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Research Article

Geochronology of Cambrian Sedimentary and Volcanic Rocks in the Illinois Basin: Defining the Illinois Aulacogen

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The Wabash #1 well, drilled for the Wabash CarbonSAFE Project and located in Vigo County, Indiana, USA, was drilled in early 2020 as a stratigraphic test well to characterize and evaluate the basal Cambrian Mt. Simon Sandstone for carbon dioxide storage (TD=8750 ft; 2667 m). The Wabash #1 well is located along the eastern flank of a newly interpreted Cambrian aulacogen that occurs in western Indiana and eastern Illinois. Here we present 938 new detrital zircon U-Pb ages (LA-ICPMS) from early Cambrian sandstones sampled near the base of the well. A basalt lava flow was penetrated at ~8530 ft (2600 m) and has an $^{40}Ar/^{39}Ar$ age of 525.03 +/- 1.10 Ma, which represents the first known Cambrian crust in the Illinois Basin. The two sandstone samples from beneath the basalt are dominated by zircons derived from the Midcontinent Granite-Rhyolite terrane. The sandstone samples from above the basalt reflect a mixture of these locally derived Mazatzal and Granite-Rhyolite terrane zircons, but also distal Archean, Grenville, and Yavapai zircons. Each sample has small numbers of Cambrian zircons, which is consistent with those in basal Cambrian sandstones in other deep wells to the west. These early Cambrian detrital zircons and early Cambrian age of the basalt, combined with sediment thickness patterns permit the interpretation of the Illinois aulacogen, which formed during the final stage of Rodinian rifting.

INTRODUCTION

The Illinois Basin is an intracratonic basin that extends across most of Illinois into Kentucky and Indiana and contains more than 5 km of Paleozoic strata (Heidlauf et al., 1986). In southern Illinois, Neoproterozoic-Cambrian rifting is evident in the Reelfoot Rift System (Kolata & Nelson, 1997) where seismic data indicates that the Cambrian Mt. Simon Sandstone unconformably overlies Precambrian basement rocks. Recent deep boreholes drilled for industrial-scale CO_2 storage projects recovered the first core samples from the lower Mt. Simon Sandstone (Freiburg, Holland, et al., 2020) which occur more than 160 km north of the Pennsylvanian Illinois Basin depocenter in southern Illinois (McBride et al., 2003; McBride & Kolata, 1999). In the central and northern the Mt. Simon Sandstone is more than 700 m thick.

The Wabash #1 well, which is part of the CarbonSAFE Wabash Project and located in Vigo County, Indiana, was drilled in early 2020 as a stratigraphic test well to characterize and evaluate the basal Cambrian sandstones for CO_2 storage (TD=8750 ft; 2670 m). This well has a thicker and more complete Cambrian succession than the other three CarbonSAFE wells to the west (Freiburg, Holland, et al., 2020; Figure 1). The Wabash #1 well penetrated the lower Mt. Simon sandstone and a basalt lava flow, which is the first Cambrian igneous rock recognized in the Laurentian midcontinent. Here we present 938 new detrital zircon U-Pb ages from four core samples of the Mt. Simon Sandstone. We also present new $^{40}Ar/^{39}Ar$ age data for the basalt. The concept presented and argued here is that an early Cambrian Illinois aulacogen, akin to the better-known Oklahoma aulacogen, formed as the Cuyania (i.e Argentine Precordillera) terrane rifted from southern Laurentia. Thus, these new data support the hypothesis advanced by Thomas et al. (2004) and further constrain the nature of the Rodinian supercontinent along the southern margin of Laurentia.

BACKGROUND

The core of Laurentia formed by a series of Paleoproterozoic collisional events between Archean cratons. Progressive addition of volcanic arc and oceanic terranes accreted onto this core (Whitmeyer & Karlstrom, 2007; Figure 2).

