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Late Ordovician tectonism in the North American midcontinent: Constraints from U-Pb detrital zircon geochronology

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Department:

LATE ORDOVICIAN TECTONISM IN THE NORTH AMERICAN MIDCONTINENT: CONSTRAINTS FROM U-PB DETRITAL ZIRCON GEOCHRONOLOGY

by

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ABSTRACT

Numerous sandstone filled depressions hosted in upper Cambrian to Middle Ordovociain dolostones in south-central Missouri have historically been identified as Pennsylvanian paleokarst structures. U-Pb detrital zircon geochronology is at odds the time of formation and sedimentological evidence challenges their classification. “Filled sink” deposits yield primary zircon age populations of 2.8-2.6 Ga (~50% of all analyzed grains), 1.2-1.1 Ga (~25%), 1.8-1.6 Ga (~15%) and 1.5-1.3 Ga (~10%). These zircon populations most likely originated from the Superior Craton and Midcontinent Rift and/or Grenville orogen, respectively. The Warrensburg and Moberly channel-fill sandstones of central Missouri were identified as good candidates for Pennsylvanian aged strata to which results from “filled sinks” may be compared. In contrast to “filled sink” deposits, channel-fill sandstones contain a population of Paleozoic zircon grains presumably derived from exhumed plutons of the uplifting and eroding Appalachian Mountains to the east. Existing data from Ordovician clastic strata (e.g., the Roubidoux and St. Peter Sandstones) in central Missouri show zircon age distributions that are strikingly similar to those “filled-sink” deposits. We suggest that the Taconic orogeny led to modest uplift in central Missouri, resulting in a significant disconformity below the St. Peter sandstone during the middle Ordovician. Far-field tectonism appears to have caused a reorganization of sediment dispersal pathways from the Archean Superior craton to the north to the growing mountains to the east, and in the process created a depositional hiatus forming the filled-sinks. The Taconic orogeny then proceeded to provide a source for detritus which arrived in the Missouri basin as early as the Upper Mississippian.

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1. INTRODUCTION

The filled-sink formations of Missouri have been almost exclusively identified as Pennsylvanian age karsting-induced features. This classification described the formation of the filled-sinks as the concurrent solutional removal of underlying strata with subsidence of overlying strata (Hinds and Greene, 1915; Keller et. al, 1954; Bretz, 1950; Asher-Bolinder 1992; He, 1995; Dunham 1916; Tarr, 1937; and Leach, 1980). Recently, this assertion has been challenged based on stratigraphic and sedimentological evidence. Primary structures within the collapse formations such as ripple marks, graded bedding, and cross bedding suggest a strong fluvial component to deposition. Additionally, overlying Mississippian detritus at outcrops and the apparent connectedness of the filled-sinks as a drainage network (Little, 2004).

The Ordovician Missouri environment was a shallow epeiric sea which received an influx of sediments from multiple sources. From the Cambrian to the Ordovician there was a major provenance shift from locally derived detritus to Superior craton detritus. Pennsylvanian formations in Missouri reflect a decline in the Superior craton zircon populations. Earlier geochronology of a “filled sink” shows a large Superior craton zircon population and no Paleozoic zircons. This led to a tentative interpretation of these “filled sinks” as Ordovician (Hua et. al., 2015).

2. LITERATURE REVIEW

2.1. DETRITAL ZIRCON GEOCHRONOLOGY

Zircon ($ZrSiO_4$) is an abundant accessory mineral in sandstones. With a hardness of 6.5-7.5, a resistance to both physical and chemical weathering and the replacement of Zr with U and Th, zircon grains are a good candidate for geochronology. Some of the oldest datable sediments on earth are detrital zircon grains and so zircons can provide a large spectra of ages (Maas et. al. 1992; Gehrels et. al. 2011; Gehrels et. al, 2014; and Cawood et. al., 2012).

2.1.1. Use as a Sedimentary Tool. Detrital zircon geochronology has been implemented as a tool for characterizing provenance of sedimentary rocks. Detrital zircons provide a multi-faceted approach to sedimentary provenance. Since the date of the measured zircon is assumed to be the crystallization age of the zircon, a sedimentary rock provenance can be characterized by the ages of the zircons it contains. These can be plotted on a normalized probability plot to visualize the various populations and identify source plutons, or they can be plotted on a cumulative probability plot to visualize a sediment mixing model.

There is some risk in assumptions about detrital zircon provenance. Four major issues include: source terrane fertility equality, that zircon generation was produced uniquely for each terrane, that each terrane produces sufficient zircon to be analyzed, and that the spot chosen for analysis on a zircon grain is representative of the last source terrane (Moecher and Samson, 2006). Those issues are especially important for analysis of an individual rock sample; however as the analysis spans multiple rocks in a basin across a period of time you can identify trends and make interpretations from those trends (Black et. al., 2004; Jackson et. al., 2004; and Woodhead et. al., 2004).

2.1.2. Identifying Sedimentary Provenances. Zircon age data on a normalized probability plot can show multiple age peaks. These peaks can represent one or more source terranes. The larger the peak around a certain age, the more likely a randomly selected zircon from the sample will have the same age. Primary source terrane zircon ages have been identified by a variety of authors (Mackey et al., 2012; Gehrels et al., 2011; Park et al., 2010; Hua et. al., 2015; and Blum and Pecha, 2014). Generally, age populations are grouped around known peaks; however there may be multiple provenances that may contribute to a single peak. Consistent interpretation then requires the recognition and either inclusion or exclusion of those sedimentary provenances based on geological evidence. Cathodoluminescence can be used to examine the zircons in detail and compare their cores, rims, and other textures to zircons from other plutons. The provenance can also be constrained based on the tectonic history of the basin, its spatial relations to zircon sources, and geochronology of other minerals such as monazite.

2.2. “FILLED SINK” FORMATIONS

The “filled sink” formations of Missouri are an important set of features found in central Missouri. They have been studied for nearly a century and have had many theories generated about the cause of their formation.

2.2.1. Background. The “filled sink” formations of Missouri have historically been interpreted as Pennsylvanian aged karst collapse formations, typically hosted in Ordovician units and either not capped or capped by Pennsylvanian formations or

Mississippian formations or detritus. These formations have played some economic significance both from clays found within them and from their spatial and temporal relation to major lead deposits in Missouri (Asher-Bolinder, 1992; Bretz, 1950; Little, 2004, Thacker, 1977).

2.2.2. Theories on Formation. The three most commonly accepted theories for the formation of the chaotic collapse formations of central southern Missouri include: filled sinks formed and filled during the Pennsylvanian, caves with collapsed roofs, and concurrent subsidence of overlaying rocks with solutional removal (Bretz, 1950). Regardless of the theory, the driving creation force is karstification, whether in the vadose zone, via cave networks, or even fluvial or paludal in origin (Asher-Bolinder, 1992).

2.2.3. Evidence Challenging Classification and Age. In spite of the accepted age and nature of the chaotic collapse formations, there is evidence inconsistent with this interpretation. Sedimentological and structural evidence suggests that these are pre-Pennsylvanian in age and represents a drainage network. The pre-Pennsylvanian age assertion was made on the presence of overlying Mississippian aged residuum and strata and the state maps showing overlying Devonian and Mississippian stratae. Sedimentological evidence was used to point out that these collapse-deposits were not very chaotic, had internal structures consistent with fluvial deposition, and had most of their disturbances towards the edge of the formation (Little, 2004). Additionally, there is a notable lack of any Pennsylvanian fossils in the “filled sinks” themselves, whereas the overlying cover has definitively Mississippian fossils or is sometimes even in situ Mississippian strata.

2.3. ORDOVICIAN MISSOURI CLASTIC FORMATIONS

The Ordovician time period in Missouri was typified by a shallow epeiric inland sea, depositing large, extensive carbonate near shore facies formations (Overstreet et. al. 2003). This basin flanked the Ozark Dome uplift, and during the Ordovician was the deposition site of siliciclastic and carbonate units such as the Jefferson City Formation, Gasconade Dolomite, St. Peter Sandstone, and Rubidoux Formation. The St. Peter Sandstone is of special interest considering its apparent similarity to the chaotic collapse formations of Missouri based on stratigraphic, outcrop, and detrital zircon data.

2.4. PENNSYLVANIAN MISSOURI CHANNEL FILL SANDSTONES

The Warrensburg and Moberly sandstones are Pennsylvanian Channel filled sandstones in central Missouri. Geological maps suggest these channels are separate branches of an ancient river disconnected by modern fluvial action. The deposits range from tens of feet to two hundred feet thick, extend 40 to 50 miles in length, and even extend further than that based on paleochannel geometry. Early investigations into the channel sandstones tended to focus on their economic significance and relation to coal beds. (Winslow, 1890; Doty and Hubert, 1961; Hinds and Green, 1915; Marbut, 1898). Lithologically these channels are dominated by sandstones, with interbedded limestones and shales with a basal conglomerate member. Quartz-Feldspar-Lithic ternary plots of these sandstones classify them as micaceous quartzite to quartzose greywacke. The relative abundance of quartz and lack of feldspars likely is a result of extensive sorting from transportation.

PAPER

I. LATE ORDOVICIAN TECTONISM IN THE NORTH AMERICAN MIDCONTINENT: CONSTRAINTS FROM U-PB DETRITAL ZIRCON GEOCHRONOLOGY

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ABSTRACT

Numerous sandstone filled depressions hosted in upper Cambrian to Middle Ordovociain dolostones in south-central Missouri have historically been identified as Pennsylvanian paleokarst structures. U-Pb detrital zircon geochronology is at odds the time of formation and sedimentological evidence challenges their classification. “Filled sink” deposits yield primary zircon age populations of 2.8-2.6 Ga (~50% of all analyzed grains), 1.2-1.1 Ga (~25%), 1.8-1.6 Ga (~15%) and 1.5-1.3 Ga (~10%). These zircon populations most likely originated from the Superior Craton and Midcontinent Rift and/or Grenville orogen, respectively. The Warrensburg and Moberly channel-fill sandstones of central Missouri were identified as good candidates for Pennsylvanian aged strata to which results from “filled sinks” may be compared. In contrast to “filled sink” deposits, channel-fill sandstones contain a population of Paleozoic zircon grains presumably derived from exhumed plutons of the uplifting and eroding Appalachian Mountains to the

east. Existing data from Ordovician clastic strata (e.g., the Roubidoux and St. Peter Sandstones) in central Missouri show zircon age distributions that are strikingly similar to those “filled-sink” deposits. We suggest that the Taconic orogeny led to modest uplift in central Missouri, resulting in a significant disconformity below the St. Peter sandstone during the middle Ordovician. Far-field tectonism appears to have caused a reorganization of sediment dispersal pathways from the Archean Superior craton to the north to the growing mountains to the east, and in the process created a depositional hiatus forming the filled-sinks. The Taconic orogeny then proceeded to provide a source for detritus which arrived in the Missouri basin as early as the Upper Mississippian.

