-1 U-Pb Geochronological analysis (cont.).

ACHAPMAN_CZ1-22 <>	2598.4	10.6	2664.4	18.0	2714.8	30.4	2714.8	30.4	95.7
ACHAPMAN_CZ1-98 <>	2481.6	58.3	2613.2	27.2	2716.8	10.1	2716.8	10.1	91.3
ACHAPMAN_CZ1-100 <>	2714.6	23.5	2717.4	38.0	2719.5	63.9	2719.5	63.9	99.8
ACHAPMAN_CZ1-10 <>	2716.5	28.1	2718.3	30.4	2719.6	48.6	2719.6	48.6	99.9
ACHAPMAN_CZ1-93 <>	2703.8	30.3	2713.1	43.8	2720.1	73.0	2720.1	73.0	99.4
ACHAPMAN_CZ1-96 <>	2666.5	15.5	2698.2	9.5	2722.1	11.7	2722.1	11.7	98.0
ACHAPMAN_CZ1-99 <>	2618.5	25.9	2677.5	20.6	2722.4	30.2	2722.4	30.2	96.2
ACHAPMAN_CZ1-92 <>	2684.7	10.1	2706.5	7.6	2722.8	10.9	2722.8	10.9	98.6
ACHAPMAN_CZ1-55 <>	2754.4	10.8	2736.2	14.4	2722.9	23.8	2722.9	23.8	101.2
ACHAPMAN_CZ1-60 <>	2724.0	15.8	2723.8	21.0	2723.7	34.6	2723.7	34.6	100.0
ACHAPMAN_CZ1-84 <>	2718.0	14.9	2723.1	18.2	2726.9	29.7	2726.9	29.7	99.7
ACHAPMAN_CZ1-48 <>	2708.8	17.3	2720.5	12.2	2729.1	17.0	2729.1	17.0	99.3
ACHAPMAN_CZ1-76 <>	2698.0	18.2	2716.0	21.8	2729.4	35.4	2729.4	35.4	98.8
ACHAPMAN_CZ1-97 <>	2697.8	15.1	2716.1	20.8	2729.8	34.4	2729.8	34.4	98.8
ACHAPMAN_CZ1-88 <>	2706.4	18.1	2721.1	14.8	2731.9	21.9	2731.9	21.9	99.1
ACHAPMAN_CZ1-102 <>	2671.3	11.8	2706.0	20.4	2732.1	34.5	2732.1	34.5	97.8
ACHAPMAN_CZ1-26 <>	2694.3	15.6	2716.4	17.6	2732.9	28.2	2732.9	28.2	98.6
ACHAPMAN_CZ1-70 <>	2685.2	22.5	2714.5	19.1	2736.5	28.6	2736.5	28.6	98.1
ACHAPMAN_CZ1-25 <>	2729.2	17.2	2735.4	11.2	2740.0	14.6	2740.0	14.6	99.6
ACHAPMAN_CZ1-58 <>	2662.0	28.4	2708.5	43.0	2743.4	71.7	2743.4	71.7	97.0
ACHAPMAN_CZ1-32 <>	2743.3	19.2	2745.5	51.7	2747.2	88.5	2747.2	88.5	99.9
ACHAPMAN_CZ1-14 <>	2665.7	12.5	2720.6	8.7	2761.5	11.8	2761.5	11.8	96.5
ACHAPMAN_CZ1-94 <>	2740.0	14.1	2753.0	19.0	2762.6	31.2	2762.6	31.2	99.2
ACHAPMAN_CZ1-91 <>	2718.3	25.2	2750.6	34.2	2774.4	56.2	2774.4	56.2	98.0
ACHAPMAN_CZ1-85 <>	2706.6	12.8	2746.8	18.8	2776.5	31.2	2776.5	31.2	97.5
ACHAPMAN_CZ1-75 <>	2774.7	19.2	2776.9	28.8	2778.4	47.8	2778.4	47.8	99.9
ACHAPMAN_CZ1-62 <>	2768.1	18.8	2775.3	20.0	2780.6	31.7	2780.6	31.7	99.5
ACHAPMAN_CZ1-7 <>	2757.1	37.8	2778.7	32.9	2794.4	49.4	2794.4	49.4	98.7
ACHAPMAN_CZ1-49 <>	2774.6	11.9	2793.8	14.3	2807.8	23.0	2807.8	23.0	98.8
ACHAPMAN_CZ1-43 <>	2808.6	12.9	2808.4	17.6	2808.2	28.7	2808.2	28.7	100.0
ACHAPMAN_CZ1-87 <>	2818.6	29.1	2825.3	19.9	2830.0	26.9	2830.0	26.9	99.6
ACHAPMAN_CZ1-83 <>	2833.4	17.6	2831.8	18.1	2830.6	28.3	2830.6	28.3	100.1
ACHAPMAN_CZ1-27 <>	2797.5	14.1	2821.4	9.1	2838.4	11.8	2838.4	11.8	98.6
ACHAPMAN_CZ1-86 <>	2799.3	17.4	2841.9	8.2	2872.2	6.6	2872.2	6.6	97.5

Table 2. CZ-2 U-Pb Geochronological analysis.