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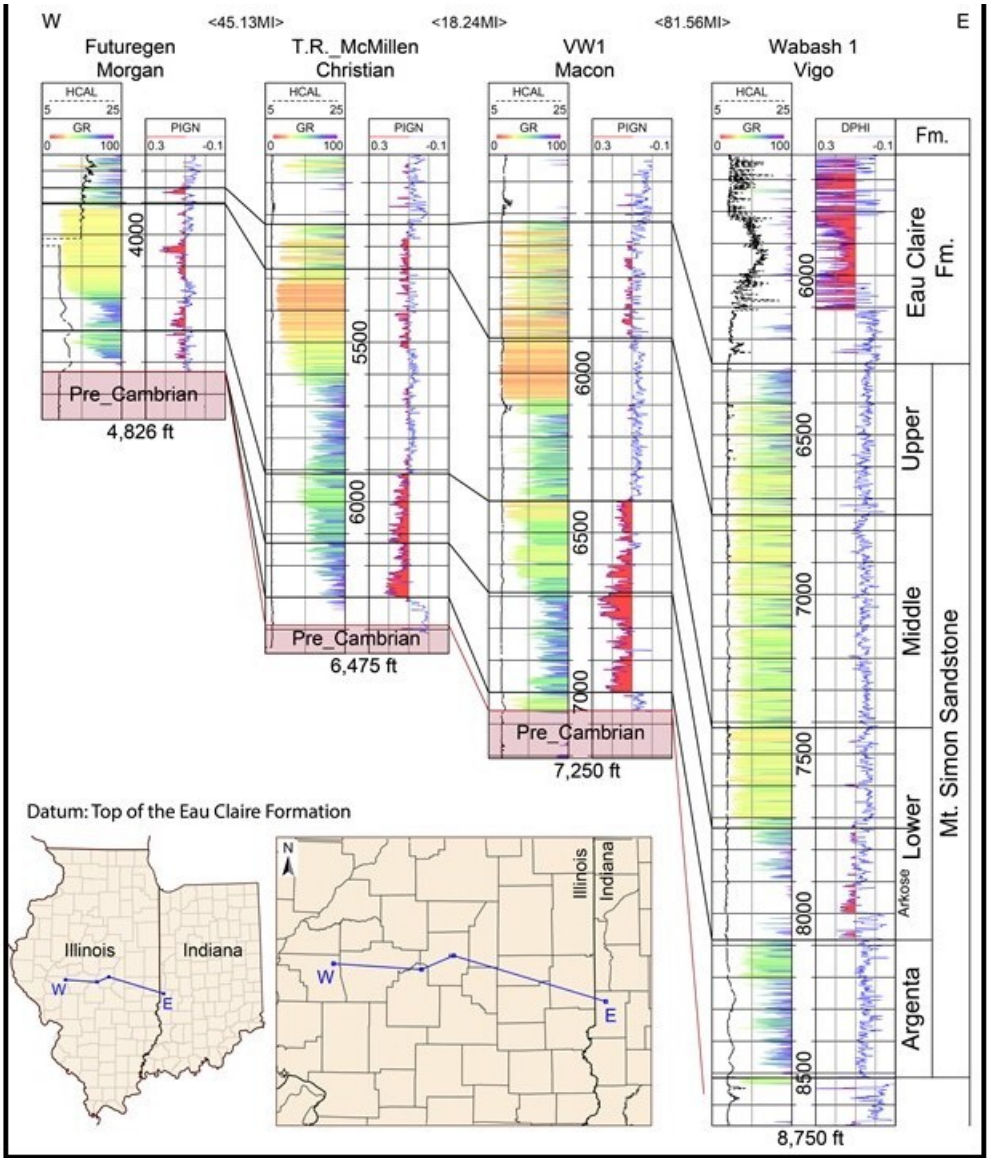

Figure 1. Geophysical log cross-section of the Mt. Simon Sandstone in the (right to left) Wabash #1 well, Vigo Co., Indiana; Verification #1 well (VW1), Macon Co., Illinois; T.R. McMillen #2 well, Christian Co., Illinois; and the FutureGen Alliance #1 well, Morgan Co., Illinois.

The Archean Superior province is bounded to the south by the Penokean orogen, which includes the Archean Marshfield terrane (Craddock et al., 2018). Further to the south, Yavapai (1.8-1.70 Ga) and Mazatzal Province (1.70 -1.60 Ga) occur and are overprinted by rocks related to Grenville-age tectonism to the east (Craddock et al., 2017). Yavapai and Penokean age rocks are the basement for ~1.6 Ga Baraboo Interval strata (Stewart et al., 2021). Igneous and sedimentary rocks of the ~1.1 Ga Midcontinent rift are present in the Lake Superior area and extend southward into Ohio and Indiana (Craddock et al., 2013; Malone et al., 2020; Moecher et al., 2018; Stein et al., 2015).