1. INTRODUCTION

Detrital zircon geochronology is a powerful tool with a variety of applications. We used detrital zircon data from several samples in Missouri to resolve a stratigraphic question about “filled sink” formations, and to resolve the influence of regional tectonism. These “filled sinks” have been historically identified as Pennsylvanian paleokarst formations. The method of sink filling has been debated through time; however the most widely accepted hypothesis asserts that they were filled from concurrent subsidence and dissolution. These assertions were based on the circular geometry in map view, apparently disturbed bedding, and presence of clay mineral alteration (Hinds and Greene, 1915; Keller et. al, 1954; Bretz, 1950; Asher-Bolinder 1992). These formations lack Pennsylvanian aged fossils. This paper calls into question the timing and nature of the “filled sinks.” Many outcrops show evidence of fluvial origin including graded bedding, ripple marks, and trough-cross stratification. Additionally they are frequently covered by strata containing Mississippian aged fossils.

In Ordovician time the North American midcontinent region was covered by a shallow epeiric sea (Figure 1). Detrital zircon data suggests a major sediment provenance change from the Cambrian to Ordovician, and the Ordovician through the Pennsylvanian time period in Missouri, and shows several Ordovician units that have similar detrital zircon profiles to the “filled sinks”. This detrital zircon evidence and the petrographic and stratigraphic similarity suggests a strong connection between the Ordovician units and the “filled sinks.”

Detrital zircon geochronology of Ordovician formations in Missouri shows two primary peaks at 2.7 Ga and 1.1 Ga, both stronger than the same peaks found in Cambrian strata. This likely reflects the change from locally derived basement detritus to sediment from the Superior Craton (Hua et. al., 2015). The Warrensburg and Moberly channel sandstones are Pennsylvanian aged formations found in Missouri, two separated branches of an ancient river. Since the Moberly and Pennsylvanian sandstones are channel fill deposits and definitively Pennsylvanian, they provide a good comparison for the filled-sink formations which are alleged to have formed during the Pennsylvanian.

We used detrital zircon geochronology from Ordovician (Roubidoux and St. Peter sandstones) and Pennsylvanian strata (Moberly-Warrensburg channel sandstones) to provide guideposts to compare to the age populations of detrital zircons recovered from "filled sink" deposits. Ordovician and Pennsylvanian detrital zircon age spectra will provide two end members for comparison with “filled sink” deposits. Additionally, the changes in age populations over time must be considered in light of the regional tectonic history- what role did tectonics play in the formation of "filled sink" deposits? What was the impact of global sea level change at this time? These questions must be properly considered and treated in light of the given data.

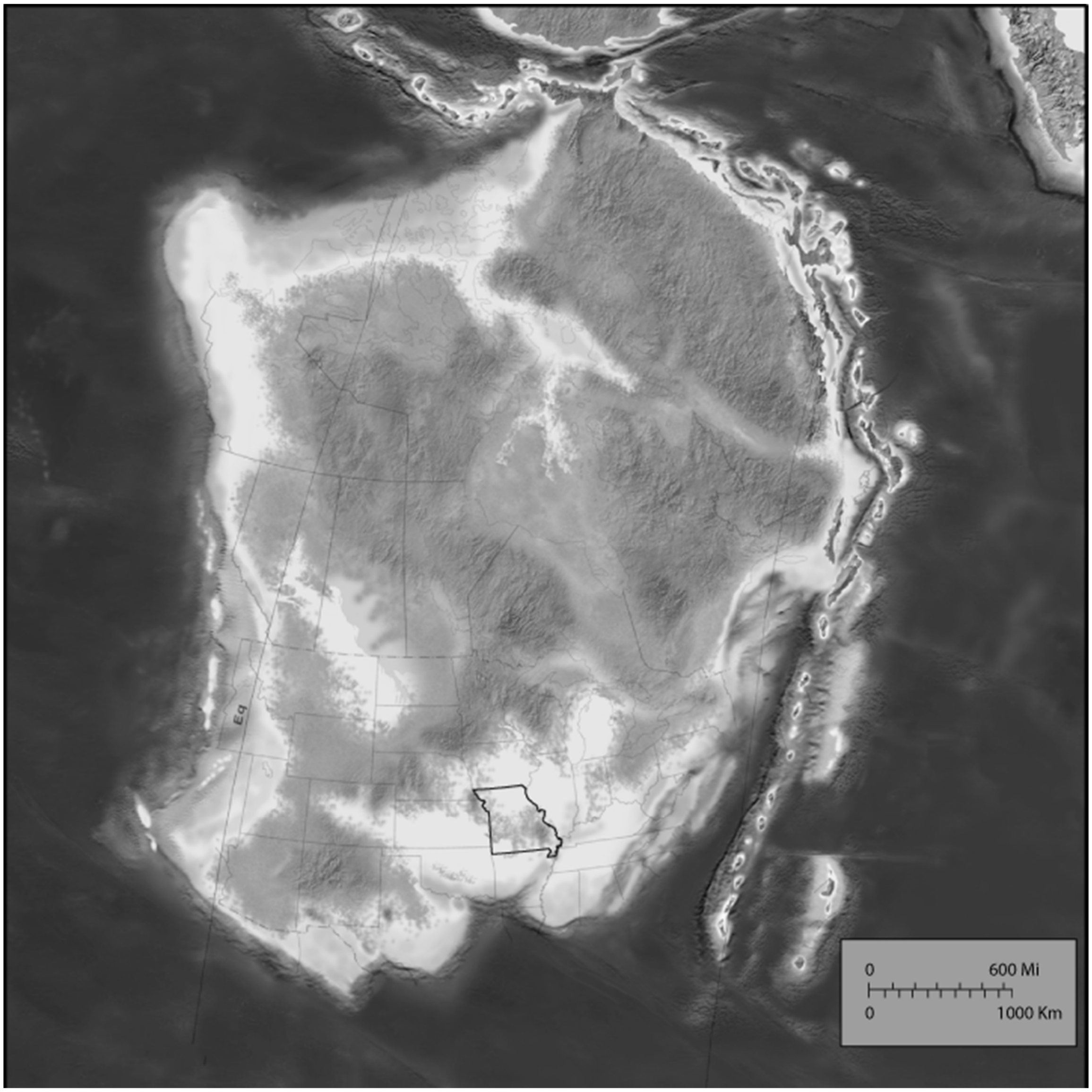

Fig. 1. Paleoenvironment map of Ordovician Missouri. Adapted from Blakey (2011). Missouri is mostly covered by the shallow inland sea at this time.

2. GEOLOGIC BACKGROUND

In order to properly understand the nature of the issues presented, we must examine the rocks used to identify the problems, and the rocks that can be used to test our hypothesis. The Pennsylvanian channel sands are the litmus test for the filled sink hypothesis.

2.1 Pennsylvanian Samples

The Warrensburg and Moberly channel sandstone formations of Missouri have been recognized and studied for over a century (see Hinds and Greene, 1915; Winslow, 1890; Marbut, 1898; Doty and Hubert, 1961). The Moberly and Pennsylvanian formations were first identified as channels and mapped by Winslow in 1890 for the following reasons:

1) the great thickness (10-50 meters thick) of the deposit,

2) the long and narrow shape of the outcrop/subcrop belt,

3) the superposition of the sandstone upon the 'Middle Coal Measure' rocks, and

4) the inclusion of fragments of adjacent rocks within the channels themselves.

The geometry of the sandstones themselves- narrow at the base and wider towards the top- also suggests that these sandstones are filling in channels. The channels are very long and deep compared to their width- the Moberly had been mapped at nearly 64 kilometers long and the Warrensburg at 80 kilometers long, and their paleochannel geometry indicates they were likely much longer. They range in thickness from tens of feet to two hundred feet thick, but are typically less than two to four kilometers wide. The lithological makeup of the channel fills tend to be dominated by sandstone, with some interbedded limestones and shales and typically a basal conglomerate.

We collected one sample each of Warrensburg and Moberly sandstones from outcrops near Warrensburg and Moberly, Missouri. The petrographic properties of each sandstone are nearly identical- dominantly quartz (75% on average), with feldspar, biotite, muscovite, and tourmaline. Zircon dominates the heavy mineral assemblage. Scanning electron microscope images of the zircon grains show three primary zircon morphologies in these channel sandstones- idiomorphic grains, fragmental grains, and rounded grains (Doty and Hubert, 1961). Figures 2 and 3 were obtained on the Hitachi S-4700 SEM at the Missouri University of Science and Technology.

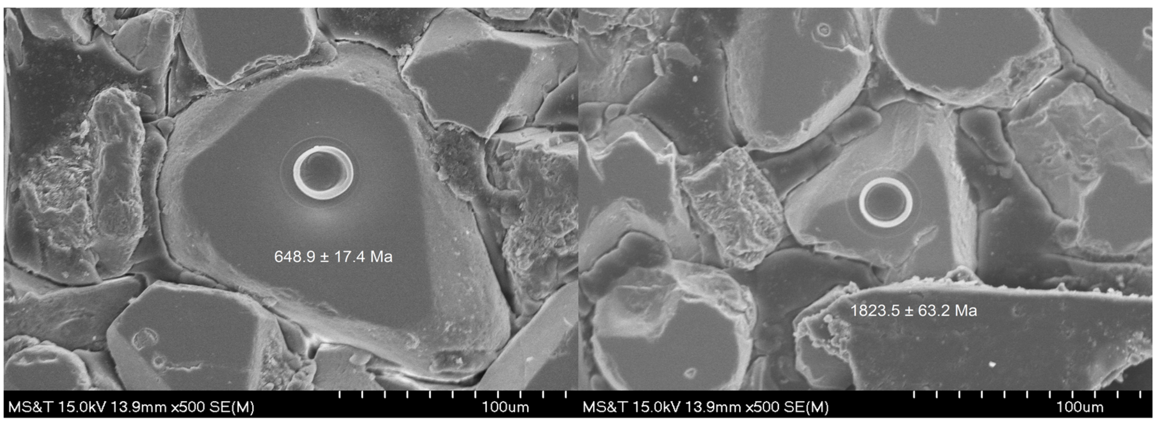

Fig. 2. Scanning electron microscope (SEM) image of Warrensburg channel sandstone detrital zircons. Ages and errors overlain on zircons analyzed. Scale includes entire tick bar. Analytical pits were produced by laser ablation at the Arizona Laserchron Center.

2.2 "Filled Sinks"

The "filled sinks" of South-Central Missouri have historically been interpreted as paleokarst formations generated during the Pennsylvanian. These "filled-sinks" consist of "more than 1000 roofless solution cavities… [that] lie on the northern and western slopes of the Ozark dome" (Bretz, 1950). These formations are typically hosted in Ordovician strata or rarely in Cambrian strata, and are either not capped, or overlain by sediments ranging in age from Mississippian to Pennsylvanian (Asher-Bolinder, 1992; Bretz, 1950).