ACHAPMAN_CZ2-48 <>	1006.3	9.0	995.5	26.1	971.8	81.4	971.8	81.4	103.5
ACHAPMAN_CZ2-35 <>	998.5	7.3	990.6	15.1	973.3	45.7	973.3	45.7	102.6
ACHAPMAN_CZ2-13 <>	1014.8	9.5	1015.3	14.3	1016.2	40.0	1016.2	40.0	99.9
ACHAPMAN_CZ2-5 <>	1021.7	11.1	1021.0	14.8	1019.7	40.1	1019.7	40.1	100.2
ACHAPMAN_CZ2-74 <>	1020.0	6.8	1020.6	6.9	1021.9	16.0	1021.9	16.0	99.8
ACHAPMAN_CZ2-76 <>	1015.7	7.5	1017.8	12.8	1022.4	37.1	1022.4	37.1	99.3
ACHAPMAN_CZ2-18 <>	1025.2	6.0	1026.8	18.4	1030.4	56.2	1030.4	56.2	99.5
ACHAPMAN_CZ2-73 <>	1068.4	7.6	1058.8	8.9	1038.9	22.3	1038.9	22.3	102.8
ACHAPMAN_CZ2-7 <>	1022.2	6.1	1027.7	7.1	1039.2	18.1	1039.2	18.1	98.4
ACHAPMAN_CZ2-16 <>	1026.4	5.6	1030.9	5.9	1040.5	13.8	1040.5	13.8	98.7
ACHAPMAN_CZ2-17 <>	1022.8	7.4	1030.1	13.8	1045.5	40.1	1045.5	40.1	97.8
ACHAPMAN_CZ2-36 <>	1037.1	7.5	1042.0	21.2	1052.1	63.8	1052.1	63.8	98.6
ACHAPMAN_CZ2-38 <>	1057.8	13.1	1062.5	9.8	1072.2	13.1	1072.2	13.1	98.7
ACHAPMAN_CZ2-77 <>	1073.6	5.2	1074.6	6.2	1076.8	15.4	1076.8	15.4	99.7
ACHAPMAN_CZ2-62 <>	1158.0	9.5	1155.5	9.3	1150.7	20.1	1150.7	20.1	100.6
ACHAPMAN_CZ2-40 <>	1146.8	4.2	1149.1	3.0	1153.4	3.8	1153.4	3.8	99.4
ACHAPMAN_CZ2-60 <>	1162.4	6.9	1162.1	8.4	1161.5	20.3	1161.5	20.3	100.1
ACHAPMAN_CZ2-103 <>	1090.4	11.9	1115.8	32.6	1165.5	92.6	1165.5	92.6	93.6
ACHAPMAN_CZ2-72 <>	1142.9	6.1	1150.9	10.0	1165.9	26.3	1165.9	26.3	98.0
ACHAPMAN_CZ2-101 <>	1167.3	9.9	1176.0	11.1	1192.1	25.5	1192.1	25.5	97.9
ACHAPMAN_CZ2-50 <>	1236.4	13.9	1230.8	13.1	1221.1	26.7	1221.1	26.7	101.3
ACHAPMAN_CZ2-28 <>	1249.7	15.8	1246.7	24.8	1241.4	62.1	1241.4	62.1	100.7
ACHAPMAN_CZ2-22 <>	1253.3	7.1	1257.6	9.6	1265.1	23.0	1265.1	23.0	99.1
ACHAPMAN_CZ2-20 <>	1178.7	85.3	1209.8	58.9	1265.9	49.8	1265.9	49.8	93.1
ACHAPMAN_CZ2-30 <>	1257.2	3.9	1265.0	5.0	1278.4	11.7	1278.4	11.7	98.3
ACHAPMAN_CZ2-55 <>	1252.1	7.5	1261.9	11.2	1278.6	27.4	1278.6	27.4	97.9
ACHAPMAN_CZ2-87 <>	1260.1	16.2	1268.0	12.9	1281.3	21.1	1281.3	21.1	98.3
ACHAPMAN_CZ2-1 <>	1250.9	12.4	1266.2	14.9	1292.2	34.1	1292.2	34.1	96.8
ACHAPMAN_CZ2-105 <>	1247.0	8.3	1264.4	19.9	1294.0	51.5	1294.0	51.5	96.4
ACHAPMAN_CZ2-9 <>	1290.8	6.8	1300.6	8.4	1316.7	19.1	1316.7	19.1	98.0
ACHAPMAN_CZ2-15 <>	1322.8	28.4	1322.4	25.4	1321.8	48.2	1321.8	48.2	100.1
ACHAPMAN_CZ2-51 <>	1335.1	6.8	1346.8	9.0	1365.4	20.5	1365.4	20.5	97.8
ACHAPMAN_CZ2-67 <>	1372.4	8.0	1377.2	8.3	1384.5	17.1	1384.5	17.1	99.1
ACHAPMAN_CZ2-92 <>	1341.1	15.6	1358.8	18.4	1386.8	40.2	1386.8	40.2	96.7
ACHAPMAN_CZ2-26 <>	1373.8	12.4	1379.8	9.8	1389.1	16.0	1389.1	16.0	98.9
ACHAPMAN_CZ2-29 <>	1363.4	6.6	1375.6	5.9	1394.6	11.0	1394.6	11.0	97.8
ACHAPMAN_CZ2-97 <>	1364.3	13.9	1378.9	9.7	1401.6	11.5	1401.6	11.5	97.3
ACHAPMAN_CZ2-59 <>	1391.5	10.6	1395.8	9.7	1402.3	18.5	1402.3	18.5	99.2
ACHAPMAN_CZ2-34 <>	1398.5	13.6	1400.5	9.9	1403.5	13.9	1403.5	13.9	99.6
ACHAPMAN_CZ2-78 <>	1402.1	6.5	1404.9	7.8	1409.1	16.8	1409.1	16.8	99.5

Table 2. CZ-2 U-Pb Geochronological analysis (cont.).