The basement rocks of Illinois consist of a voluminous Mesoproterozoic magmatic belt (ca. 1.37-1.48 Ga) referred to as the Granite-Rhyolite province (GRP; Bickford et al., 2015; Van Schmus et al., 1993). Although no Mazatzal crustal rocks have been sampled by deep drilling in this area as yet, its presence is interpreted through the abundance of Mazatzal age zircons in the basal Cambrian strata (Freiburg, Holland, et al., 2020) in Illinois and the uppermost Baraboo Interval strata in Wisconsin (Medaris et al., 2021). The GRP is bisected by a southwest–northeast trending isotopic discontinuity dubbed the "Nd line" (Van Schmus et al., 1996). The Nd line separates Mesoproterozoic igneous rocks with Nd model ages > 1.55 Ga to the northwest from those with <1.55 Ga model ages to the southeast. Mesoproterozoic rocks to the south-east are thought to represent 1.55–1.35 Ga juvenile crust that accreted as part of a long- lived arc system, whereas rocks to the northwest were derived from melting of Paleoproterozoic crust during Granite-Rhyolite magmatism (Bickford et al., 2015; Van Schmus et al., 1996; Whitmeyer & Karlstrom, 2007).

The rifting and eventual breakup of the Rodinian supercontinent occurred from ~780-530 Ma, with the thickest (~10 km) and best exposed being along the Cordilleran con-

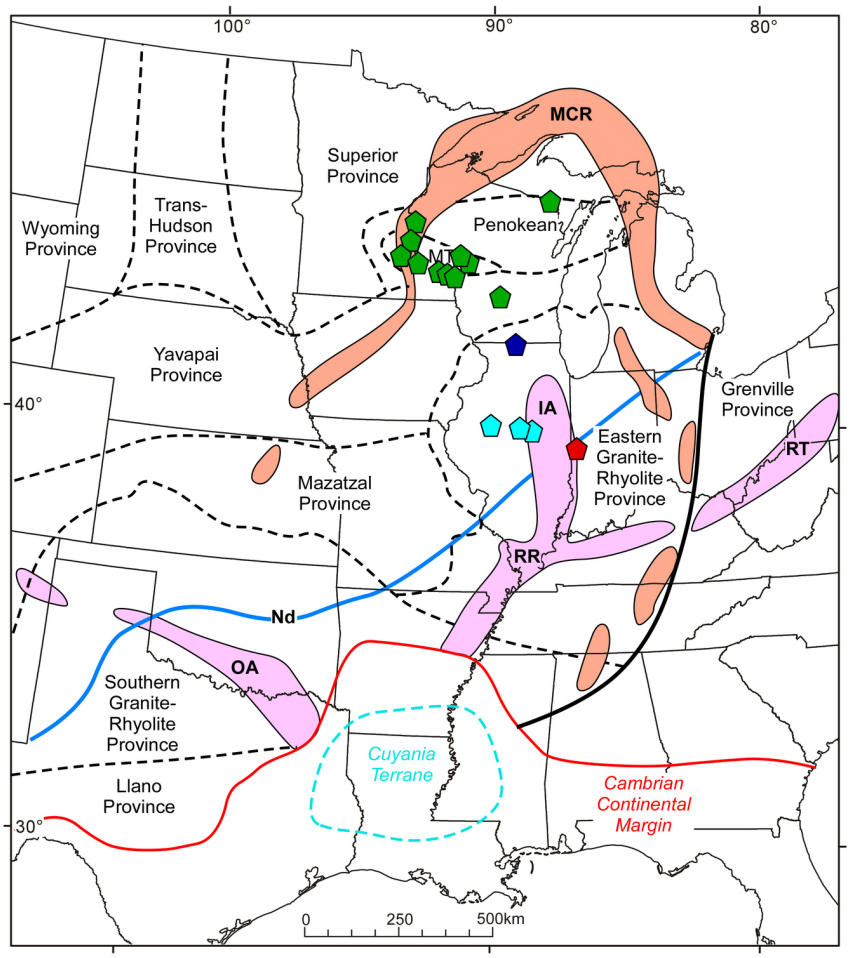

Figure 2. Map of basement terranes of the Laurentian midcontinent (modified from Bickford et al., 2015; Freiburg, McBride, et al., 2020 and Malone et al., 2016).

