Detrital zircons from crystalline rocks along the Southern Oklahoma fault system, Wichita and Arbuckle Mountains, USA

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ABSTRACT

Detrital zircons with ages of 535 ± 10 Ma in many North American Midcontinent sandstones are commonly attributed to sources in Cambrian synrift igneous rocks along the Southern Oklahoma fault system. New analyses are designed to test the characteristics of proximal detritus from the Wichita and Arbuckle uplifts. Detrital zircons from a sandstone (Lower Permian Post Oak Conglomerate) directly above an unconformable contact with the Wichita Granite Group in the Wichita Mountains have strongly unimodal U-Pb ages of 540–520 Ma and εHf values of +4.7 to +10.1. In contrast, two sandstone samples (Upper Pennsylvanian Vanoss Conglomerate) in the onlapping succession above an angular unconformity on Paleozoic strata of the Wichita and Arbuckle anticline have detrital zircons with U-Pb ages that correspond dominantly to the Superior (~2700 Ma) and secondarily to the Granite-Rhyolite (~1480–1320 Ma) or Grenville (1300–970 Ma) provinces of the Laurentian craton. The Vanoss zircons indicate recycling from quartzose sandstones within the Middle Ordovician platform carbonates in the Arbuckle passive-margin cover succession. A stratigraphically higher sandstone (Permian Wellington Formation) above the onlapping conglomerates has a more diverse detrital-zircon population, indicating that sediment dispersal from external sources overwhelmed the proximal detritus in the immediate cover of the Wichita and Arbuckle uplifts. The distinctive εHf values of the proximal detritus from the Cambrian synrift igneous rocks offer potential discrimination from zircons of the same age from Gondwana accreted terranes, which are represented in the Wellington sample.

INTRODUCTION

Detrital zircons with ages of 535 ± 10 Ma, although generally not abundant, are common in many Paleozoic sandstones across the North American Midcontinent, and almost universally are attributed to a source in the well-known Cambrian igneous rocks along the Southern Oklahoma fault system (e.g., Riggs et al., 1996; Dickinson and Gehrels, 2003, 2008; Gleason et al., 2007; Soreghan and Soreghan, 2010). Emplacement of the Cambrian (539–530 Ma) synrift magmas accompanied the late stages of rifting of southeastern Laurentia and opening of the Iapetus Ocean during final breakup of supercontinent Rodinia (Hogan and Gilbert, 1998; Thomas et al., 2012; Hanson et al., 2013). A thick post-rift, Cambrian–Ordovician, passive-margin carbonate succession covered the Cambrian igneous rocks and associated Mesoproterozoic basement rocks (Denison, in Johnson et al., 1988). Late Paleozoic basement-rooted uplifts (Wichita and Arbuckle) along the Southern Oklahoma fault system incorporated the Cambrian igneous rocks and Precambrian basement rocks (Fig. 1). Unroofing of the Wichita and Arbuckle uplifts and Pennsylvanian–Permian stratigraphic onlap rimmed the Southern Oklahoma fault system with proximal clastic deposits, including the classic “Granite Wash” from the crystalline rocks (Johnson et al., 1988).

Gondwanan accreted terranes, which are distributed along the late Paleozoic Appalachian-Ouachita orogenic belt, include Brasiliano–Pan-African and Pampean components, the ages of which range through 700–530 Ma (Lopez et al., 2001; Mueller et al., 2014). The accreted terranes offer an alternative source of ~535 Ma zircons, which are not distinguishable from zircons of the Southern Oklahoma igneous rocks on the basis of age alone.

In order to characterize the detritus from the Southern Oklahoma provenance, new samples of proximal Pennsylvanian and Permian sandstones along the uplifts were analyzed for U-Pb ages and Hf isotopes of detrital zircons. Analyses of detrital zircons from a Permian sandstone stratigraphically above the proximal detritus were conducted to test sediment dispersal in space and time, as well as to document the early evolution of sediment-dispersal systems around the Southern Oklahoma (Wichita and Arbuckle) uplifts. Ultimately, these results may provide a basis for discrimination of the Southern Oklahoma provenance from Gondwana accreted terranes.