ACHAPMAN_CZ2-52 <>	1372.4	10.3	1390.0	8.0	1417.1	12.3	1417.1	12.3	96.8
ACHAPMAN_CZ2-53 <>	1410.6	4.4	1420.0	5.1	1434.2	10.8	1434.2	10.8	98.4
ACHAPMAN_CZ2-24 <>	1398.5	13.3	1414.0	8.7	1437.4	8.1	1437.4	8.1	97.3
ACHAPMAN_CZ2-14 <>	1441.3	22.0	1439.9	24.3	1437.8	50.8	1437.8	50.8	100.2
ACHAPMAN_CZ2-32 <>	1456.5	8.6	1449.6	8.8	1439.4	17.9	1439.4	17.9	101.2
ACHAPMAN_CZ2-45 <>	1462.6	11.0	1456.8	8.6	1448.3	13.8	1448.3	13.8	101.0
ACHAPMAN_CZ2-46 <>	1385.4	17.7	1410.9	11.9	1449.7	12.1	1449.7	12.1	95.6
ACHAPMAN_CZ2-11 <>	1436.1	8.2	1441.7	6.4	1450.0	10.1	1450.0	10.1	99.0
ACHAPMAN_CZ2-25 <>	1396.3	13.9	1418.2	9.2	1451.2	9.1	1451.2	9.1	96.2
ACHAPMAN_CZ2-102 <>	1509.6	8.7	1509.0	17.4	1508.1	39.9	1508.1	39.9	100.1
ACHAPMAN_CZ2-83 <>	1393.9	14.9	1444.9	14.6	1520.9	27.8	1520.9	27.8	91.7
ACHAPMAN_CZ2-33 <>	1559.7	22.8	1584.0	16.7	1616.6	23.9	1616.6	23.9	96.5
ACHAPMAN_CZ2-31 <>	1644.2	14.5	1647.0	10.3	1650.7	14.4	1650.7	14.4	99.6
ACHAPMAN_CZ2-61 <>	1678.8	8.3	1681.5	6.8	1684.7	11.1	1684.7	11.1	99.7
ACHAPMAN_CZ2-21 <>	2347.1	17.8	2439.0	8.6	2516.5	3.9	2516.5	3.9	93.3
ACHAPMAN_CZ2-44 <>	2584.5	17.5	2600.7	8.4	2613.4	5.9	2613.4	5.9	98.9
ACHAPMAN_CZ2-100 <>	2605.2	19.6	2610.7	9.8	2615.0	8.2	2615.0	8.2	99.6
ACHAPMAN_CZ2-86 <>	2601.7	18.1	2618.7	12.4	2631.8	16.8	2631.8	16.8	98.9
ACHAPMAN_CZ2-71 <>	2647.3	36.9	2642.1	16.7	2638.1	8.3	2638.1	8.3	100.3
ACHAPMAN_CZ2-4 <>	2651.4	15.3	2645.9	7.7	2641.6	6.9	2641.6	6.9	100.4
ACHAPMAN_CZ2-6 <>	2611.5	14.9	2633.2	6.8	2650.0	3.3	2650.0	3.3	98.5
ACHAPMAN_CZ2-98 <>	2627.4	8.3	2645.5	3.8	2659.3	2.2	2659.3	2.2	98.8
ACHAPMAN_CZ2-75 <>	2682.3	6.8	2676.4	3.5	2672.0	3.4	2672.0	3.4	100.4
ACHAPMAN_CZ2-2 <>	2638.7	12.4	2659.1	5.6	2674.7	2.5	2674.7	2.5	98.7
ACHAPMAN_CZ2-54 <>	2683.2	9.6	2679.7	4.6	2677.0	3.5	2677.0	3.5	100.2
ACHAPMAN_CZ2-3 <>	2678.5	7.5	2677.8	3.6	2677.2	2.6	2677.2	2.6	100.0
ACHAPMAN_CZ2-88 <>	2673.7	23.7	2676.2	22.4	2678.1	35.1	2678.1	35.1	99.8
ACHAPMAN_CZ2-89 <>	2681.9	10.1	2680.6	4.9	2679.7	3.8	2679.7	3.8	100.1
ACHAPMAN_CZ2-96 <>	2686.7	14.4	2682.9	7.5	2680.0	7.4	2680.0	7.4	100.3
ACHAPMAN_CZ2-80 <>	2679.3	11.6	2681.1	5.7	2682.4	4.9	2682.4	4.9	99.9
ACHAPMAN_CZ2-90 <>	2721.8	16.8	2703.0	10.0	2688.9	12.3	2688.9	12.3	101.2
ACHAPMAN_CZ2-56 <>	2662.9	25.3	2679.1	11.4	2691.3	5.5	2691.3	5.5	98.9
ACHAPMAN_CZ2-65 <>	2710.4	13.6	2699.7	6.0	2691.6	2.8	2691.6	2.8	100.7
ACHAPMAN_CZ2-8 <>	2680.2	22.2	2689.0	10.4	2695.6	7.2	2695.6	7.2	99.4
ACHAPMAN_CZ2-66 <>	2704.9	16.2	2699.6	9.2	2695.7	10.7	2695.7	10.7	100.3
ACHAPMAN_CZ2-10 <>	2821.6	57.3	2749.6	24.1	2697.1	6.9	2697.1	6.9	104.6
ACHAPMAN_CZ2-27 <>	2678.7	21.0	2689.5	10.1	2697.6	7.9	2697.6	7.9	99.3