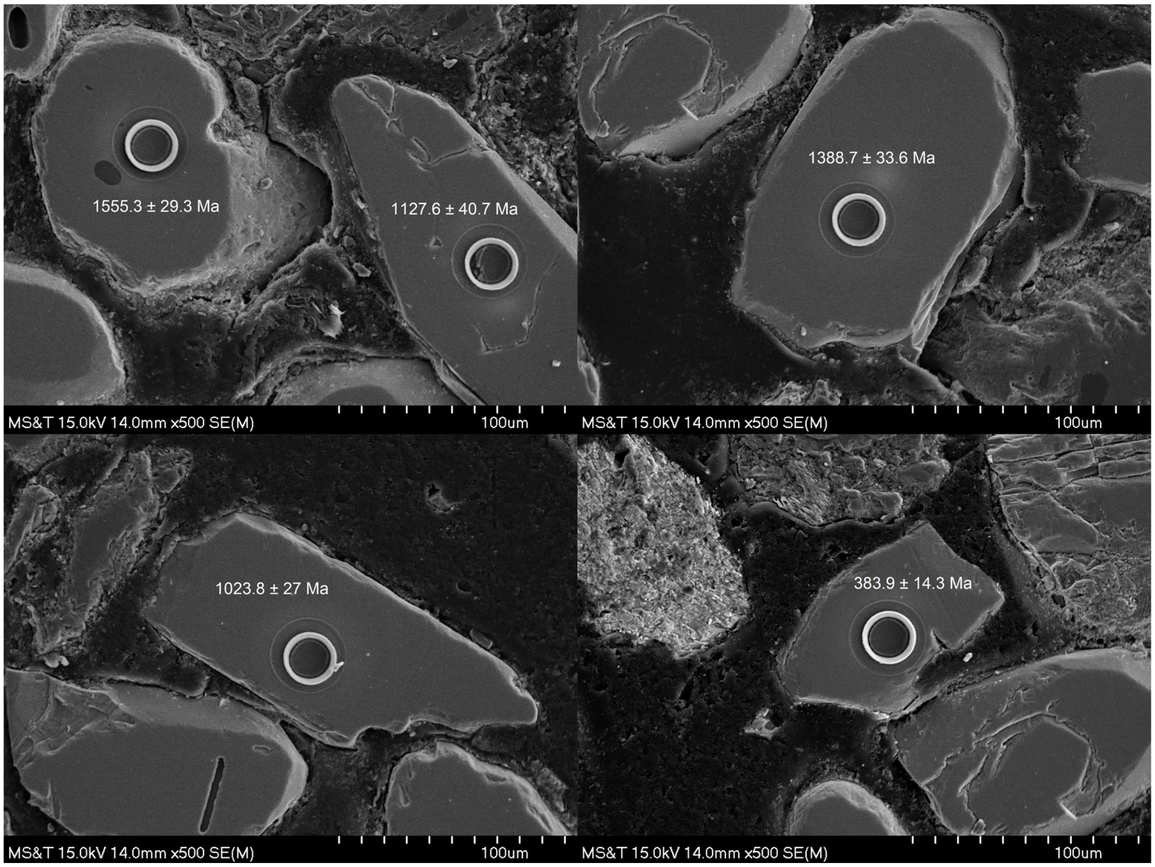

Fig. 3. SEM image of Moberly channel sandstone detrital zircons. Ages and errors overlain on zircons analyzed. Scale includes entire tick bar. Analytical pits were produced by laser ablation at the Arizona Laserchron Center.

Debate as to the exact nature of the filled-sinks provided a multitude of theories for their origin. Three of the most popular theories are that they are filled sinks, collapsed cave roofs, or that they result from concurrent subsidence and solution filling (Asher-Bolinder, 1992). The filled-sink theory is supported by the centripetally dipping strata found in the sinks themselves, with brecciation, faulting, and a lack of evidence for compressional stresses evident in outcrop (Asher-Bolinder, 1992). The collapsed cave roof theory is supported by the presence of breccia-fill from wall and roof rock, and this group is generally associated with economically significant circle-deposits found in Missouri. These tend to be filled with clays which are commonly mineralized. The solutional-removal theory is supported by the formations which are compacted, chaotic, and require the in-filling of cavities at nearly the same rate as basin subsidence (Bretz, 1950).

Asher-Bolinder (1992) suggested that the “filled sinks” subsided at the same rate with basin subsidence, suggesting that “Pennsylvanian seas would have allowed sinks to develop… as sea level continued to drop. As the water table fell and dissolution proceeded downward, sediments within the sinks sagged deeper into their centers, making room for more sediment to accumulate at the surface”.

None of the above hypotheses address the issues of the overlying Mississippian strata or the observed fining upward gradation of the deposits; in fact this observation has generally been passed over in discussions. In each scenario it is assumed that there is a degree of replacement of the Ordovician rock with newer sediment which would mark the timing of the creation of the “filled sinks”. The removal of sediment between the Pennsylvanian and Ordovician is kept relatively local, and so the “filled sinks” would represent a recycling of overlying rocks.

One “filled sink” structure near Rolla, Missouri is hosted in the Ordovician Jefferson City Dolomite and the infill consists primarily of shales and sandstones. Proctor and Lance (1993) note the internal structure of this “filled sink” deposit as containing typically shallow bedding (<30°) which dips towards the center of the sink (see Figure 4). The central portion of the sink is folded, dipping at high angles, and sometimes overturned. Importantly, they interpret the origin of this sink as subsiding contemporaneously with the solution removal of the Jefferson City Dolomite so that the sink is made up of younger, overlying sediment.

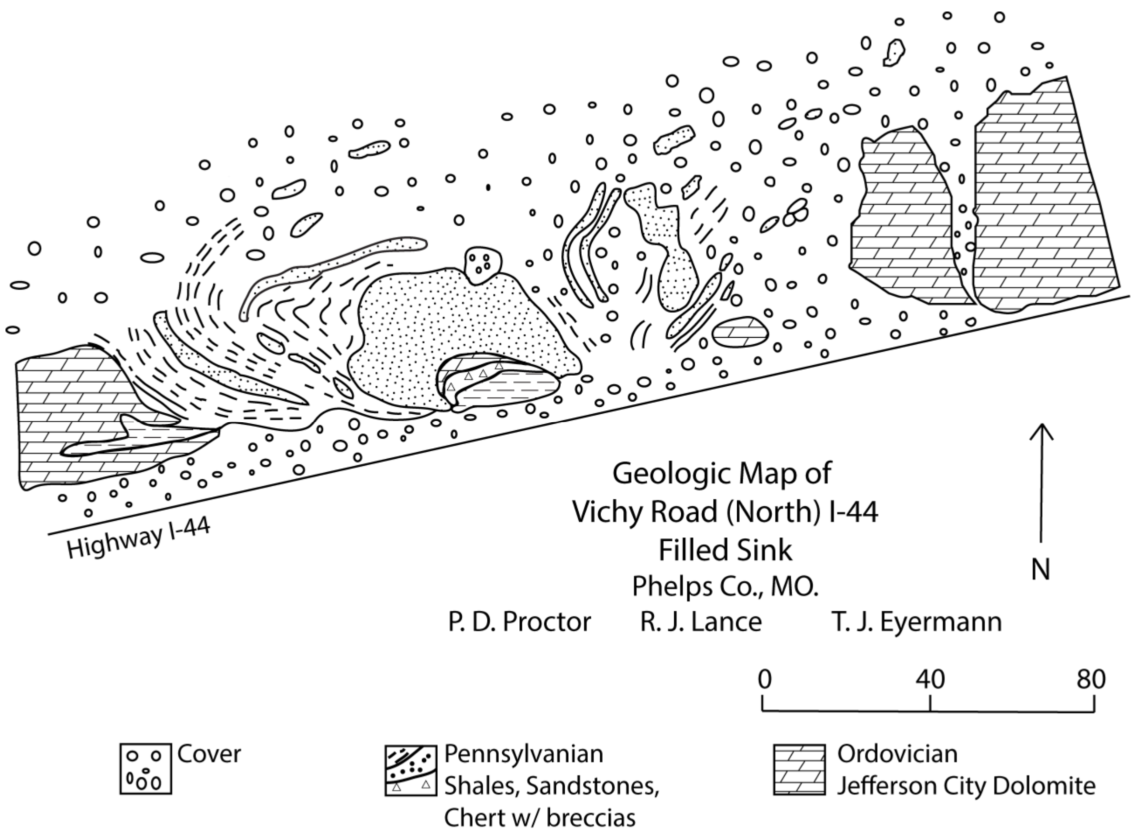

Fig. 4. Geological sketch of "filled sink" near I-44 in Rolla, Missouri. Adapted from Proctor, Lance, and Eyermann (1993).

Alternatively, it could be argued that the "filled sinks" formed prior to the Pennsylvanian time based on the presence of overlying Mississippian aged residuum and strata and the state maps showing overlying Mississippian strata as evidence for a Pre-Pennsylvanian age. Sedimentological evidence shows these collapse-deposits have internal structures consistent with fluvial deposition, and most of their disturbances are limited to the edges of the formation (Figure 5). The Mississippian aged residuum has been shown to be definitively Mississippian based on fossils found within it. The chaotic features towards the edges and rim related to fluvial action and karsting, respectively. Internal structures including cross bedding, ripple marks, and graded bedding have been found at collapse structures near Truman Lake, north of Rolla, and in other filled sinks.

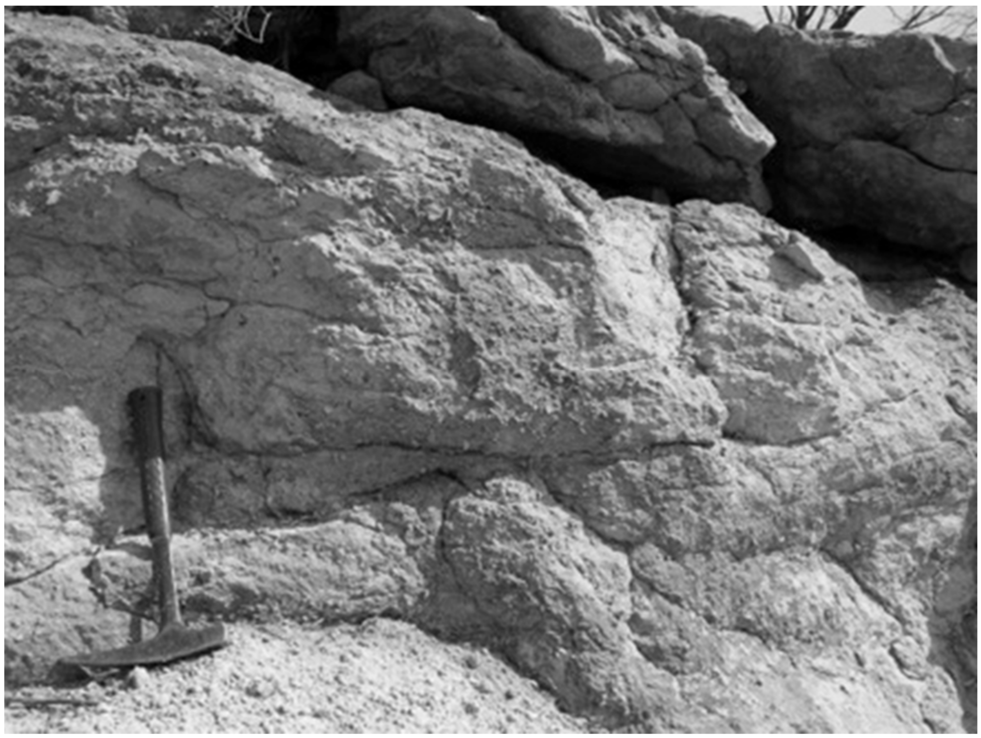

Fig. 5. Trough cross bedded sandstone in the Truman Lake "filled sink" deposit.