GEOLOGIC SETTING AND EVOLUTION OF THE SOUTHERN OKLAHOMA FAULT SYSTEM

Mesoproterozoic Basement Rocks

Basement rocks in the Arbuckle uplift belong to the Southern Granite-Rhyolite province (Fig. 1) (e.g., Ham et al., 1964; Van Schmus et al., 1993). U-Pb zircon ages for various granites and gneisses in the Arbuckle uplift range from 1399 ± 95 and 1397 ± 7 Ma to 1364 ± 2 and 1363 ± 8 Ma (Bickford and Lewis, 1979; Thomas et al., 1984; Rohs and Van Schmus, 2007; Thomas et al., 2012).
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Data from U-Pb analyses of zircons from the igneous rocks give a range of possible ages for detrital zircons available from this provenance. U-Pb ages of zircons from rhyolites in the Wichita Mountains bracket a short time interval of 533–530 Ma (Wright et al., 1996; Hogan and Gilbert, 1998; Hanson et al., 2013). A U-Pb zircon age of 552 ± 7 Ma for gabbro (Bowring and Hoppe, 1982) is older than indicated by geologic relationships to other dated rocks and may have an inherited component (Hogan and Gilbert, 1998; Hanson et al., 2013). U-Pb ages of zircons from rhyolites in the Arbuckle Mountains are 539 ± 5 and 538 ± 5 Ma (Thomas et al., 2012). Previously determined U-Pb zircon ages of 525 ± 25 Ma for rhyolite and granite (Tilton et al., 1982) are within error of the more recent data. Some components of the igneous suite are older on the basis of geologic relationships than the geochronologically dated rocks; however, no data are available to quantify the time span of those rocks. Combining all of the available U-Pb data, zircons with ages of 539–530 Ma and possibly somewhat older are available to the supply of sediment from the Southern Oklahoma synrift igneous rocks.

Cambrian–Ordovician Passive-Margin Carbonate Succession

A transgressive passive-margin succession of basal sandstone and overlying shallow-marine carbonates onlaps the Cambrian igneous rocks along the Southern Oklahoma fault system. Cambrian–Ordovician rocks along the Southern Oklahoma fault system are part of a craton-wide passive-margin carbonate (referred to as the Great American Carbonate Bank, Derby et al., 2012). The age of the sandstone at the base of the transgressive succession is middle Late Cambrian; and the overlying carbonate succession extends up through the Middle Ordovician (Denison, in Johnson et al., 1988). The Middle Ordovician part of the carbonate succession includes mature quartzose sandstone. The carbonate succession is exceptionally thick (as much as 2.2 km) along the Southern Oklahoma fault system, consistent with large-magnitude synrift thermal uplift followed by post-rift cooling and deep subsidence (Thomas and Astini, 1999).

Late Paleozoic Uplifts and Clastic Sedimentary Rocks

A relatively thin, unconformity-punctuated, heterolithic, Upper Ordovician–Mississippian succession overlies the thick Cambrian–Ordovician carbonate succession, representing deposition on a stable continental shelf (Johnson et al., 1988). In contrast, a very thick, dominantly clastic succession of Pennsylvanian–Permian age reflects the rise of multiple components of the Arbuckle and Wichita uplifts along large-magnitude basement faults (Johnson et al.,

CAMBRIAN SYNFRIT IgNEOUS ROCKS

Along the Southern Oklahoma fault system (Arbuckle and Wichita uplifts), a Cambrian bimodal suite of plutonic and volcanic rocks includes gabbro, basalt, granite, and rhyolite (Hogan and Gilbert, 1998; Hanson et al., 2013), the composition of which indicates magma sources in the upper mantle. High-amplitude, short-wavelength gravity and magnetic anomalies indicate a narrow, elongate mass of dense mafic rocks with steep boundaries in the shallow continental crust (Keller and Stephenson, 2007). The Cambrian igneous rocks are interpreted to be along a system of intracratonic fractures associated with continental rifting and breakup of supercontinent Rodinia and opening of the Iapetus Ocean (Fig. 1) (e.g., Thomas, 2006, 2014).