ACHAPMAN_CZ2-43 <>	2699.1	18.0	2698.4	11.8	2697.9	15.6	2697.9	15.6	100.0
ACHAPMAN_CZ2-70 <>	2703.9	10.7	2700.9	5.5	2698.7	5.5	2698.7	5.5	100.2
ACHAPMAN_CZ2-47 <>	2692.6	15.1	2696.2	7.0	2699.0	4.7	2699.0	4.7	99.8
ACHAPMAN_CZ2-99 <>	2734.6	17.2	2714.4	8.8	2699.4	8.7	2699.4	8.7	101.3
ACHAPMAN_CZ2-104 <>	2675.4	13.3	2689.3	6.8	2699.7	6.5	2699.7	6.5	99.1
ACHAPMAN_CZ2-19 <>	2712.0	21.3	2705.1	10.6	2699.9	9.4	2699.9	9.4	100.4
ACHAPMAN_CZ2-63 <>	2743.9	19.0	2718.7	9.2	2700.0	7.7	2700.0	7.7	101.6
ACHAPMAN_CZ2-23 <>	2668.6	9.5	2686.6	5.8	2700.1	7.0	2700.1	7.0	98.8
ACHAPMAN_CZ2-42 <>	2689.9	15.8	2695.8	7.2	2700.2	4.2	2700.2	4.2	99.6
ACHAPMAN_CZ2-79 <>	2752.2	24.9	2723.1	11.9	2701.6	9.7	2701.6	9.7	101.9
ACHAPMAN_CZ2-41 <>	2726.8	17.5	2714.6	7.7	2705.5	3.8	2705.5	3.8	100.8
ACHAPMAN_CZ2-58 <>	2739.7	24.4	2721.5	14.1	2708.0	16.6	2708.0	16.6	101.2
ACHAPMAN_CZ2-49 <>	2688.3	8.5	2699.7	4.5	2708.3	4.6	2708.3	4.6	99.3
ACHAPMAN_CZ2-93 <>	2690.1	15.5	2701.0	8.9	2709.1	10.4	2709.1	10.4	99.3
ACHAPMAN_CZ2-64 <>	2697.4	13.5	2704.4	7.7	2709.5	8.9	2709.5	8.9	99.6
ACHAPMAN_CZ2-69 <>	2702.0	19.6	2707.0	9.2	2710.7	6.8	2710.7	6.8	99.7
ACHAPMAN_CZ2-81 <>	2679.7	14.0	2697.6	8.0	2711.0	9.2	2711.0	9.2	98.8
ACHAPMAN_CZ2-91 <>	2721.1	21.7	2716.7	12.3	2713.5	14.2	2713.5	14.2	100.3
ACHAPMAN_CZ2-84 <>	2744.0	15.0	2729.1	14.3	2718.1	22.2	2718.1	22.2	101.0
ACHAPMAN_CZ2-12 <>	2756.5	44.7	2734.9	20.0	2719.0	11.8	2719.0	11.8	101.4
ACHAPMAN_CZ2-37 <>	2737.0	17.0	2730.8	9.2	2726.2	9.9	2726.2	9.9	100.4
ACHAPMAN_CZ2-68 <>	2743.9	20.0	2734.9	12.1	2728.3	14.9	2728.3	14.9	100.6
ACHAPMAN_CZ2-81 <>	2709.1	17.1	2720.8	7.9	2729.5	5.3	2729.5	5.3	99.3
ACHAPMAN_CZ2-57 <>	2743.8	26.7	2736.1	13.6	2730.4	13.2	2730.4	13.2	100.5
ACHAPMAN_CZ2-85 <>	2671.1	15.6	2707.2	13.4	2734.2	20.1	2734.2	20.1	97.7
ACHAPMAN_CZ2-39 <>	2727.5	21.6	2733.0	13.3	2737.1	16.6	2737.1	16.6	99.6
ACHAPMAN_CZ2-R33 <>	426.1	5.7	379.8	37.4	106.5	277.7	426.1	5.7	399.9
ACHAPMAN_CZ2-R33 <>	427.4	5.2	426.9	18.5	423.8	115.0	427.4	5.2	100.9
ACHAPMAN_CZ2-R33 <>	426.0	9.2	445.2	29.8	545.7	174.5	426.0	9.2	78.1
ACHAPMAN_CZ1-R33 <>	419.7	10.9	441.9	55.2	559.4	332.4	419.7	10.9	75.0
ACHAPMAN_CZ2-R33 <>	414.0	14.4	482.0	60.1	819.8	319.4	414.0	14.4	50.5
ACHAPMAN_CZ2-R33 <>	426.7	1.6	430.6	10.2	451.7	63.8	426.7	1.6	94.5
ACHAPMAN_CZ1-R33 <>	423.4	8.3	377.8	92.4	106.6	701.5	423.4	8.3	397.2
ACHAPMAN_CZ1-R33 <>	439.7	5.9	442.5	75.3	457.0	468.1	439.7	5.9	96.2
ACHAPMAN_CZ1-R33 <>	414.4	8.7	375.5	168.2	141.8	1335.2	414.4	8.7	292.3
ACHAPMAN_CZ1-R33 <>	420.3	6.5	409.5	70.9	349.3	478.4	420.3	6.5	120.3

Table 3. CZ-5 U-Pb Geochronological analysis.

Table _____. U-Pb geochronologic analyses.									