3. METHODOLOGY

Zircon grains were separated from samples collected from two separate collapse structures- representing both sink fill (samples 14MO6 and 14MO9) and rimrock (14MO10) facies - and one sample each from Warrensburg (15MO2) and Moberly (15MO1) channel sandstones by crushing and mineral separation at the Missouri

University of Science and Technology. Rocks were crushed in a jaw crusher, ground in a pulverizer, washed, and hand panned to separate out the heavy minerals. These heavy minerals were sieved and dried, then passed through a Frantz magnetic separator and methylene iodide to isolate the zircon grains. Samples were mounted for analysis at the University of Arizona LaserChron facility with in-house Sri Lanka (SL) and secondary R33 (Black et al., 2004) standards and polished to expose grain interiors prior to analysis. The U/Pb ratios were analyzed using a Nu-Plasma laser ablation multi-collector inductively couple plasma mass spectrometer (LA-MC-ICPMS). To ensure statistical significance, approximately 100 zircon grains were analyzed per sample, following methods outlined in Gehrels et al., (2008). The Sri Lanka standard, the age of which was determined by isotope dilution–thermal ionization mass spectrometry (ID-TIMS) of 563.5±3.2 Ma (2σ), was analyzed once per every 5 unknown analyses to correct for potential mass fractionation and drift (Gehrels et al., 2008). A secondary standard R33 (Black et al., 2004) with ID-TIMS age of 418.9 ± 0.4 Ma (2σ) was also analyzed once per every fifty unknown analyses. Data reduction was done using in-house Microsoft Excel programs and ISOPLOT/Ex, version 3 (Ludwig, 2003).

4. AGE SPECTRA RESULTS

Normalized probability plots for the analyzed Missouri clastic strata provide a data set which can be used for interpreting local and regional scale problems. The plots consist of ~100 grains per sample.

Figure 6 shows a collection of normalized probability plots for Missouri clastic strata. Sample14MO6 and 14MO9, and 14MO10, from a “filled sink” and its rim rock were collected and analyzed for this paper. Samples 15MO1 and 15MO2, from the Moberly and Warrensburg channel sandstones, were also collected and analyzed for this paper.

4.1 Pennsylvanian Channel Sandstones

Sample 15MO1 is of the Pennsylvanian Moberly channel sandstone. It was collected from an exposure in Norris Quarry in the Salt Springs Township of Missouri. It is a quartzose arkose, with paleocurrent indicators showing an East-West channel flow. Sample 15MO2 is of the Pennsylvanian Warrensburg channel sandstone. It was collected from an exposure in Cave Hollow Park in Warrensburg, Missouri. It is a micaceous quartzite and paleocurrent indicators show a North-South channel flow.

The age spectra for the Pennsylvanian Moberly and Warrensburg channel sandstones- 15MO1 and 15MO2 respectively- have two primary age populations- 1.3-1.1 Ga (comprising ~70% of analyzed grains) and 600-400 Ma (~20%). There are also zircon grain age populations from 2.8-2.6 Ga (~5%) and 1.6-1.4 Ga (~5%).

4.2 Collapse Structure Fill

Sample 14MO6 is from a “filled sink” in western Franklin County, Missouri. It is an orthoquartzite. Sample 14MO9 is from a “filled sink” North of Rolla, Missouri. It is a quartzose graywacke.

The age spectrum for the collapse structure zircon grains from 14MO6 and 14MO9 reflects two primary populations. The first, 2.8-2.6 Ga (~50%) and second, 1.2-1.1 Ga (~25%) comprise more than half of the detrital zircon ages. Other populations of 1.8-1.6 Ga (~15%) and 1.5-1.3 Ga (~10%) were also measured. There was also one zircon grain date 469.1 Ma ± 8.5.

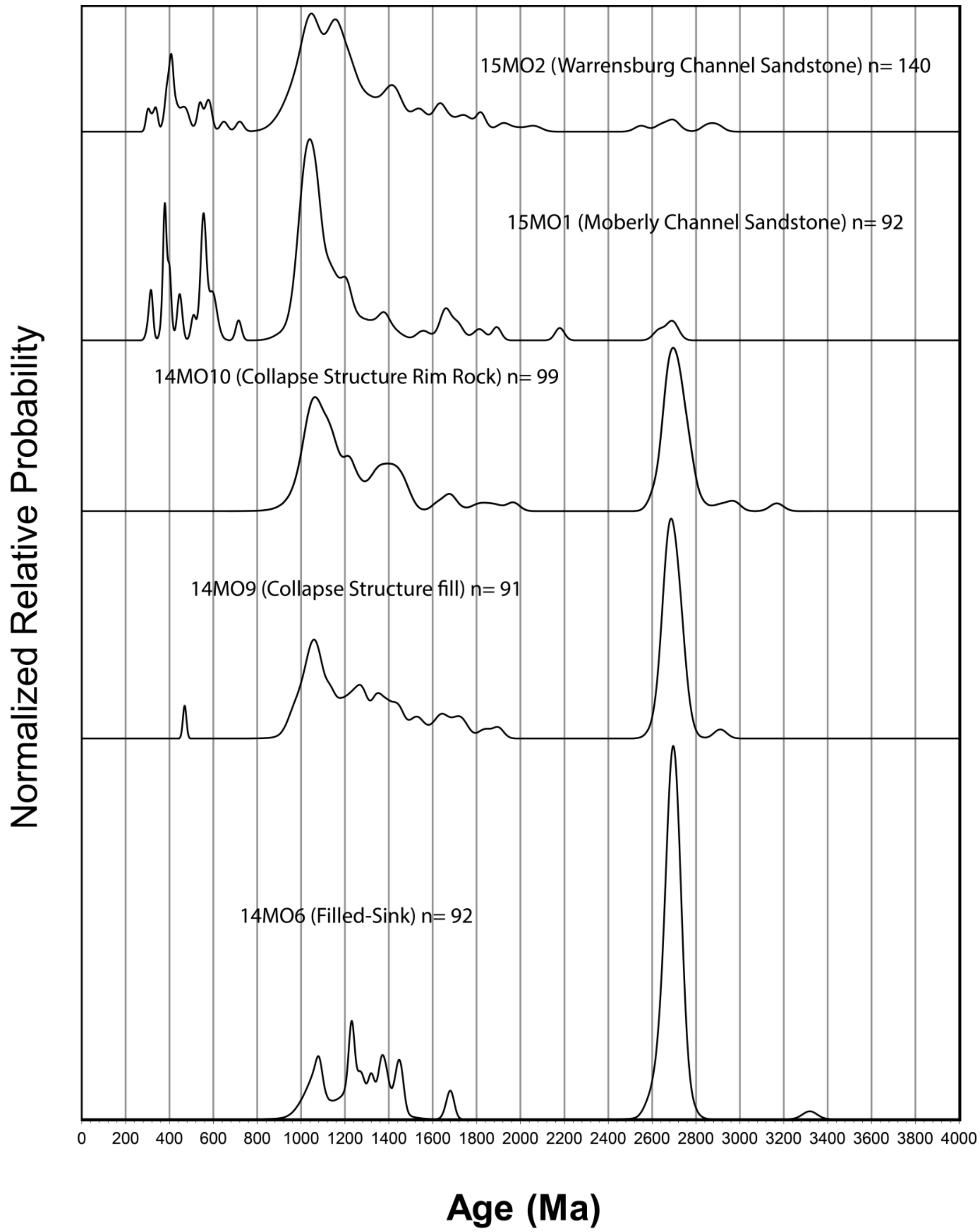

Fig. 6. Normalized probability plots from the detrital zircon grains of the analyzed Missouri clastic strata. 14MO6 data from Hua et. al. (2015).

4.3 Collapse Structure Rim

Sample 14MO10 is from the Fossil Hill sediments found in Rolla, Missouri. It is correlative to the rim rock from the "filled sink" 14MO9. It is a micaceous quartzite.

The age spectrum for the collapse structure rim zircon grains from 14MO10 reflects two primary populations. The first, 2.8-2.6 Ga (~50%) and second, 1.2-1.1 Ga (~25%) comprise more than half of the detrital zircon ages. Other populations of 1.8-1.6 Ga (~15%) and 1.5-1.3 Ga (~10%) were also measured.

5. DISCUSSION

The issues surrounding the filled sinks are not cut and dry either stratigraphically or tectonically. Detrital zircon results do shed light on certain things and conclusions can be drawn from these data sets. In the following sections we discuss and interpret the results.

5.1 Interpreting Normalized Probability Plots

Zircon grain dates can be grouped together in age populations. ISOPLOT/Ex can create a normalized relative probability plot (NPP) for a sample which allows one to visually identify zircon populations with similar dates. Taller spikes on the graph indicate a higher likelihood that a randomly selected zircon grain from the sample would be measured at that age.

Zircons of a particular provenance population can have a range of crystallization ages. Thus any zircon grain with an age between 2.8-2.6 Ga might represent the Superior craton, since grains dated directly from the Superior craton date from 2.8-2.6 Ga. The presence of a spike at 2.8-2.6 Ga on an NPP can be identified as a “Superior craton signal”. Other zircon age populations treated in this study include the Midcontinent Rift and/or Grenville orogeny (1.3-1.0 Ga), the Yavapai-Mazatzal province (1.8-1.6), the Granite-Rhyolite province (1.5-1.3 Ga), and the Paleozoic Appalachian basement (650-

350 Ma) (ages from: Mackey et al., 2012; Gehrels et al., 2011; Park et al., 2010; Hua et. al., 2015; and Blum and Pecha, 2014).

5.2 Sedimentary Provenance in Missouri

The detrital zircon data from the “filled sink” deposits and the Pennsylvanian strata provide fingerprints for the provenance of these rocks. Figure 7 displays source regions of variable basement age that may have contributed detrital zircons to the midcontinent during the Paleozoic era.

Previous detrital zircon in the Ozark Dome region indicates that detrital zircons in Ordovician strata in Missouri are characterized by a large peak centered at ca. 2.8 Ga, with lesser populations centered around 1.1 Ga, from 1.6-1.3 Ga, and at ca. 1.8 Ga. The most likely ultimate sources for these populations are the Superior Craton, Midcontinent Rift/Grenville orogeny, midcontinent graintoids, and Mazatzal-Yavapai orogens, respectively (see: Mackey et al. (2012); Gehrels et al. (2011); Park et al. (2010), Hua et. al. (2015); and Blum and Pecha (2014))..