The locations of the Marshfield Terrane (MT), Oklahoma Aulocogen (OA), Reelfoot rift (RR), Rome Trough (RT), and Illinois aulacogen (IA). The 1.1 Ga Midcontinent rift (MCR) is indicated in orange. Light blue pentagons = Illinois Basin Decatur Project and CarbonSAFE Macon Co. Project samples. Green pentagons = sampling sites for late Cambrian arenites reported in Konstantinou et al. (2014). Dark blue pentagon = Mt. Simon drill core sampling locality reported in Lovell and Bowen (2013). Red pentagons = Mt. Simon samples from the Wabash #1 well. Dark blue line is the "Nd line" Bickford et al. (2015), which separates crust yielding Nd model ages greater than 1.55 Ga to the north and less than 1.55 Ga to the south. The rifted Cuyania terrane is indicated.

tinental margin (Yonkee et al., 2014). Neoproterozoic to Cambrian passive margin strata are also occur along the Appalachian continental margin (Smoot & Southworth, 2014; Walsh & Aleinikoff, 1999). The Oklahoma aulacogen, which consists of 530–540 Ma rift-related volcanic and plutonic rocks, represent the latest stage of Rodinian rifting and the departure of the Cuyania terrane, which later accreted to South America (Hanson et al., 2013; Thomas, 1991; Thomas et al., 2004, 2012). Freiburg et al. (2020) presented Early Cambrian detrital zircon ages in the lower Mt. Simon and pre-Mt. Simon sandstones in central Illinois.

METHODS

Sandstone was sampled from a full-diameter (10 cm) core near the base of the Wabash #1 well at a depth of 7,972.0-7,972.5 ft (2429.8-2430.0 m). Five rotary side wall cores (2.5 cm) were recovered and sampled from sandstone at depths of 8500 ft (2591 m), 8655 ft (2638 m), 8660 (2640 m), and 8680 ft (2646 m), and basalt at 8530 ft (2600 m; Figure 3). The core taken at 8655 ft did not yield zircons. Zircons were separated using standard gravitational and magnetic techniques. U–Pb geochronology of zircon was conducted by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center, following the methods of Gehrels et al. (2006, 2008) and Gehrels and Pecha (2014). Unknown zircons were mounted with the standard Sri Lanka, FC-1, and R33 zircons on a 1″ puck with epoxy, sanded down to a depth of ~20 µm, polished, and cleaned prior to analysis. The analyses were performed by ablation of zircon with a Photon Machines Analyte G2 excimer laser equipped with HelEx ablation cell using a spot diameter of 20 µm. Figure 4 is a stacked probability plot of the detrital zircon age spectra for the sandstone samples.

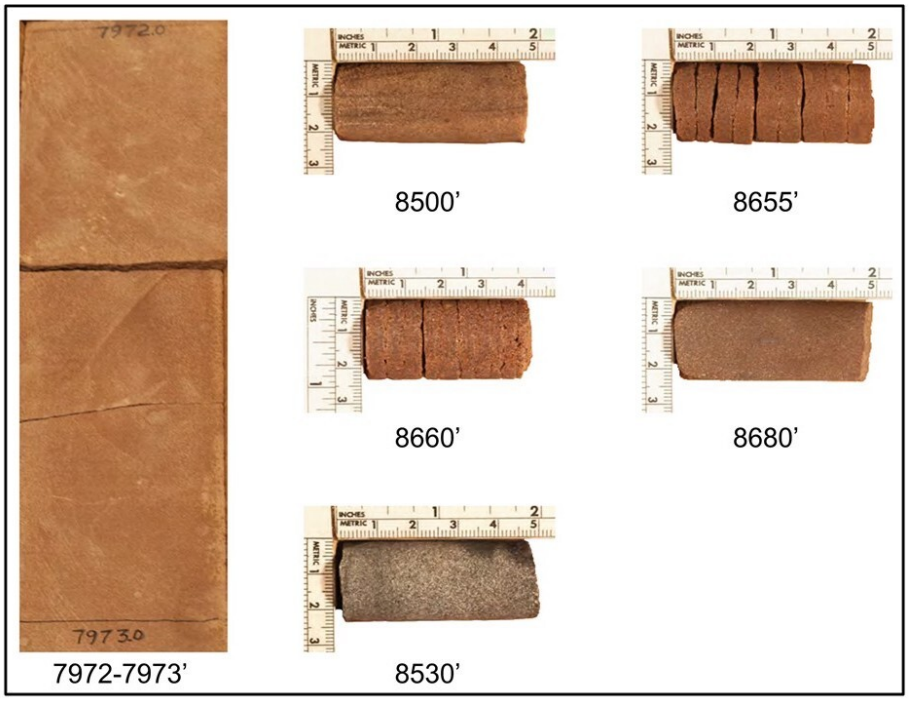

Figure 3. Photographs of Wabash #1 well Mt. Simon Sandstone full diameter (3.5 inch) core sample from 7,972-7,973 and rotary sidewall core samples (1-inch diameter) from the Wabash #1 well.