			Apparent ages (Ma)						
Analysis	206Pb* 238U*	± (Ma)	207Pb* 235U	± (Ma)	206Pb* 207Pb*	± (Ma)	Best age (Ma)	± (Ma)	Conc (%)
ACHAPMAN-CZ5-76 <>	88.6	6.8	247.2	154.2	2282.0	1414.7	88.6	6.8	NA
ACHAPMAN-CZ5-93 <>	372.7	7.4	377.2	38.3	404.7	268.8	372.7	7.4	NA
ACHAPMAN-CZ5-56 <>	413.2	11.5	353.5	170.4	-22.2	1479.7	413.2	11.5	NA
ACHAPMAN-CZ5-1 <>	423.5	5.0	403.3	37.5	289.2	256.8	423.5	5.0	146.5
ACHAPMAN-CZ5-59 <>	433.5	3.3	378.9	120.3	57.0	932.1	433.5	3.3	759.9
ACHAPMAN-CZ5-50 <>	449.3	5.3	441.9	29.2	403.6	180.3	449.3	5.3	111.3
ACHAPMAN-CZ5-75 <>	452.5	9.8	441.5	21.5	384.4	125.3	452.5	9.8	117.7
ACHAPMAN-CZ5-55 <>	453.7	3.6	463.4	30.7	511.3	180.9	453.7	3.6	88.7
ACHAPMAN-CZ5-77 <>	496.7	19.1	499.4	105.0	511.7	585.3	496.7	19.1	97.1
ACHAPMAN-CZ5-92 <>	935.8	5.2	938.5	6.5	944.8	18.1	944.8	18.1	99.1
ACHAPMAN-CZ5-6 <>	989.8	8.0	979.8	32.9	957.5	105.6	957.5	105.6	103.4
ACHAPMAN-CZ5-99 <>	982.0	9.4	981.4	23.3	980.1	72.7	980.1	72.7	100.2
ACHAPMAN-CZ5-19 <>	1001.8	13.8	995.7	27.3	982.3	82.4	982.3	82.4	102.0
ACHAPMAN-CZ5-9 <>	1032.5	5.3	1019.1	11.8	990.4	35.6	990.4	35.6	104.3
ACHAPMAN-CZ5-8 <>	1044.0	9.5	1029.4	21.3	998.5	63.7	998.5	63.7	104.6
ACHAPMAN-CZ5-68 <>	1033.5	14.8	1022.6	22.8	999.2	64.7	999.2	64.7	103.4
ACHAPMAN-CZ5-34 <>	1017.9	9.9	1012.1	50.4	999.5	158.3	999.5	158.3	101.8
ACHAPMAN-CZ5-17 <>	1038.0	4.8	1026.8	22.0	1002.9	68.5	1002.9	68.5	103.5
ACHAPMAN-CZ5-15 <>	1052.2	5.2	1044.7	22.1	1029.0	67.7	1029.0	67.7	102.3
ACHAPMAN-CZ5-94 <>	1016.9	6.9	1021.2	22.9	1030.5	70.3	1030.5	70.3	98.7
ACHAPMAN-CZ5-49 <>	1039.6	6.6	1036.9	19.7	1031.2	59.6	1031.2	59.6	100.8
ACHAPMAN-CZ5-25 <>	1060.1	4.5	1050.7	7.1	1031.2	20.0	1031.2	20.0	102.8
ACHAPMAN-CZ5-18 <>	933.0	48.8	967.4	40.9	1046.7	67.9	1046.7	67.9	89.1
ACHAPMAN-CZ5-58 <>	1042.4	3.7	1044.2	45.2	1048.1	139.6	1048.1	139.6	99.5
ACHAPMAN-CZ5-84 <>	1015.7	8.7	1026.1	48.6	1048.4	150.7	1048.4	150.7	96.9
ACHAPMAN-CZ5-54 <>	1075.9	6.5	1067.5	34.3	1050.3	103.9	1050.3	103.9	102.4
ACHAPMAN-CZ5-28 <>	1009.9	9.5	1024.0	45.1	1054.5	139.4	1054.5	139.4	95.8
ACHAPMAN-CZ5-40 <>	1066.8	6.4	1063.0	21.3	1055.2	63.9	1055.2	63.9	101.1
ACHAPMAN-CZ5-97 <>	1036.2	9.6	1043.3	17.8	1058.1	51.3	1058.1	51.3	97.9
ACHAPMAN-CZ5-30 <>	1088.4	16.2	1078.8	57.2	1059.4	170.3	1059.4	170.3	102.7
ACHAPMAN-CZ5-32 <>	1067.0	10.2	1066.5	47.7	1065.7	143.8	1065.7	143.8	100.1
ACHAPMAN-CZ5-89 <>	1062.9	6.1	1065.7	15.9	1071.4	46.8	1071.4	46.8	99.2
ACHAPMAN-CZ5-90 <>	1057.8	4.7	1065.6	11.8	1081.6	34.6	1081.6	34.6	97.8
ACHAPMAN-CZ5-42 <>	1084.8	4.9	1084.8	12.5	1084.8	36.3	1084.8	36.3	100.0
ACHAPMAN-CZ5-87 <>	1056.7	4.8	1067.8	7.3	1090.6	19.8	1090.6	19.8	96.9
ACHAPMAN-CZ5-85 <>	1077.5	6.2	1083.4	13.4	1095.1	38.1	1095.1	38.1	98.4
ACHAPMAN-CZ5-60 <>	1114.2	5.4	1108.6	27.2	1097.8	80.1	1097.8	80.1	101.5
ACHAPMAN-CZ5-100 <>	1145.3	44.9	1132.1	36.5	1106.8	64.0	1106.8	64.0	103.5
ACHAPMAN-CZ5-38 <>	1125.0	38.1	1122.6	40.5	1117.9	93.3	1117.9	93.3	100.6
ACHAPMAN-CZ5-24 <>	1151.1	11.1	1139.8	13.1	1118.5	31.8	1118.5	31.8	102.9
ACHAPMAN-CZ5-12 <>	1160.8	10.4	1147.8	22.5	1123.2	62.1	1123.2	62.1	103.3
ACHAPMAN-CZ5-39 <>	1107.1	13.2	1114.4	62.7	1128.8	183.0	1128.8	183.0	98.1