Pennsylvanian Moberly-Warrensburg channel sandstones record two primary populations- one Paleozoic group from 650 to 350 Ma, and a group centered around 1.1 Ga. Lesser populations of 1.6-1.3 Ga, and 1.8-1.7 Ga are also recorded. This stands in stark contrast to the Ordovician signal because of its lack of Superior craton zircons, or a population of 2.8 Ga zircons and the influx of Paleozoic, probably Appalachian zircon grains. Appalachian zircon grains in this case refers to the relatively young (650 to 350 Ma) grains derived from volcanic or plutonic activity from the Taconic phase of the Appalachian orogeny and not necessarily older basement grains from the Appalachian terrane itself.

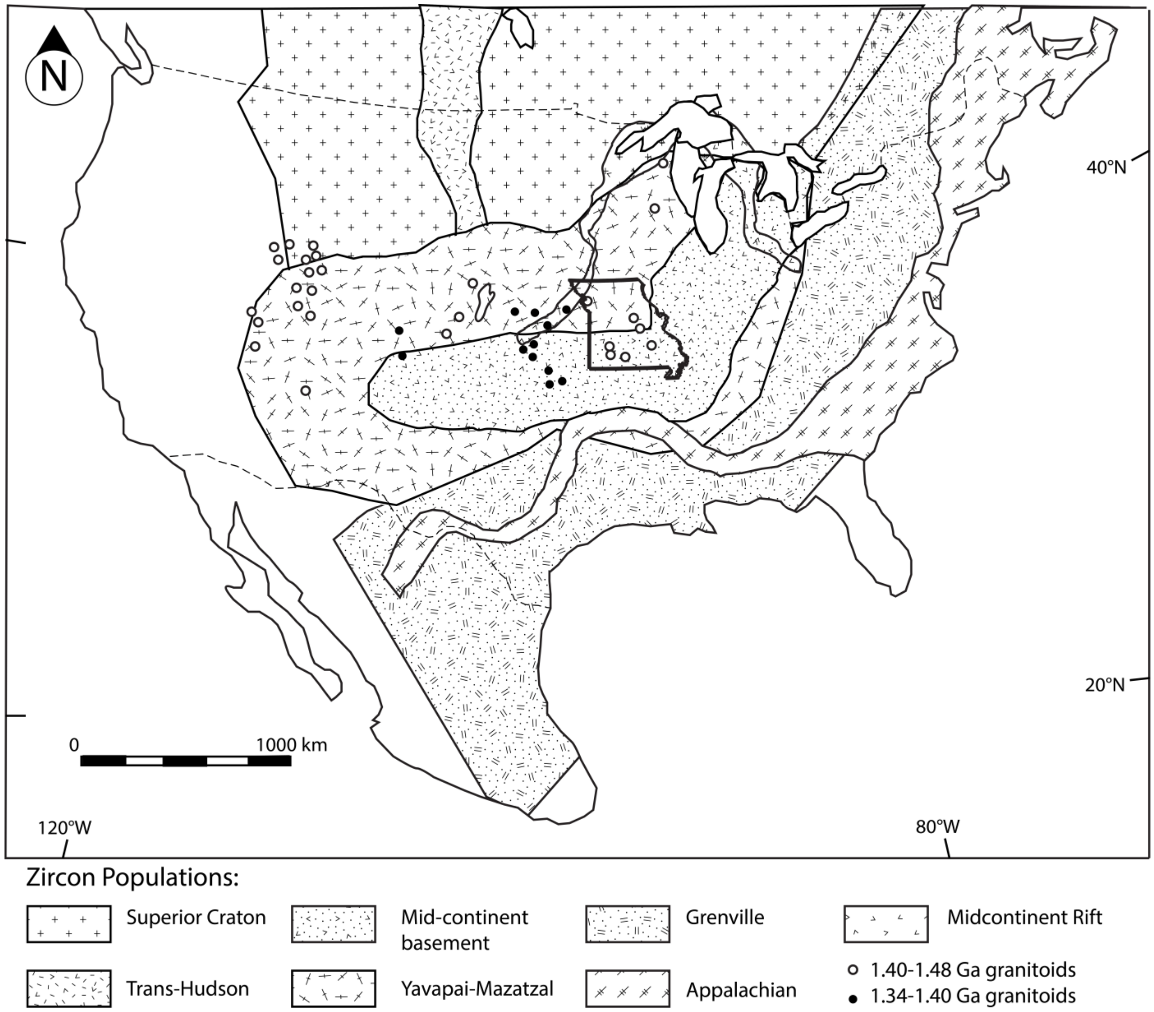

Fig. 7. Potential source regions from which zircon grains may have been derived to be deposited in Missouri from the Ordovician through Pennsylvanian time period. Adapted from Chapman et. al. (2015), Blum and Pecha (2014), Hua et. al (2015) and Gehrels et. al. (2011).

5.3 Filled-Sinks

Detrital zircon populations of the filled-sinks of Missouri are distinctly different from the detrital zircon populations of the Pennsylvanian channel sandstones (Figures 5 and 7). The "filled-sinks" do not contain the Appalachian basement population and contain an abundant population of Superior craton-aged zircon. The sediment which filled the Pennsylvanian channels and the sediment which filled the sinks have distinctly different sources; therefore, it is highly unlikely that the sediment that filled the "filled sinks" was Pennsylvanian in age. In spite of their historical identification as Pennsylvanian, the "filled sinks" are notably lacking in fossils.

It could be argued that "filled sinks" were originally deposited sometime prior to the Pennsylvanian (e.g., the Ordovician through Mississippian), but were reworked into sink fills later. However, this scenario is unlikely given the primary features found in the filled sinks (e.g., continuous bedding and cross-bedding), the lack of chaotic structures, and the apparent map view connectivity of "filled sinks" (Figure 8). Additionally, the literature is conspicuously absent in describing any Pennsylvanian aged fossils in the "Pennsylvanian" aged formations. These sinks are also consistently overlain by Mississippian sediment, which has been identified as Mississippian base on the fossils it contains.

The filled-sink detrital zircon NPP plots do look similar to the Ordovician formations found in Missouri, particularly the St. Peter sandstone. They share a large Superior craton zircon population, as well as the Grenville orogen and midcontinent grains. The St. Peter sandstone is found above a well-known unconformity and is at its thickest when filling Upper Ordovician sink holes. The erosional unconformity below the St. Peter is better documented to the North and East, and it may reflect a period of uplift and karstification of the lower Ordovician units (Thompson, 1995). As karstification continued small sinkholes and linear features began to grow and connect, forming solution valleys. The St. Peter was then deposited during the middle/upper Ordovician, filling in solution valleys which include both the documented sink holes and, as we suggest, the "filled-sinks" as well.

Fig. 8. State geological map of channel fills overlain by Devonian strata. Devonian strata (D) found overlaying Pennsylvanian age sandstones. The Pennsylvanian sandstones appear to be a drainage network. Adapted from state geological maps maps of Missouri.

The interpretation of the “filled sinks” as Pennsylvanian in age and how they have been generated is not supported by detrital zircon geochronology. It is more likely that these are an established, interconnected drainage system that formed concurrently or just after the unconformity found near the top of the Ordovician, as in the one found below the St. Peter. It is indeed likely that the St. Peter Sandstone and the sediments which fill these sinks are genetically very similar. It may be possible that the solution valley infill- previously “filled sinks”- are correlative with the St. Peter. That is to say that the St. Peter formation is a sand sheet equivalent facies to the solution valley facies.

5.4 Cause of Provenance Changes

The Pennsylvanian and Ordovician strata display a number of differences. First, the Ordovician samples exhibit a strong Superior craton zircon signal and a large Midcontinent rift and/or Grenville orogeny zircon signal. Secondly, the Pennsylvanian samples contain the Paleozoic zircon grains presumably from the Appalachian basement. This transport of Paleozoic zircon grains from East to West continued in other basins in the midcontinent, including the Ouachita basin. These grains appear to have arrived in the Ouachita basin around the same time as they did in the Ozark Dome region (Gleason et. al., 2001). This may indicate that the zircons travelled essentially East to West across the North American continent, and can be found in the Grand Canyon in Pennsylvanian strata (Gehrels et.al, 2011), suggesting a rapid transport across the continent. It is possible that volcanism from the Taconic orogeny was responsible for the abundance of these Paleozoic grains and their extensive dispersal.

The large difference in detrital zircon NPP profiles found in the Ordovician and Pennsylvanian strata indicate a major shift in provenance over this time interval. What caused the Ozark dome to move up relative to sea level during this time? According to sea level curves, sea level was rising during this time (Haq and Schutter, 2008; Sloss, 1963). Since sea level was rising and the Ozark Dome was moving up relative to sea level (i.e., base level was rising), some tectonic influence must have occurred. The Taconic orogeny, well into its development by 450 Ma, may have put the Ozark Dome on an inland forebulge. Far field tectonism was influential enough to cause a pronounced uplift of the Ozark Dome during this time (Cox, 2009).