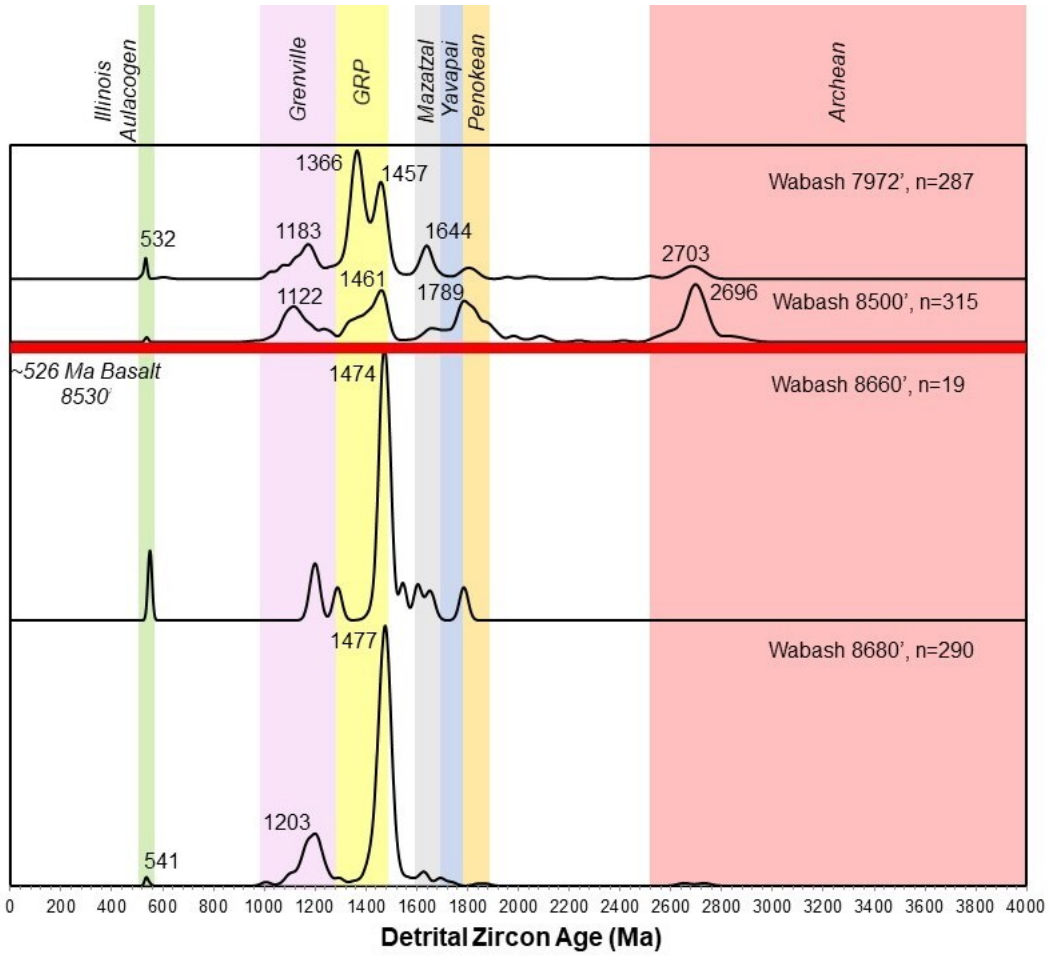

Figure 4. Stacked probability plots of detrital zircon age spectra from the Wabash #1 well core samples.

$^{40}Ar/^{39}Ar$ ages were obtained by incremental heating methods using the ThermoFisher Scientific ARGUS-VI mass spectrometer and data collection using internal lab software ArArExperiments version 4.5.7. The samples were irradiated for 6 Megawatt hours (Irradiation 21-OSU-01) in the CLICIT position in the Oregon State University's TRIGA nuclear reactor. The $^{40}Ar/^{39}Ar$ incremental heating age determinations were performed on a multi-collector ARGUS-VI mass spectrometer at Oregon State University. Data reduction and age calculation were processed using Ar-Ar Calc 2.7.0. Figure 5 presents a photomicrograph and plateau age for the basalt. The details of these analytical procedures and geocryological data are provided in the supplementary files.