ACHAPMAN-CZ5-45 <>	1169.0	15.0	1155.2	44.8	1129.5	126.4	1129.5	126.4	103.5
ACHAPMAN-CZ5-64 <>	1050.8	4.0	1077.0	30.9	1130.6	92.5	1130.6	92.5	92.9
ACHAPMAN-CZ5-36 <>	1145.8	9.2	1141.3	9.1	1132.6	19.8	1132.6	19.8	101.2
ACHAPMAN-CZ5-88 <>	1098.3	29.2	1111.3	27.6	1136.8	57.5	1136.8	57.5	96.6
ACHAPMAN-CZ5-69 <>	1143.4	16.9	1150.8	18.3	1164.6	41.7	1164.6	41.7	98.2
ACHAPMAN-CZ5-66 <>	1167.7	7.2	1167.0	8.7	1165.8	20.9	1165.8	20.9	100.2
ACHAPMAN-CZ5-70 <>	1162.6	32.9	1165.3	22.0	1170.3	13.8	1170.3	13.8	99.3
ACHAPMAN-CZ5-20 <>	1190.5	7.1	1183.6	25.0	1171.1	69.6	1171.1	69.6	101.7
ACHAPMAN-CZ5-71 <>	1188.2	5.7	1183.1	8.6	1173.9	22.1	1173.9	22.1	101.2
ACHAPMAN-CZ5-46 <>	1219.4	6.0	1206.0	15.4	1182.0	41.8	1182.0	41.8	103.2
ACHAPMAN-CZ5-48 <>	1197.8	5.5	1196.9	21.4	1195.3	59.1	1195.3	59.1	100.2
ACHAPMAN-CZ5-72 <>	1194.2	23.7	1199.6	21.9	1209.5	43.8	1209.5	43.8	98.7
ACHAPMAN-CZ5-98 <>	1229.0	4.2	1228.1	4.2	1226.4	8.9	1226.4	8.9	100.2
ACHAPMAN-CZ5-22 <>	1268.3	5.4	1255.4	18.9	1233.3	50.5	1233.3	50.5	102.8
ACHAPMAN-CZ5-82 <>	1247.6	6.1	1251.7	7.7	1258.7	18.0	1258.7	18.0	99.1
ACHAPMAN-CZ5-35 <>	1282.5	7.0	1276.1	10.9	1265.2	27.0	1265.2	27.0	101.4
ACHAPMAN-CZ5-53 <>	1270.8	12.0	1281.7	33.7	1299.9	87.8	1299.9	87.8	97.8
ACHAPMAN-CZ5-67 <>	1499.1	7.7	1495.7	6.7	1490.9	12.1	1490.9	12.1	100.5
ACHAPMAN-CZ5-37 <>	1446.4	23.3	1467.8	18.1	1498.8	28.1	1498.8	28.1	96.5
ACHAPMAN-CZ5-83 <>	1540.2	6.2	1549.6	6.0	1562.4	11.4	1562.4	11.4	98.6
ACHAPMAN-CZ5-51 <>	1668.6	12.0	1636.5	33.5	1595.5	75.5	1595.5	75.5	104.6
ACHAPMAN-CZ5-86 <>	1685.3	12.6	1677.2	12.3	1667.1	22.9	1667.1	22.9	101.1
ACHAPMAN-CZ5-16 <>	1731.5	7.7	1716.3	11.5	1697.8	23.7	1697.8	23.7	102.0
ACHAPMAN-CZ5-61 <>	1752.2	7.6	1751.3	12.5	1750.2	25.9	1750.2	25.9	100.1
ACHAPMAN-CZ5-4 <>	1854.6	9.0	1833.5	6.2	1809.6	8.5	1809.6	8.5	102.5
ACHAPMAN-CZ5-23 <>	1921.2	12.9	1895.0	8.5	1866.5	11.1	1866.5	11.1	102.9
ACHAPMAN-CZ5-78 <>	1696.5	73.6	1797.7	46.0	1917.1	41.7	1917.1	41.7	88.5

Table 3. CZ-5 U-Pb Geochronological analysis (cont.).

ACHAPMAN-CZ5-31 <>	2782.3	47.9	2728.0	69.6	2688.0	116.4	2688.0	116.4	103.5
ACHAPMAN-CZ5-10 <>	2768.5	20.1	2745.6	11.7	2728.8	14.0	2728.8	14.0	101.5
ACHAPMAN-CZ5-R33 <>	435.0	11.3	470.2	71.3	646.2	405.2	435.0	11.3	67.3
ACHAPMAN-CZ5-R33 <>	422.9	1.9	424.6	18.3	434.3	116.8	422.9	1.9	97.4
ACHAPMAN-CZ5-R33 <>	420.1	5.9	419.5	41.1	416.5	266.1	420.1	5.9	100.9
ACHAPMAN-CZ5-R33 <>	427.2	11.6	442.1	55.0	520.4	332.5	427.2	11.6	82.1
ACHAPMAN-CZ5-R33 <>	420.6	7.5	441.8	39.5	553.7	237.8	420.6	7.5	76.0

Table 4. CZ-6 U-Pb Geochronological analysis.

Table _____. U-Pb geochronologic analyses.									
			Apparent ages (Ma)						
Analysis	206Pb*	±	207Pb*	±	206Pb*	±	Best age	±	Conc
	238U*	(Ma)	235U	(Ma)	207Pb*	(Ma)	(Ma)	(Ma)	(%)
ACHAPMAN_CZ6-8 <>	274.8	6.6	289.5	21.8	410.5	186.4	274.8	6.6	NA
ACHAPMAN_CZ6-78 <>	306.8	4.0	306.3	12.8	302.5	105.8	306.8	4.0	NA
ACHAPMAN_CZ6-51 <>	307.2	3.2	302.9	13.9	269.8	119.5	307.2	3.2	NA
ACHAPMAN_CZ6-45 <>	307.5	6.9	309.7	18.2	326.0	145.5	307.5	6.9	NA
ACHAPMAN_CZ6-71 <>	312.5	17.2	261.2	65.7	-177.1	708.4	312.5	17.2	NA
ACHAPMAN_CZ6-33 <>	313.1	1.6	312.1	15.0	304.8	126.7	313.1	1.6	NA