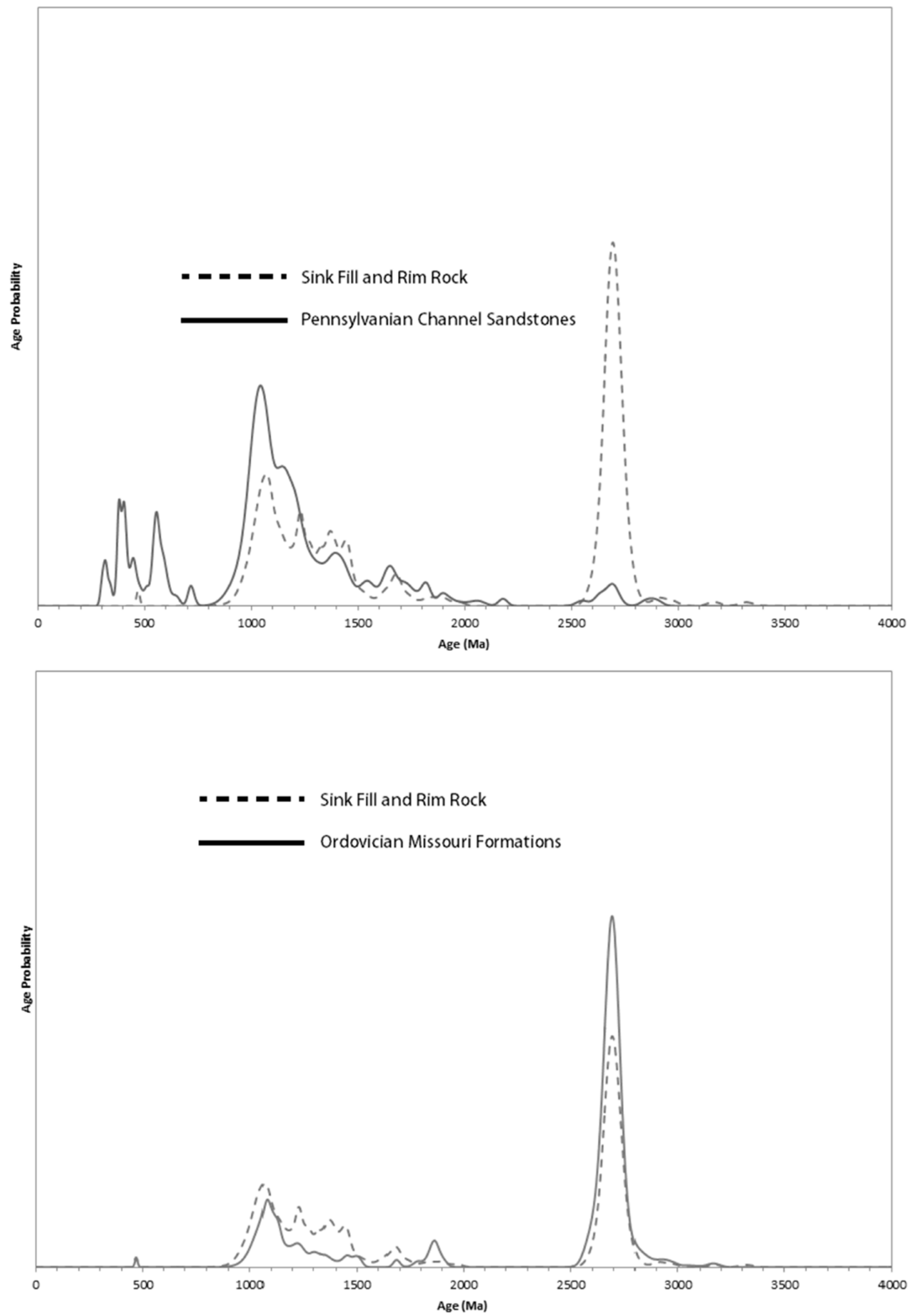

Fig. 9. Comparison of normalized probability plots. “Filled sinks” compared with Pennsylvanian Channel Sandstones (top) and Ordovician formations in Missouri (bottom). Filled sink and rim rock n=282, Pennsylvanian Channel Sandstones n=232, Ordovician formations n=379.

6. CONCLUSIONS

Detrital zircon geochronological data demonstrates that the “filled sinks” of Missouri are most likely Ordovician in age. This is because they contain a large Superior craton population of zircon grains, and they do not contain the Paleozoic Appalachian basement grains. Sedimentological, outcrop, and map data also do not support the formation of the “filled sinks” as solutional removal with concurrent subsidence. These sinks contain internal structures consistent with fluvial deposition, are interbedded with Ordovician strata, restrict most of their deformation towards the margins of the sink, and appear on a regional scale to resemble a large drainage network. These Pennsylvanian age “filled sinks” are neither Pennsylvanian in age nor are they filled sinks. It would be more consistent with evidence presented here to call them Ordovician and a solution valley facies equivalent to the St. Peter.

The Ordovician to Pennsylvanian shift in provenance for the Missouri basin reflects both changing base level due to large sedimentary sequences, as well as the tectonic influence of the Taconic orogeny. The shift in provenance from the Precambrian Superior Shield to the Paleozoic Appalachian basement was a change that affected the transportation and distribution of detritus across the North American continent. It is possible that this sediment was introduced via the Missouri basin on the way to the Grand Canyon.

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APPENDIX A.

PETROGRAPHY OF SAMPLES

Prior Petrographic Data

The Warrensburg sandstone was extensively detailed by Doty and Hubert. Their results have been reiterated in tables A1 and A2:

Table A1. From Doty and Hubert (1961) petrography of the Warrensburg and other selected sandstones, values in percent.

	Sample Member	W1-1	W1-13	W1-27	W2-1	W2-13
General Count	Muscovite	5	3	4	2	7
	Biotite	2	1	1	3	1
	Chlorite	9	8	2	-	1
	Opaques	28	28	15	14	11
	Detritial non-opaques	46	52	78	69	75
	Authigenic anatase	10	8	-	12	5
	Total	**100**	**100**	**100**	**100**	**100**
Detrital, non-micaceous, non-opaque minerals	Apatite	2	-	3	-	2
	Garnet	34	11	2	8	1
	Rutile	4	4	5	1	10
	Tourmaline- subangular to angular	30	45	48	38	16
	Tourmaline- subrounded to rounded	2	2	3	4	1
	Zircon- idiomorphic angular	4	17	18	18	30
	Zircon- fragmental angular	13	8	6	11	14
	Zircon-subrounded to rounded	2	10	13	19	25
	Miscellaneous	9	3	2	1	1
	Total	**100**	**100**	**100**	**100**	**100**

Doty and Hubert additionally propose a lithological characterization of the sediment sources, with four primary groups: Pennsylvanian soils, metamorphic rocks, feldspathic crystalline rocks, and pre-Warrensburg Sedimentary rocks. The last two categories are split further: crystalline rocks include the feldspathic plutonic rocks and pegmatites and veins; and pre-Warrensburg sedimentary rocks are split into carbonates and siliclastics.

Table A2. From Doty and Hubert (1961) petrography of the Warrensburg and other selected sandstones, values in percent.

	Sample Member	W2-35	W3-1	W3-13	W3-25	Mean
General Count	Muscovite	4	2	3	1	**3**
	Biotite	3	1	1	2	**2**
	Chlorite	1	4	2	1	**3**
	Opaques	11	11	7	7	**15**
	Detritial non-opaques	78	82	86	86	**72**
	Authigenic anatase	3	-	1	3	**5**
	Total	**100**	**100**	**100**	**100**	**100**
Detrital, non-micaceous, non-opaque minerals	Apatite	4	3	1	1	**2**
	Garnet	5	19	5	3	**8**
	Rutile	4	6	5	6	**5**
	Tourmaline-subangular to angular	53	9	8	6	**28**
	Tourmaline-subrounded to rounded	2	2	3	1	**2**
	Zircon- idiomorphic angular	10	20	31	39	**22**
	Zircon- fragmental angular	7	12	16	12	**12**
	Zircon-subrounded to rounded	14	25	30	32	**19**
	Miscellaneous	1	4	1	1	**2**
	Total	**100**	**100**	**100**	**100**	**100**

Each of these groupings and sub-groupings have specific grains which are associated with them e.g. metamorphic rocks contribute the highly undulose quartz, slate, phyllite, garnet, zircon, apatite, and others. These are cemented by silica and calcite cements over time. It is suggested that the metamorphic rocks are the strongest source of sediments, likely from the Archean Superior craton and Trans-Hudson arch.

Figure A1 is the ternary quartz-feldspar-lithic plot composed by Doty and Hubert

(1961) recreated for clarity and readability. Their samples from the Warrensburg sandstone typically plot as quartzose greywacke or micaceous quartzite. They attribute the large amount of quartz as a result of selective sorting during fluvial transportation.

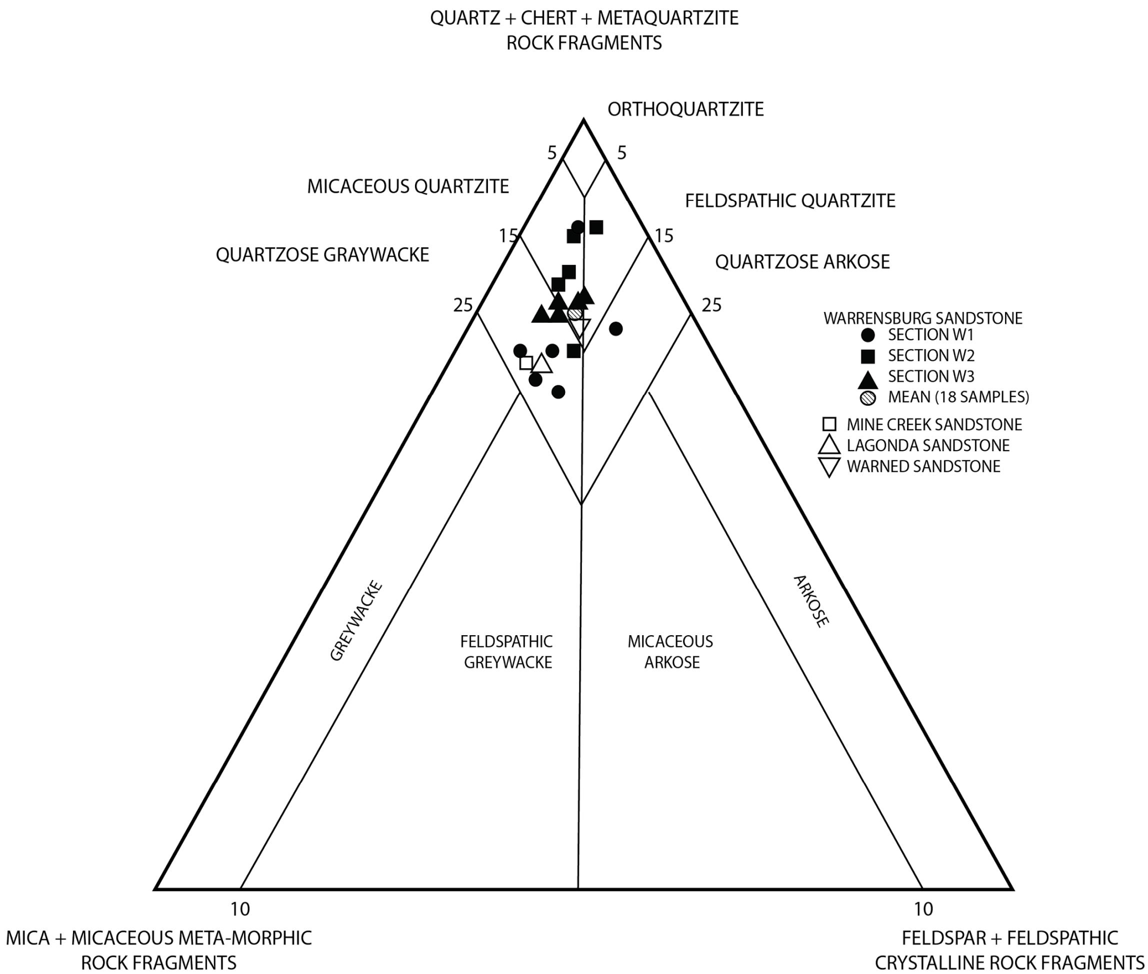

Figure A1. Ternary QFL diagram recreated from Doty and Hubert (1961), from the data recorded in Table A1.

Petrographic Data from 14 MO9,14MO10, 15MO1, and 15MO2

Table A2. QFL data from four samples analyzed as part of this research, including the collapse fill, rim rock from the collapse fill, and channel sandstones.