RESULTS

A total of 295 detrital zircon ages are presented from the lower Mt. Simon Sandstone full diameter core sampled from a depth of 7,972-7,972.5 ft (2429.8-2430.0 m). The dominant age peak is ~1,367 Ma, with lesser peaks at 1,460; 1,179; 1,643; 522; 2,678, and 1,807 Ma. The sidewall core sample at a depth of 8,500 ft. is located approximately 15 ft (5 m) above the top of the basalt. A total of 342 zircon ages are presented. The dominant age peak is at ~2,696 Ma, with lesser peaks at 1,461; 1,789; 1,122; and 541 Ma. A total of 19 detrital zircon ages were analyzed for the 8660 ft depth sample that occurs below the basalt. The dominant age peak is ~1,474 Ma. A major difference compared to shallower samples is the absence of detrital zircon ages older than ~1,900 Ma. The sample from 8,680 ft had 290 detrital zircon ages presented. The dominant age peak is ~1,477 Ma, with lesser peaks at 1,203 Ma and 541 Ma.

The basalt is about 30 ft (10 m) thick and consists of plagioclase phenocrysts in an aphanitic groundmass. The basalt is concordant with the adjacent strata and can be interpreted as either a lava flow or sill; the latter is preferred. The $^{40}Ar/^{39}Ar$ dating age (plateau ages with 2σ uncertainties) is 525.19 +/- 1.10 Ma. A succession of micaceous silt occurs below the basalt, which may have been deposited in a lacustrine environment, which are common in rift basins (Katz, 1990). Two-dimension seismic reflection across the area of the Wabash #1 well suggest several layers of basalt interbedded with the Cambrian strata (Freiburg et al., 2022).

DISCUSSION

Age of the Mt. Simon Sandstone and Rift-Related Volcanism

Cambrian strata, particularly the upper Mt. Simon sandstones exposed in Missouri and Wisconsin are late Cambrian in age (Konstantinou et al., 2014). The maximum depositional age (MDA) of basal Cambrian sandstones in the Illinois basin are Early Cambrian in age (Freiburg, Holland, et al., 2020). This Early Cambrian age is supported by the ~525 Ma age for the interbedded basalt in the Wabash #1 well. The Early Cambrian age of the basalt is consistent with other syn-rift igneous rocks reported along the southern Laurentian margin (Aleinikoff et al., 1995; Badger & Sinha, 1988; Hanson et al., 2013; Thomas et al., 2012) and marks the end of the break-up of Rodinia (Li et al., 2008). Image logs of this basalt show a sharp horizontal contact with sedimentary rocks at both the top and bottom.

Lower Zircon Chronofacies

The sandstones sampled from beneath the basalt have a distinct detrital zircon chronofacies that has a prominent unimodal age peak of ~1.475 Ga, which is slightly older than that reported by Freiburg et al. (2020) for the basal Cambrian sandstones sampled from other CarbonSAFE wells to the west. The small ~1.2 Ga Grenville age peak is also distinct, and reflects basement rocks emplaced during the earliest, Elzevirian phase of the Grenville orogeny (Bartholomew & Hatcher, 2010; McLelland et al., 1996), which occur largely in the central and southern Appalachian continental margin. Small numbers of Archean, Paleoproterozoic, younger GRP and Cambrian zircons also are present. Freiburg et al. (2020) reported an MDA of ~525 Ma for basal Mt. Simon and Argenta samples in the wells to the west and speculated that these zircons were either locally derived or transported to Illinois from elsewhere in Laurentia like the Oklahoma aulacogen, favoring the former. The presence of the basalt of 525 Ma encountered in the Wabash #1 well supports our earlier interpretation. Thus, the lower chronofacies is dominated from zircons derived from within the Illinois aulacogen, with smaller amounts of sediment from its environs, mostly from the east or southeast.