ACHAPMAN_CZ6-94 <>	313.3	4.3	302.9	14.7	223.8	125.4	313.3	4.3	NA
ACHAPMAN_CZ6-4 <>	314.5	12.7	328.9	15.2	432.4	77.6	314.5	12.7	NA
ACHAPMAN_CZ6-40 <>	315.8	4.2	304.3	19.8	217.7	171.4	315.8	4.2	NA
ACHAPMAN_CZ6-29 <>	316.4	7.0	328.6	18.6	416.0	139.0	316.4	7.0	NA
ACHAPMAN_CZ6-22 <>	317.4	3.5	311.6	15.7	268.5	131.9	317.4	3.5	NA
ACHAPMAN_CZ6-24 <>	318.2	5.1	325.5	17.9	378.5	140.1	318.2	5.1	NA
ACHAPMAN_CZ6-54 <>	318.4	8.3	322.9	13.9	355.1	96.3	318.4	8.3	NA
ACHAPMAN_CZ6-1 <>	318.7	6.2	315.9	23.5	295.7	192.6	318.7	6.2	NA
ACHAPMAN_CZ6-20 <>	318.9	4.3	320.8	11.6	334.9	90.4	318.9	4.3	NA
ACHAPMAN_CZ6-57 <>	319.5	4.6	309.9	12.1	238.8	98.6	319.5	4.6	NA
ACHAPMAN_CZ6-26 <>	320.3	5.5	320.0	26.6	318.0	217.0	320.3	5.5	NA
ACHAPMAN_CZ6-2 <>	322.2	4.7	365.7	48.5	651.8	339.2	322.2	4.7	NA
ACHAPMAN_CZ6-55 <>	327.3	5.9	336.6	12.4	401.3	87.8	327.3	5.9	NA
ACHAPMAN_CZ6-9 <>	327.5	7.5	326.4	15.8	318.4	116.9	327.5	7.5	NA
ACHAPMAN_CZ6-97 <>	426.8	12.6	429.9	12.0	446.7	34.3	426.8	12.6	95.5
ACHAPMAN_CZ6-76 <>	428.1	3.9	429.8	25.8	439.2	162.9	428.1	3.9	97.5
ACHAPMAN_CZ6-32 <>	429.3	7.5	421.9	18.4	381.9	112.8	429.3	7.5	112.4
ACHAPMAN_CZ6-56 <>	439.2	6.1	447.0	15.0	487.0	86.1	439.2	6.1	90.2
ACHAPMAN_CZ6-66 <>	442.8	5.7	443.1	27.3	444.8	166.7	442.8	5.7	99.5
ACHAPMAN_CZ6-84 <>	456.0	3.3	460.3	8.7	482.2	49.0	456.0	3.3	94.6
ACHAPMAN_CZ6-80 <>	470.6	6.4	466.6	14.4	446.7	79.9	470.6	6.4	105.4
ACHAPMAN_CZ6-60 <>	936.1	7.9	947.7	8.6	974.7	21.6	974.7	21.6	96.0
ACHAPMAN_CZ6-81 <>	996.0	12.3	990.6	19.2	978.7	55.3	978.7	55.3	101.8
ACHAPMAN_CZ6-53 <>	820.2	68.6	869.7	52.2	997.7	12.9	997.7	12.9	82.2
ACHAPMAN_CZ6-104 <>	1054.3	8.2	1044.2	13.6	1023.2	38.7	1023.2	38.7	103.0
ACHAPMAN_CZ6-44 <>	964.6	11.1	984.0	9.0	1027.7	14.6	1027.7	14.6	93.9
ACHAPMAN_CZ6-65 <>	1050.1	6.1	1047.4	12.1	1041.8	35.3	1041.8	35.3	100.8
ACHAPMAN_CZ6-13 <>	1043.0	8.1	1044.3	8.6	1046.9	20.6	1046.9	20.6	99.6
ACHAPMAN_CZ6-83 <>	1058.9	12.1	1055.6	12.0	1048.8	27.1	1048.8	27.1	101.0
ACHAPMAN_CZ6-23 <>	1063.5	16.8	1060.6	26.7	1054.6	74.0	1054.6	74.0	100.8
ACHAPMAN_CZ6-88 <>	1051.5	8.8	1055.2	12.7	1063.1	34.3	1063.1	34.3	98.9
ACHAPMAN_CZ6-34 <>	1076.8	18.2	1072.5	42.6	1063.9	124.0	1063.9	124.0	101.2
ACHAPMAN_CZ6-93 <>	1068.6	7.7	1068.4	14.6	1068.0	41.7	1068.0	41.7	100.1
ACHAPMAN_CZ6-39 <>	1047.2	58.1	1054.7	39.9	1070.2	17.7	1070.2	17.7	97.8
ACHAPMAN_CZ6-27 <>	1035.8	7.9	1047.3	21.9	1071.5	65.2	1071.5	65.2	96.7
ACHAPMAN_CZ6-59 <>	1038.5	10.9	1049.7	17.5	1073.1	48.8	1073.1	48.8	96.8
ACHAPMAN_CZ6-87 <>	1071.2	6.7	1072.2	7.9	1074.3	19.6	1074.3	19.6	99.7
ACHAPMAN_CZ6-46 <>	1058.1	8.0	1063.5	11.9	1074.6	32.4	1074.6	32.4	98.5
ACHAPMAN_CZ6-72 <>	980.9	42.1	1011.4	64.6	1077.9	179.9	1077.9	179.9	91.0
ACHAPMAN_CZ6-74 <>	1070.7	26.9	1074.3	19.2	1081.6	19.5	1081.6	19.5	99.0
ACHAPMAN_CZ6-21 <>	1064.5	5.3	1077.1	14.6	1102.8	42.6	1102.8	42.6	96.5
ACHAPMAN_CZ6-31 <>	1110.6	10.0	1110.6	11.2	1110.4	26.8	1110.4	26.8	100.0
ACHAPMAN_CZ6-82 <>	1119.7	6.0	1118.6	9.8	1116.6	26.3	1116.6	26.3	100.3
ACHAPMAN_CZ6-86 <>	1083.3	12.8	1096.7	28.8	1123.3	81.8	1123.3	81.8	96.4
ACHAPMAN_CZ6-48 <>	1173.4	16.3	1156.3	11.1	1124.3	10.7	1124.3	10.7	104.4
ACHAPMAN_CZ6-38 <>	1066.7	8.8	1088.4	7.9	1132.0	15.4	1132.0	15.4	94.2