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Erosion of the rising uplifts led to unroofing of the sedimentary cover and basement rocks, as well as set the stage for ultimate sedimentary onlap onto the eroded uplifts in the later Pennsylvanian and Permian.

**SANDSTONE SAMPLES FOR ANALYSIS OF DETRITAL ZIRCONS**

Collections were designed to sample the most proximal sandstones on the Arbuckle and Wichita uplifts, as well as a stratigraphically higher level to test for temporal and lateral extent of supply of sediment from the uplifts. One sample of Lower Permian Post Oak Conglomerate came from a pebbly sandstone ~10 cm above the unconformable contact with the underlying Mount Scott Granite of the Cambrian Wichita Granite Group along the south side of the Wichita uplift (Figs. 2 and 3). Two samples of the Upper Pennsylvanian Vanoss Conglomerate were collected on the north side of the Arbuckle uplift (Figs. 2 and 4), stratigraphically above the onlap of Pennsylvanian clastic facies onto the Ordovician carbonate succession. The Vanoss Conglomerate contains carbonate clasts in the sandstone matrix. One sample came from the stratigraphically higher Permian Wellington Formation ~40 m above the level of the Vanoss Conglomerate west of the Arbuckle uplift (Fig. 2). The Wellington is part of a succession of more blanket-like stratigraphic units deposited across the then-inactive Southern Oklahoma fault system.
METHODS

U-Pb Geochronologic Analysis

U-Pb geochronology of zircon crystals was conducted by laser ablation–inductively coupled mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center (www.laserchron.org) using methods described by Gehrels et al. (2008) and Gehrels and Pecha (2014). U-Pb analyses were conducted with a Pho-ton Machines Analyte G2 excimer laser ($\lambda = 193$ nm) coupled to a Thermo Element2 ICPMS. Analyses were conducted with a 20-micron beam diameter, which excavated a pit of 12 microns depth during a ~30 second analysis (8 seconds on backgrounds, 12 seconds on peaks, and 10 seconds for washout).

Between 306 and 344 analyses were conducted on each sample with one U-Pb measurement per grain. Grains were selected in random fashion; crystals were rejected only on the basis of small size or the presence of cracks or inclusions. The use of high-resolution, backscattered-electron (BSE) images for detrital samples provided assistance in grain selection and spot placement.

Data reduction included (1) subtraction of 204Hg based on the measured 202Hg and the natural 202Hg/204Hg; (2) subtraction of initial Pb based on the measured 206Pb/204Pb, using Stacey and Kramers (1975) to determine the composition of common Pb and Mattinson (1987) for an estimate of the compositional uncertainty; (3) calibration of 206Pb/238U and 206Pb/207Pb fractionation based on bracketed (5:1) analyses of FC-1 (primary standard) and SLF and R33 (secondary standards); (4) calculation of ages utilizing decay constants of Steiger...

Figure 4. Geologic map (generalized from 1954 map by Ham and McKinley et al., and revised by Johnson, 1990) and cross section (vertical exaggeration ~10x) of Arbuckle uplift (location of map shown in Fig. 2). Locations of samples OK-1-VN and OK-2-V2. Map unit of lower Middle Ordovician limestone and sandstone formations includes sandstones analyzed by Pickell (2012) and interpreted to be the source of recycled zircons in the Vanoss Conglomerate.
and Jager (1977) and $^{206}\text{U}/^{238}\text{U}$ of Hiess et al. (2012); (5) propagation of internal uncertainties from measurement of isotope ratios and a small overdispersion factor; and (6) propagation of all external uncertainties (including fractionation calibration, age of the primary standard, common Pb composition, and decay constants) (Horstwood et al., 2016).

For interpretation, U-Pb data are filtered to exclude ages with >20% discordance, >5% reverse discordance, >10% uncertainty, or high common Pb. Data are presented on normalized age-probability diagrams, which sum all relevant analyses and uncertainties and then divide by the number of analyses such that each curve contains the same area. Age groups are characterized by the ages of peaks in age probability. Complete U-Pb isotopic data, including concordia and age-probability plots for each sample, are presented in Supplemental Table 1.