Geologic unit	**Collapse Fill**	**Collapse Rim**	**Moberly**	**Warrensburg**
	14MO9	14MO10	15MO1	15MO2
Location	HWY 63 N of Rolla	HWY 63 N of Rolla	Outside of Moberly, MO	Outside of Warrensburg, MO
UTM zone	15S	15S	15S	15S
Easting	610286	608945	533851	434292
Northing	4203449	4203622	4360992	4291426
Petrography				
Quartz	144	162	170	165
Feldspar	51	24	37	31
Lithic Fragments	44	33	26	22
	239	219	233	218
% Quartz	60.251	73.973	72.961	75.688
% Feldspar	21.339	10.959	15.88	14.22
% Lithic Fragments	18.41	15.068	11.159	10.092

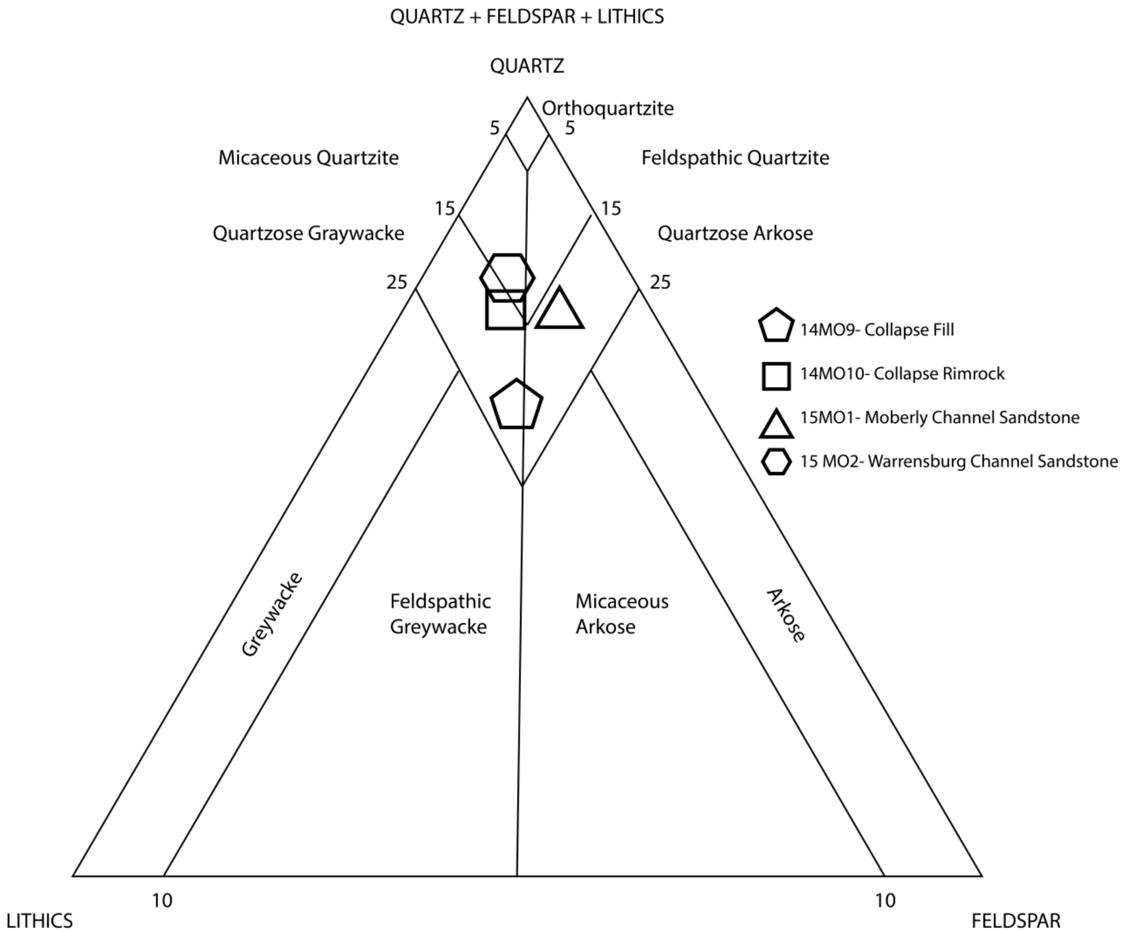

Figure A2. Ternary QFL diagram of four Missouri samples analyzed. Data recorded in Table A1.

Photos of 15MO1 and 15MO2

Figure A3. Moberly sandstone exposed in a quarry owned and operated by Norris Quarries located in Salt Springs Township, MO. Photo credit to Dr. John P. Hogan.

Figure A4. Moberly sandstone outcrop displaying planar bedding. Rock hammer for scale. Photo credit to Dr. John P. Hogan.

Figure A5. Warrensburg sandstone outcrop displaying cross stratification. Photo taken at outcrop of Warrensburg Sandstone located within Cave Hollow Park in Warrensburg, MO. Photo credit to Dr. John P. Hogan.

Figure A6. Photograph of shaly portion of Warrensburg sandstone. Photo credit to Dr. John P. Hogan.

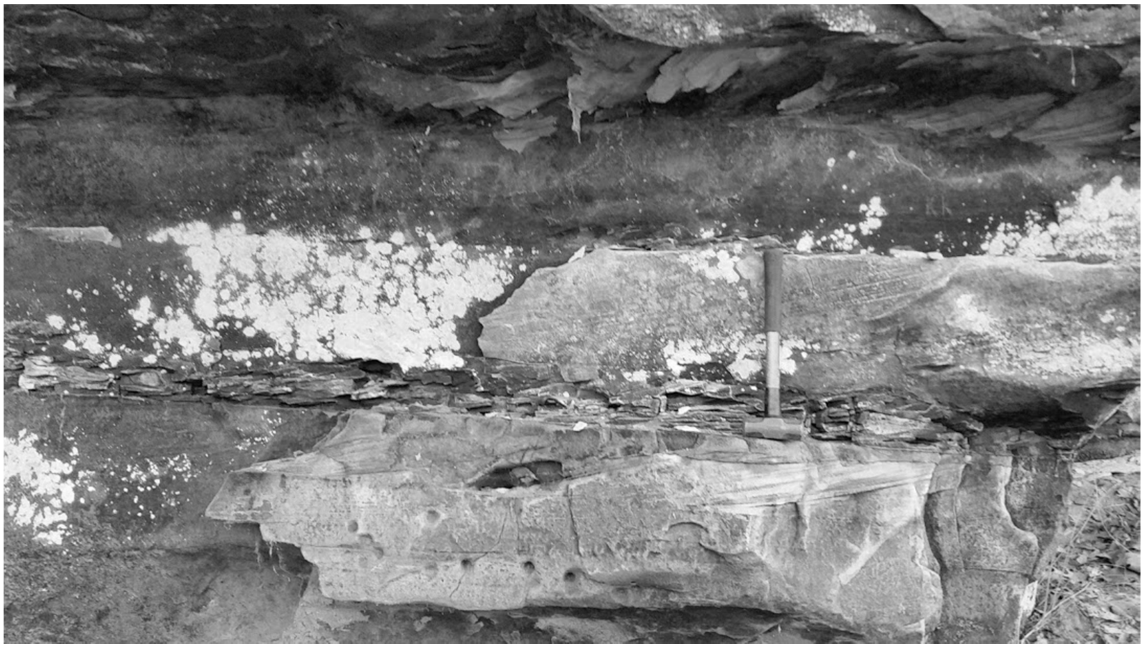

Figure A7. Outcrop of Warrensburg Channel Sandstone in Cave Hollow Park showing shaly layer in between cross-stratified sandstone layers. Photo credit to Dr. John P. Hogan.

Figure A8. Outcrop of Warrensburg channel sandstone in Cave Hollow Park displaying prominent cross-stratification and terminations. Photo credit to Dr. John P. Hogan.

APPENDIX B.

DETRITAL ZIRCON DATA

Five samples were analyzed at Laserchron on the University of Arizona campus in Tuscon Arizona. These samples consisted of 14MO8 – the Gunter Sandstone, 14MO9 and 14MO10 – filled sinks, and 15MO1 and 15MO2 – the Pennsylvanian Channel sandstones. Data reduction and creation of NPP were done using in-house ALC Microsoft Excel programs and ISOPLOT/Ex, version 3 (Ludwig, 2003), and this data is presented in the following figures. Raw data is available in supplemental file 1.

14MO8 Discordance Diagram and raw detrital zircon data

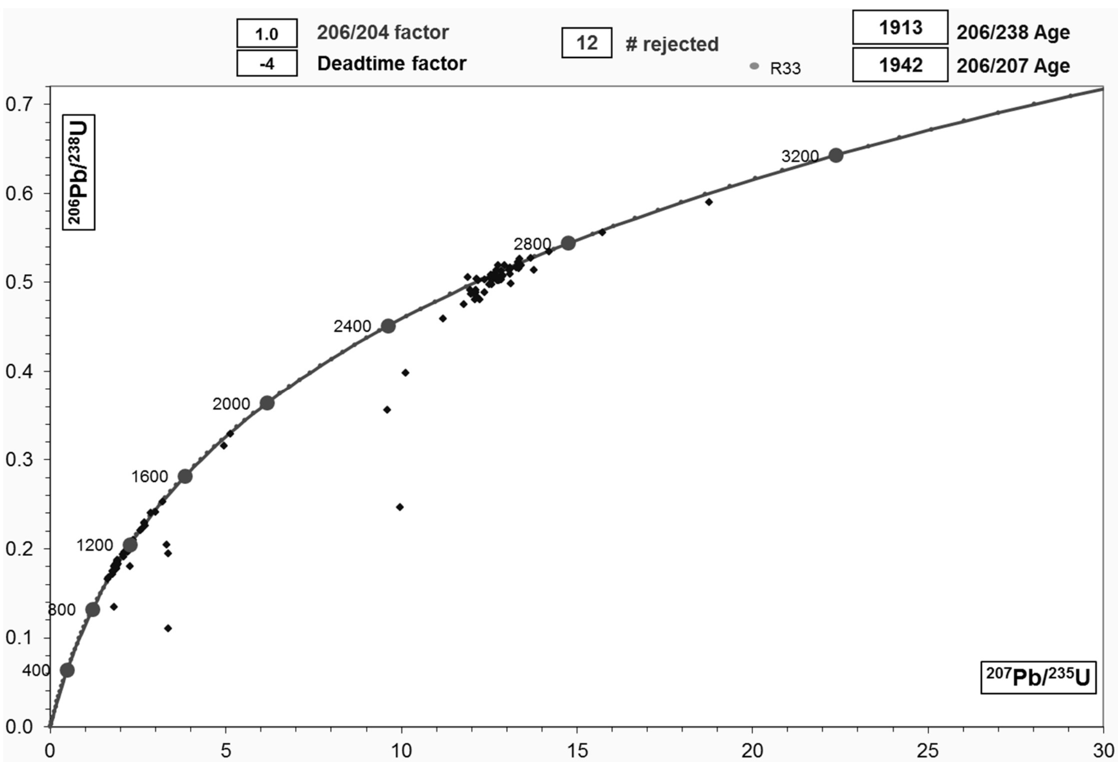

Figure B1. Discordance Diagram of sample 14MO8.