Upper Zircon Chronofacies

The Mt. Simon sandstone sampled from above the basalt has small ~2.7 Ga age peaks. This age peak is definitive of the Archean Superior province, which occurs more than 500 km to the north (Freiburg, Holland, et al., 2020; Konstantinou et al., 2014). Zircons of this age don't occur along the western flank of the aulacogen (Freiburg, Holland, et al., 2020) but are common outside of the aulacogen particularly in the upper Mt. Simon (Lovell & Bowen, 2013). This absence may reflect the burial of localized sediment sources as the aulacogen was filled and more input from the north. Penokean, Yavapai, and Mazatzal age peaks are also unique to the samples taken from above the basalt. Like the Archean grains, these reflect derivation from distal sediment source areas to the north (Craddock et al., 2018; Medaris et al., 2021). The uppermost sample has a small 1660 Ma peak, which is not known in the southern Superior province or in the Illinois Basin basement. Zircons of this age are present in abundance in the Neoproterozoic Jacobsville Sandstone of the Midcontinent Rift (Malone et al., 2016, 2020), and Baraboo Interval quartzites from the Waterloo area and Baraboo Hills of southern Wisconsin (Malone et al., 2022; Medaris et al., 2021).

GRP zircons in the uppermost sandstones have prominent ~1.37 and ~1.46 Ga age peaks. Rocks of these ages are exposed in the St. Francis Mtns of Missouri and are interpreted to be the basement rock of much of the Illinois Basin (Bickford et al., 2015; Van Schmus et al., 1996). Freiburg et