### Hafnium Isotopic Analysis

Hafnium isotopic analyses were determined using methods described by Cecil et al. (2011) and Gehrels and Pecha (2014) utilizing a Photon Machines Analyte G2 excimer laser ($\lambda = 193$ nm) coupled to a NU multicollector HR ICPMS. Between 18 and 65 analyses were conducted per sample; analysis spots were located on top of the U-Pb pit in an attempt to link the Hf and U-Pb data. A 40-micron beam diameter was used for an 80 second acquisition (20 seconds on backgrounds, 40 seconds on peaks, and 20 seconds for washout).

Hafnium data were reduced to achieve minimum offset of the measured $^{176}\text{Hf}/^{177}\text{Hf}$ of standards relative to the known values. Solution standards included JMC475 mixed with varying amounts of Lu and Yb; zircon standards (included on each mont with the unknowns) included FC1, R33, Temora, 91500, Mud Tank, and Plesovice. The best fit of standards was achieved with a 0.4 epsilon unit increase in $\epsilon$Hf, and utilizing $\delta$Hf rather than $\epsilon$Yb for samples with $<0.7$ mv of $^{171}$Yb.

Reported results were determined from all measured isotope ratios, and outliers were rejected only using a 2σ filter. The resulting uncertainty is 2.6 epsilon units (2σ), which, together with the reproducibility of standards zircons, yields an external precision of 2–3 epsilon units (2σ). Complete Hf isotopic data, including Hf-evolution plots of individual samples, are presented in Supplemental Table 2; results are plotted in Figure 5.

### RESULTS OF ANALYSES

#### Post Oak Conglomerate

Detrital zircons from the Post Oak Conglomerate have a very strong unimodal distribution (Fig. 5). The dominant concentration at ~535 Ma has 77% of the grains in the range of 540–520 Ma and 95% of the grains between 560 and 515 Ma. The oldest grain is 580 Ma. A few grains are scattered between 515 and 425 Ma. The $\epsilon$Hf values range between +4.7 and +10.1 (Fig. 5).

#### Vanoss Conglomerate

Both samples of Vanoss Conglomerate have dominant concentrations (~48% of total grains) of detrital zircons between 2860 and 2620 Ma with probability peaks at 2710 and 2708 Ma (Fig. 5). Both samples have two secondary concentrations, in the range of 1520–1300 Ma and 1240–970 Ma (Fig. 5). Both samples have minor components with ages of 1910–1760 Ma and 1710–1580 Ma (Fig. 5). One sample has two grains with ages of 563 and 525 Ma (Fig. 5). The samples have a few younger grains (nine grains total) with ages of 437–375 Ma (Fig. 5). Hafnium analyses of one of the two Vanoss samples (Fig. 5) show juvenile to intermediate $\epsilon$Hf, values that are typical for Precambrian cratons of the central United States (Gehrels and Pecha, 2014). The younger grains also yield juvenile to intermediate $\epsilon$Hf, values but not as juvenile as the Post Oak zircons.

### DISCUSSION OF RESULTS AND PROVENANCE

#### Post Oak Conglomerate

The detrital-zircon population of the Wellington Formation contrasts markedly with those of both the Post Oak Conglomerate and Vanoss Conglomerate. Two groups of ages dominate the Wellington zircons: 1340–960 Ma with peaks at 1326, 1151, and 1040 Ma; and 673–329 Ma with peaks at 563, 437, and 339 Ma (Fig. 5). Smaller numbers of zircons are scattered at 2904–2305, 2062–1359, and 857–728 Ma (Fig. 5). Hafnium analyses are similar to the results from the Vanoss Conglomerate, except that $\epsilon$Hf, values for 600–500 Ma grains extend to more negative values (Fig. 5).