ACHAPMAN_CZ6-43 <>	1076.5	11.1	1095.9	16.3	1134.6	43.0	1134.6	43.0	94.9
ACHAPMAN_CZ6-99 <>	1178.6	8.6	1168.4	13.6	1149.5	35.6	1149.5	35.6	102.5
ACHAPMAN_CZ6-91 <>	1159.7	10.6	1161.9	14.7	1166.0	37.1	1166.0	37.1	99.5
ACHAPMAN_CZ6-47 <>	1106.0	9.6	1129.5	13.7	1175.1	35.0	1175.1	35.0	94.1
ACHAPMAN_CZ6-14 <>	961.4	82.9	1031.7	69.2	1183.8	104.0	1183.8	104.0	81.2
ACHAPMAN_CZ6-100 <>	1214.3	10.4	1213.1	18.9	1211.1	49.1	1211.1	49.1	100.3
ACHAPMAN_CZ6-36 <>	1184.7	12.3	1220.2	12.7	1283.5	27.0	1283.5	27.0	92.3
ACHAPMAN_CZ6-105 <>	1343.6	6.5	1329.2	9.9	1305.9	23.8	1305.9	23.8	102.9
ACHAPMAN_CZ6-75 <>	1284.6	16.3	1301.8	12.9	1330.2	20.7	1330.2	20.7	96.6
ACHAPMAN_CZ6-19 <>	1327.1	25.2	1333.3	18.9	1343.2	27.7	1343.2	27.7	98.8
ACHAPMAN_CZ6-49 <>	1334.7	9.9	1342.4	12.7	1354.7	28.8	1354.7	28.8	98.5
ACHAPMAN_CZ6-12 <>	1304.8	23.7	1334.4	16.1	1382.2	15.9	1382.2	15.9	94.4
ACHAPMAN_CZ6-3 <>	1429.6	42.8	1419.3	25.6	1403.8	5.4	1403.8	5.4	101.8
ACHAPMAN_CZ6-11-1 <>	1434.6	49.4	1445.4	63.0	1461.2	137.1	1461.2	137.1	98.2
ACHAPMAN_CZ6-67 <>	1363.2	17.4	1405.0	15.3	1468.9	27.0	1468.9	27.0	92.8
ACHAPMAN_CZ6-90 <>	1545.8	65.3	1565.6	40.5	1592.5	32.7	1592.5	32.7	97.1
ACHAPMAN_CZ6-10 <>	1608.2	8.9	1621.2	5.8	1638.0	6.5	1638.0	6.5	98.2

Table 4. CZ-6 U-Pb Geochronological analysis (cont.).

ACHAPMAN_CZ6-101 <>	1495.8	63.7	1557.2	39.3	1641.6	23.7	1641.6	23.7	91.1
ACHAPMAN_CZ6-17 <>	1592.5	15.2	1614.7	23.9	1643.8	51.2	1643.8	51.2	96.9
ACHAPMAN_CZ6-18 <>	1655.2	14.4	1659.1	12.7	1664.1	22.2	1664.1	22.2	99.5
ACHAPMAN_CZ6-5 <>	1704.1	23.5	1689.2	28.5	1670.6	57.0	1670.6	57.0	102.0
ACHAPMAN_CZ6-64 <>	1729.8	15.7	1732.4	9.5	1735.5	9.1	1735.5	9.1	99.7
ACHAPMAN_CZ6-62 <>	1667.9	16.9	1706.5	10.3	1754.3	8.9	1754.3	8.9	95.1
ACHAPMAN_CZ6-28 <>	1777.4	20.4	1767.2	11.5	1755.1	7.7	1755.1	7.7	101.3
ACHAPMAN_CZ6-102 <>	1808.8	11.5	1808.3	7.2	1807.7	8.3	1807.7	8.3	100.1
ACHAPMAN_CZ6-16 <>	1771.6	70.2	1789.8	38.3	1811.1	6.5	1811.1	6.5	97.8
ACHAPMAN_CZ6-52 <>	1917.1	42.8	1904.7	74.4	1891.2	148.7	1891.2	148.7	101.4
ACHAPMAN_CZ6-92 <>	1898.8	15.4	1895.5	10.0	1891.7	12.7	1891.7	12.7	100.4
ACHAPMAN_CZ6-29-1 <>	1552.3	97.9	1710.3	59.1	1909.6	13.6	1909.6	13.6	81.3
ACHAPMAN_CZ6-77 <>	2295.8	11.0	2307.3	5.7	2317.5	4.3	2317.5	4.3	99.1
ACHAPMAN_CZ6-25 <>	2595.3	15.1	2652.4	7.1	2696.2	4.2	2696.2	4.2	96.3
ACHAPMAN_CZ6-95 <>	2722.7	34.1	2722.8	17.6	2722.9	17.4	2722.9	17.4	100.0
ACHAPMAN_CZ6-7 <>	2639.1	20.7	2688.8	9.5	2726.3	5.3	2726.3	5.3	96.8
ACHAPMAN_CZ6-85 <>	2682.1	25.1	2711.1	11.2	2732.7	4.9	2732.7	4.9	98.1
ACHAPMAN_CZ6-58 <>	2848.7	39.0	2826.7	16.2	2811.1	2.6	2811.1	2.6	101.3
ACHAPMAN_CZ6-70 <>	2744.2	30.5	2818.9	16.8	2872.7	18.1	2872.7	18.1	95.5
ACHAPMAN_CZ6-69 <>	3347.9	83.0	3279.8	31.4	3238.4	8.1	3238.4	8.1	103.4
ACHAPMAN_CZ6-R33 <>	424.4	15.8	401.0	74.3	268.4	511.2	424.4	15.8	158.1
ACHAPMAN_CZ6-R33 <>	417.4	6.4	428.9	23.8	491.2	145.9	417.4	6.4	85.0
ACHAPMAN_CZ6-R33 <>	420.1	5.9	412.2	60.8	368.0	405.5	420.1	5.9	114.2
ACHAPMAN_CZ6-R33 <>	430.0	9.9	386.5	49.4	133.6	358.1	430.0	9.9	322.0
ACHAPMAN_CZ6-R33 <>	400.5	7.7	402.2	25.0	412.3	162.5	400.5	7.7	97.1

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