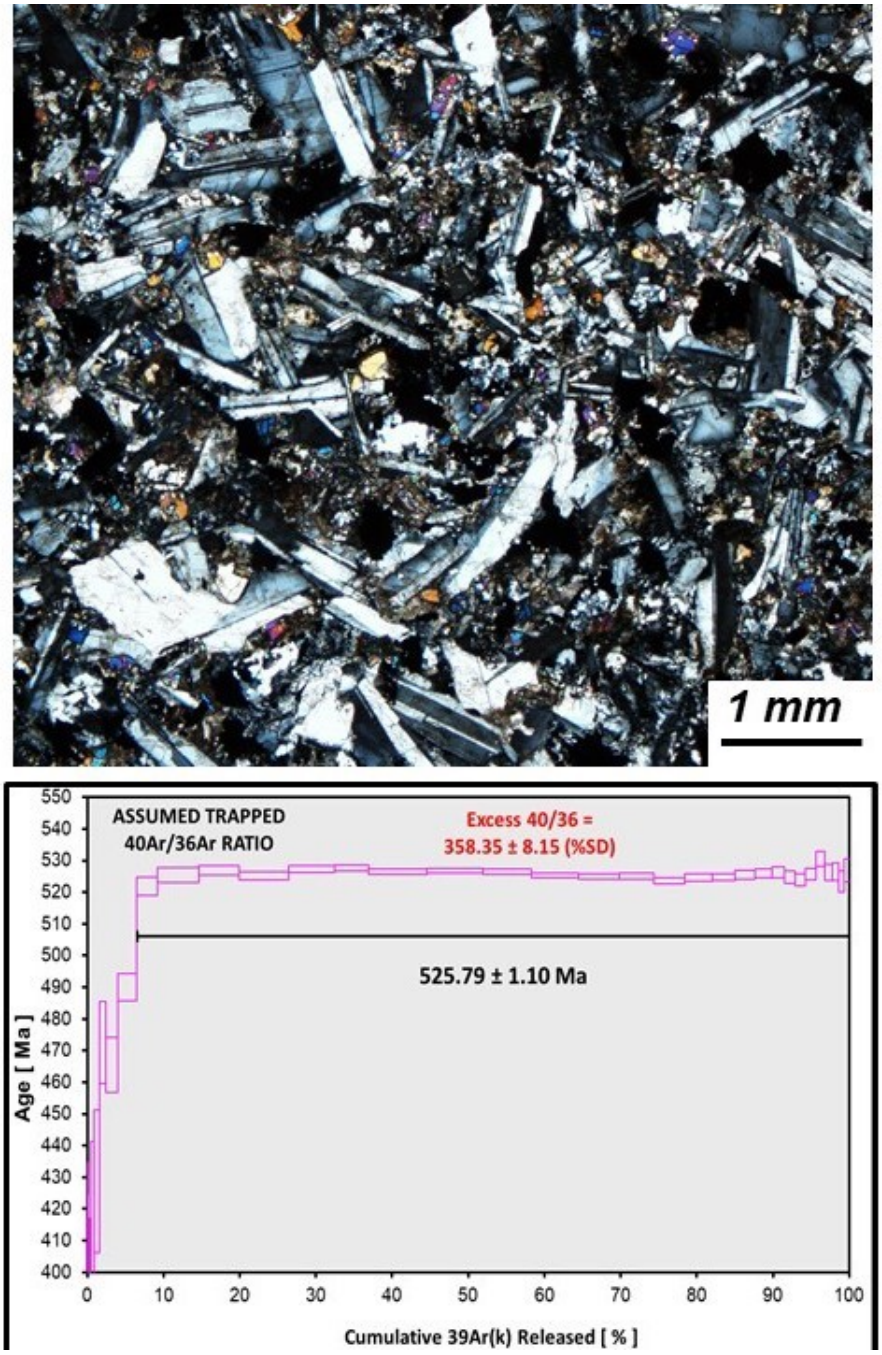

Figure 5. Thin section cross-polarized light photomicrographs of the basalt, which consists of plagioclase phenocryst in a fine-grained groundmass of pyroxene, amphibole, and magnetite (upper). Groundmass plateau age of 525.79 +/- 1.10 Ma (lower).

al. (2020) reported a 1.467 Ga rhyolite penetrated by Verification well # 1 at the Decatur CarbonSAFE project (Figure 1).

Small Grenville age peaks of ~1.1-1.2 Ga age peaks reflecting the Shawingian phase of the Grenville orogeny (Craddock et al., 2017; McLelland et al., 1996) are present in both sandstone units that overlie the basalt. The abundance of Grenville zircons is well known throughout the Laurentian midcontinent (Moecher & Samson, 2006), including rift basins of the eastern midcontinent (Moecher et al., 2018; Schneider Santos et al., 2002), in the Midcontinent Rift (Craddock et al., 2013; Malone et al., 2016), the Cambro-Ordovician arenites in the Laurentian midcontinent (Konstantinou et al., 2014) and the Neorproterozoic-Cambrian Cordilleran continental margin (Spencer et al., 2014; Yonkee et al., 2014).

In summary, the upper zircon chronofacies represents distally derived sediment, mainly to the north and east, and outside of the Illinois aulacogen. Small amounts of locally derived Cambrian and MGR sediment also is present, but these zircons wane in abundance as the Illinois aulacogen was filled and the local sediment source areas were buried. By late Cambrian time, most of the crust in the Illinois basin area was buried, leaving distally derived sedi-

ment from the Superior province and Grenville orogen to dominate the Cambrian depositional environments (Konstantinou et al., 2014; Lovell & Bowen, 2013).

Defining the Illinois Aulacogen

Aulacogens are long troughs extending into continental interiors from rifted continental margin and contain accumulations of mainly terrestrial siliciclastic and volcanic strata several times thicker than the adjacent cratonic successions (Burke, 1977). Early Cambrian Mt. Simon sandstone thickness patterns, detrital zircon geochronology, and the occurrence of an Early Cambrian (~525 Ma) basalt lava flow interbedded with the Mt. Simon sandstone require a re-evaluation of the northern Illinois basin sedimentary and tectonic history. Freiburg et al. (2020) speculated on a northern extension of the Realfoot rift (Kolata & Nelson, 1997), which occurs beneath the depocenter of the Illinois basin to the south. We herein name this northern extension of the Realfoot rift the Illinois aulacogen. The Wabash #1 likely occurs along the axis or deep eastern margin of this aulacogen. The CarbonSAFE wells to the west penetrate progressively shallower parts of the western shoulder of the aulacogen. The Illinois aulacogen is temporally (i.e. Late Neoproterozoic and Early Cambrian in age) and tectonically related to the Oklahoma aulacogen (i.e. both related to the Rodinian breakup along the southern margin of Laurentia), which occurs about 1000 km to the southwest.

CONCLUSIONS

Several conclusions can be drawn from this effort:

1. The lowermost sandstone samples beneath the basal have a unique detrital zircon provenance, which reflects GRP and Cambrian zircons derived locally from within the Illinois aulacogen. In contrast, sandstone samples from above the basalt have a mixed provenance with zircons derived locally and distally, with Archean, Paleoproterozoic, MGR and Grenville source areas indicated.
2. The first direct evidence of early Cambrian crust in the Laurentian midcontinent occurs as a 525 Ma basalt lava flow that is interbedded within Early Cambrian sandstone.
3. The Illinois aulacogen, which extends north from the Reelfoot rift, is another failed arm of Rodinian rifting along southern Laurentia, which culminated during the early Cambrian with the departure of the Cuyania terrane.

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Supplementary Materials

The U-Pb data

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The details of the analytical methodology

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