#### Vanoss Conglomerate

The strongly dominant mode (2860–2620 Ma) of detrital-zircon ages in the Post Oak Conglomerate (Fig. 5) corresponds to the age of the Cambrian igneous rocks along the Southern Oklahoma fault system, consistent with a single proximal source. Two groups of ages dominate the Wellington zircons: 1340–960 Ma with peaks at 1326, 1151, and 1040 Ma; and 673–329 Ma with peaks at 563, 437, and 339 Ma (Fig. 5). Smaller numbers of zircons are scattered at 2904–2305, 2062–1359, and 857–728 Ma (Fig. 5). Hafnium analyses are similar to the results from the Vanoss Conglomerate, except that $\epsilon$Hf, values for 600–500 Ma grains extend to more negative values (Fig. 5).
Figure 5. Relative age-probability plots (lower panel) and Hf-evolution diagram (upper panel) showing results from sandstones in and near the Wichita and Arbuckle uplifts (data in Supplemental Tables 1 and 2 [see footnotes 1 and 2]). Lower panel: relative age-probability plots for four analyzed samples and a composite plot of the two Vanoss samples; vertical color bands represent the age ranges of potential provenance provinces in North America. Upper panel: εHf data for three samples (data points are color coded as shown in the lower panel); the average uncertainty of Hf isotope analyses (2.6 epsilon units at 2σ) is shown in upper right. The Hf-evolution diagram shows the Hf isotopic composition at the time of zircon crystallization, in epsilon units, relative to the chondritic uniform reservoir (CHUR) (Bouvier et al., 2008) and to the depleted mantle (DM) (Vervoort and Blichert-Toft, 1999). Shown for reference is the evolution of typical felsic crust, which is based on a 176Lu/177Hf ratio of 0.0115 (Vervoort and Patchett, 1996; Vervoort et al., 1999). Reference fields summarize published Hf isotopic data for the Appalachians (Mueller et al., 2007, 2008) and associated Gander (Willner et al., 2014) and Mira (Willner et al., 2013) terranes, the Grenville orogen (Bickford et al., 2010; Gehrels and Pecha, 2014), Mesoproterozoic rocks of the Mid-continent Granite-Rhyolite province and Paleoproterozoic rocks of the Central Plains orogen (Goodge and Vervoort, 2006; Bickford et al., 2008; Gehrels and Pecha, 2014), and Penokean and Superior provinces of the Canadian Shield (Gehrels and Pecha, 2014).
age of the Granite-Rhyolite province, which is represented specifically by the basement rocks in the Arbuckle uplift (1399–1363 Ma), suggesting a possible local primary source for at least some of these grains. The younger secondary group (1240–970 Ma), equivalent in age to the Grenville province of eastern North America, has no counterpart in the Arbuckle basement (Fig. 5). Minor components of the detrital-zircon population (1910–1760 Ma and 1710–1580 Ma) correspond in age to the Trans-Hudson–Penokean and Yavapai-Mazatzal–Central Plains orogens, respectively (Fig. 5); neither is represented in the Arbuckle basement. The two grains with ages of 563 and 525 Ma are similar to ages of Cambrian igneous rocks along the Southern Oklahoma fault system (Fig. 5); however, εHf values of +4.1 and –4.7, respectively, are more negative than the range of values for the ~535 Ma zircons in the Post Oak Conglomerate. The εHf values suggest that these grains in the Vanoss Conglomerate are not from the Southern Oklahoma igneous rocks. The few younger grains (437–375 Ma) have no evident source from uplifts along the Southern Oklahoma fault system. The very abundant grains with ages of 2860–2620 Ma correspond in age to the Superior province of the eastern Canadian Shield (Fig. 5), posing an apparently difficult quandary of distant provenance and sediment dispersal. The Cambrian–Ordovician craton-wide carbonate bank includes quartzose sandstone units that are distributed across the Midcontinent from outcrops near the onlap onto the Canadian Shield as far southwest as the Southern Oklahoma fault system (Fig. 5). Throughout the extent of the sandstones in the Middle Ordovician part of the carbonate succession, the detrital-zircon populations are dominated by Superior-age grains (Fig. 7) (Pickell, 2012; Konstantinou et al., 2014) from either a primary source on the Shield or recycled from Proterozoic sedimentary basins on the Shield. Paleogeographic reconstruction (Konstantinou et al., 2014) places the sediment-dispersal pathway from the Shield onto the carbonate shelf along Ordovician latitude 10°S. Westward (in Ordovician coordinates; southward in present coordinates) transport of mature quartz sand on the carbonate shelf inboard from the Appalachian-Ouachita margin of eastern Laurentia suggests the effects of trade winds on sediment dispersal across the shelf. The dominance of Superior-age detrital zircons, as well as the carbonate clasts, in the Vanoss Conglomerate indicates a source for recycling from the Ordovician carbonate succession and quartzose sandstone (Tulip Creek, McLish, and Oil Creek Formations of the Simpson Group; Fig. 4) on the Arbuckle uplift.