14MO9 Discordance Diagram and raw detrital zircon data

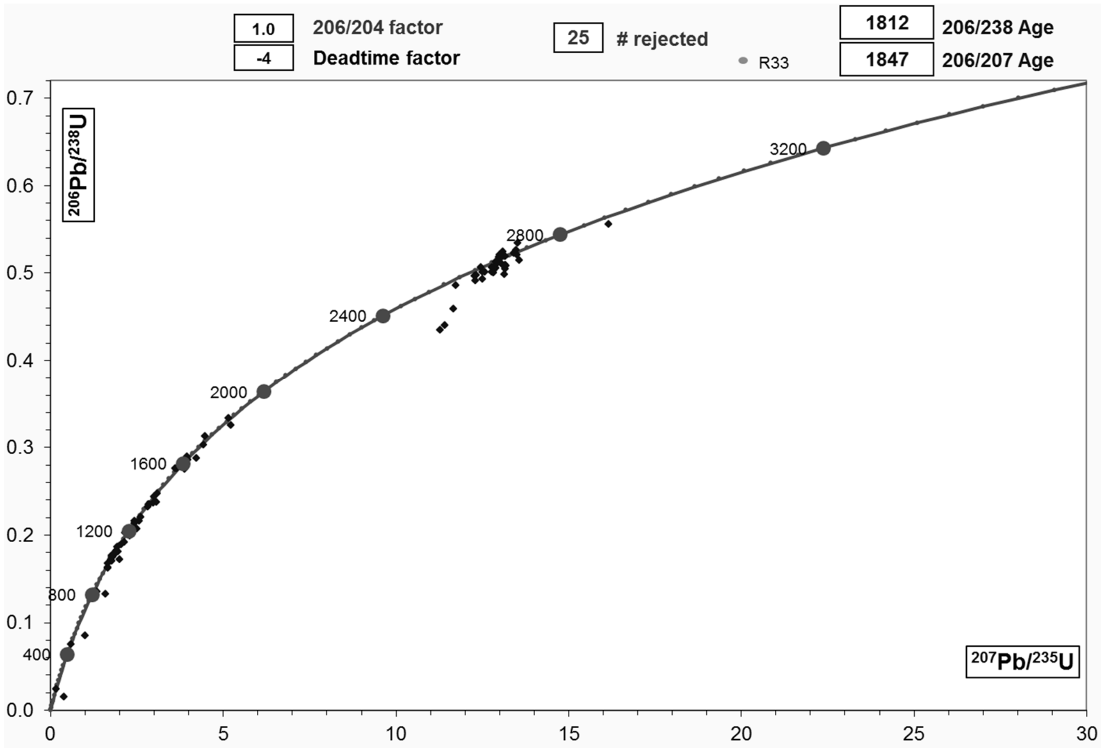

Figure B2. Discordance Diagram of sample 14MO9.

14MO10 Discordance Diagram and raw detrital zircon data

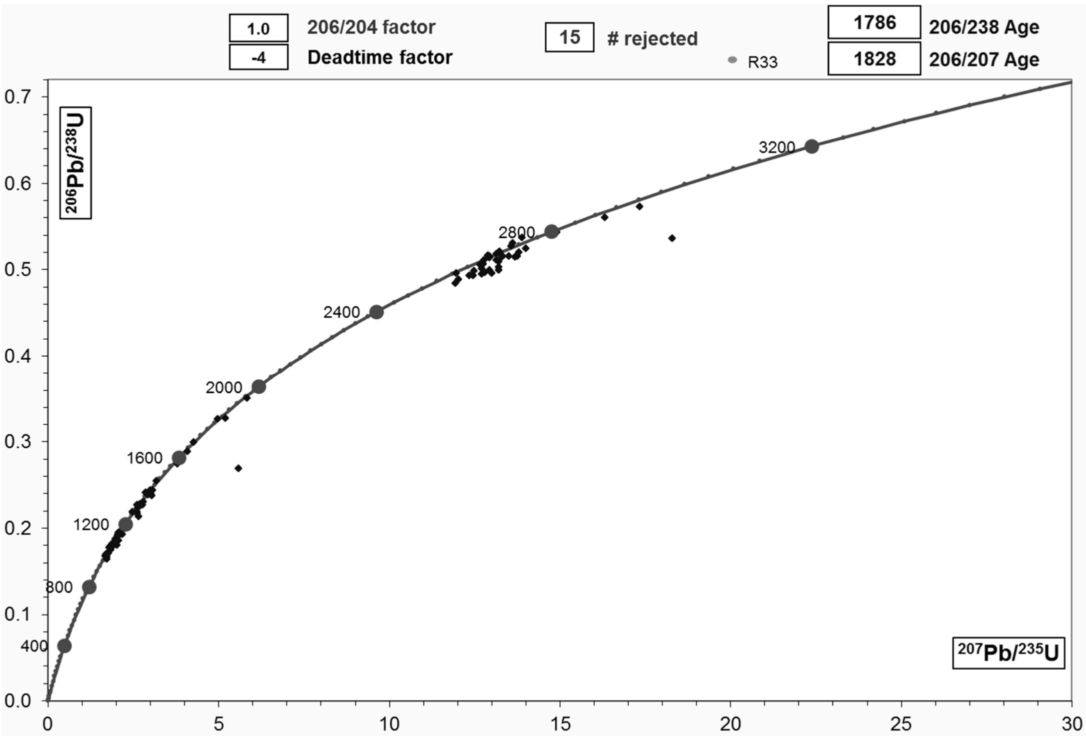

Figure B3. Discordance Diagram of sample 14MO10.

15MO1 Discordance Diagram and raw detrital zircon data

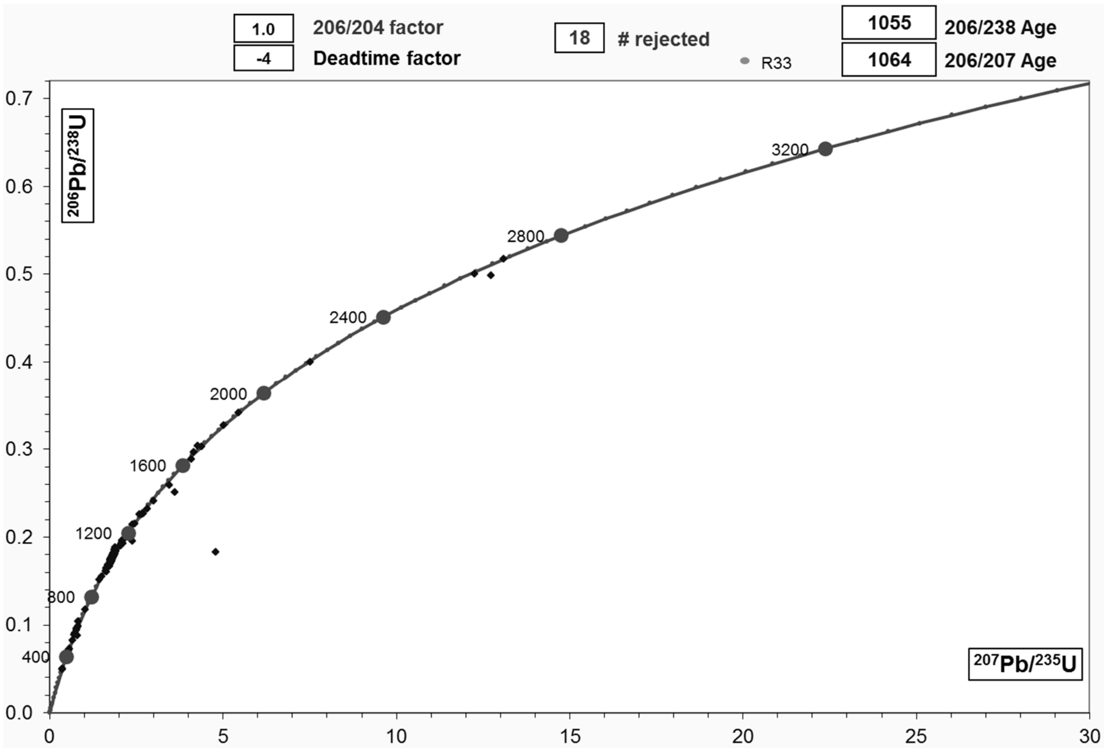

Figure B4- Discordance Diagram of sample 15MO1.

15MO2 Discordance Diagram and raw detrital zircon data

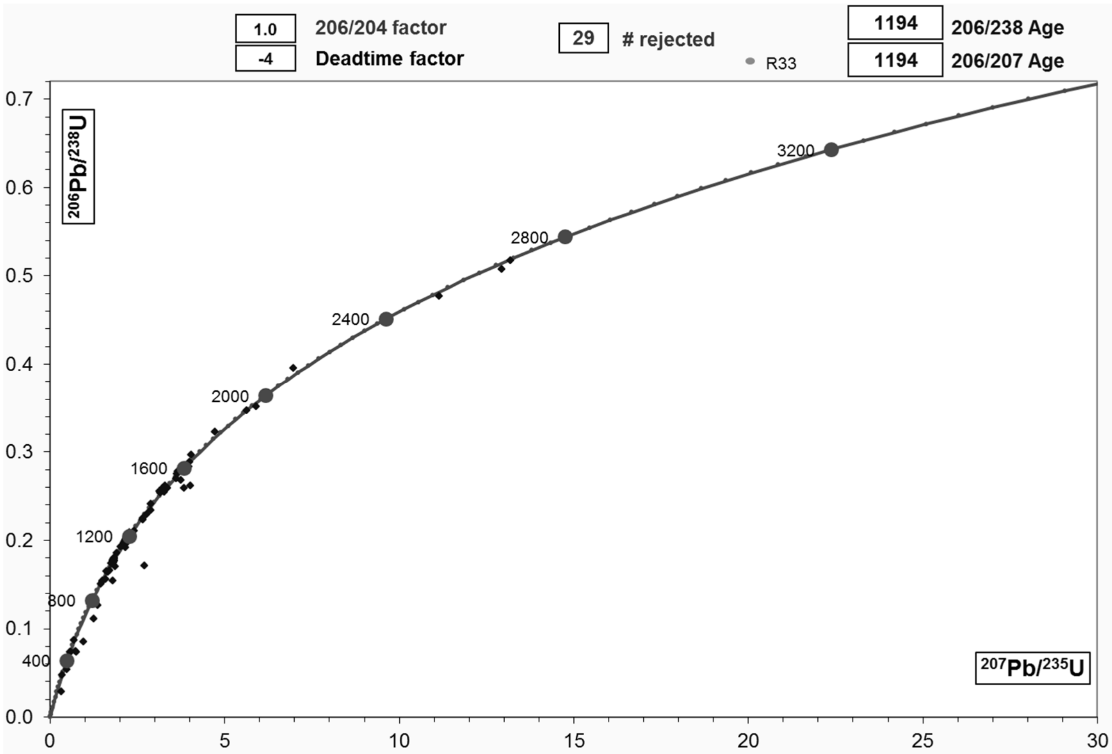

Figure C5- Discordance Diagram of sample 15MO2.

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VITA

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