In addition to being a source for recycled Superior-age zircons, the sandstones in the Cambrian–Ordovician succession contain zircons of other ages in smaller amounts, indicating recycling as a probable source for most of the grains in the Vanoss Conglomerate (Fig. 7). In particular, the most prominent secondary mode in the Ordovician sandstones corresponds in age to the Grenville province (Fig. 7); the lower Paleozoic transgressive succession onlaps the Grenville province along the southeast side of the Superior province (Fig. 6). Although some Vanoss detrital zircons of the age of the Granite-Rhyolite province may have been derived from a local primary source in the Arbuckle basement, some of the Ordovician sandstones also contain a component of detrital zircons of that age (Fig. 7). Lesser concentrations of grains with ages between 1910 and 1580 Ma suggest probable recycling as the source of those ages in the Vanoss (Fig. 7). None of the Ordovician sandstones contain zircons younger than ~950 Ma (Fig. 7), indicating that the younger grains in the Vanoss either had a source outside the Arbuckle uplift or were possibly recycled from the middle Paleozoic succession (for which no confirming zircon data are available) in the Arbuckle uplift.
The $\varepsilon$Hf values are consistent with Superior and Penokean zircons from the eastern Canadian Shield, with Yavapai-Mazatzal–Central Plains zircons, with the Granite-Rhyolite province, and with Grenville-age zircons from eastern Laurentia, including the eastern Shield (Fig. 5). U-Pb ages and $\varepsilon$Hf values of the Vanoss zircons with ages >985 Ma are consistent with recycling from sandstones within the Ordovician limestone succession in the Arbuckle uplift. For the rare younger zircons in the Vanoss Conglomerate, $\varepsilon$Hf values range from +7.7 to −7.3. For zircons with ages (563 and 525 Ma) similar to those of the Southern Oklahoma synrift igneous rocks, the $\varepsilon$Hf values (+4.1 to −4.7) do not overlap with $\varepsilon$Hf values of zircons from the Post Oak Conglomerate, suggesting that these zircons were not derived locally from Southern Oklahoma igneous rocks. The youngest zircons (437–375 Ma) in the Vanoss Conglomerate are distinctly younger than the Southern Oklahoma synrift igneous rocks, and the $\varepsilon$Hf values (+7.7 to −7.3) are mostly more negative than $\varepsilon$Hf values of zircons from the eastern Canadian Shield.
from the Post Oak Conglomerate. The U-Pb ages and εHf, values together indicate sources outside the Southern Oklahoma basement uplifts, consistent with primary sources in accreted terranes along the Paleozoic Appalachian-Ouachita orogen or recycling from the middle Paleozoic cover succession on the Arbuckle uplift.

**Wellington Formation**

The strong concentration of Superior-age zircons in the recycled source for the Vanoss Conglomerate is not evident in the detrital zircons from the Wellington Formation. The local supply of zircons from the Cambrian synrift igneous rocks, as in the Post Oak Conglomerate, along the Southern Oklahoma fault system may be represented in a subset (673–500 Ma) of the younger dominant mode in the Wellington. Some of those grains have εHf values (+6.5) that are similar to those in the Post Oak Conglomerate; however, others (+2.9 to −15.3) are not (Fig. 5).

The mix of zircon ages in the Wellington Formation suggests a more composite source separate and probably somewhat distant from the Arbuckle and Wichita uplifts. The grains older than 960 Ma are permissive of recycling from the Ordovician sandstones or from the Vanoss Conglomerate; however, the proportions contrast strongly, especially in the Superior-age component. The grains younger than ~500 Ma have no counterpart in the basement rocks of the Ordovician strata onlap onto the Arbuckle uplift (Figs. 4 and 5), whereas the Post Oak detrital zircons represent only the unroofed Wichita Granite Group in the Wichita uplift (Figs. 3 and 5). Predictably, samples from other fans along the system may have different detrital-zircon populations, depending on which rocks were exposed in the heads of drainage.

The lateral and vertical variability of the sedimentary deposits along the uplifts has led to difficulties in stratigraphic subdivision and definition of geologic map units. The samples reported here are from an outcrop area most recently mapped as Vanoss Conglomerate (Stanley and Chang, 2012). Geologists of the Oklahoma Geological Survey currently are studying the stratigraphic subdivisions, and new mapping units are likely to be defined (N.H. Suneson and T.M. Stanley, 2015, personal commun.). Ultimately, the samples reported here as from the Vanoss Conglomerate may be reassigned. The effort to distinguish different fan deposits as stratigraphic units could benefit from the use of detrital zircons to define fan systems.

**Detritus from the Wichita and Arbuckle Uplifts**

The Wichita and Arbuckle uplifts along the Southern Oklahoma fault system include numerous separate fault blocks along which the faults were active episodically, leading to a non-systematic evolution of erosional unroofing and sedimentary reworking and onlap of proximal detritus (e.g., Ham et al., 1964; Johnson et al., 1988; Denison, 1989; Perry, 1989). The highly distinct differences in detrital-zircon populations of the Post Oak and Vanoss Conglomerates (Fig. 5) clearly illustrate the contrast in unroofing history between those specific segments of the uplifts. The Vanoss samples represent a level of unroofing down only to the Middle Ordovician carbonate succession with quartzose sandstone components, and the detrital-zircon population includes no grains that indicate an unroofed basement source. In contrast, the detrital-zircon population of the Post Oak sample (Fig. 5) indicates complete unroofing of the Wichita Granite Group and no recycling from the eroded sedimentary cover.

Around the Arbuckle uplift, the Vanoss Conglomerate is within a succession of Upper Pennsylvanian clastic rocks, the base of which is an angular unconformity that cuts across the older Paleozoic sedimentary cover. For example, along the Arbuckle anticline, within a distance of ~25 km along strike, the unconformity cuts across the Ordovician sedimentary succession down to the basal Cambrian sandstone just above the Colbert (Carlton) Rhyolite (Fig. 4) (Stanley and Chang, 2012). The two Vanoss samples reported here are from sandstones near the unconformable onlap onto the Ordovician strata (Fig. 4), and the detrital-zircon population reflects recycling from the sandstones within the carbonate succession (Fig. 7). By analogy, nearby, where the Pennsylvanian strata onlap down to the basal sandstone just above the Colbert Rhyolite (Stanley and Chang, 2012), the detrital-zircon population more likely might be dominated by zircons with ages of 539–536 Ma.

Interpretations of depositional systems within the Pennsylvanian–Permian cover around the Arbuckle and Wichita uplifts include multiple alluvial fans, prograding down from relatively restricted drainage areas within the uplifts into marine settings (e.g., Johnson et al., 1988). In the context of variable unroofing along the uplifts, the different local fans potentially tapped different rocks at the head of the drainage. For example, the recycled detrital zircons in the Vanoss samples represent only the Middle Ordovician sandstones on the Arbuckle uplift (Figs. 4 and 5), whereas the Post Oak detrital zircons represent only the unroofed Wichita Granite Group in the Wichita uplift (Figs. 3 and 5). Predictably, samples from other fans along the system may have different detrital-zircon populations, depending on which rocks were exposed in the heads of drainage.

**CONCLUSIONS**

Detrital-zircon populations document localized proximal sources for sedimentary rocks along the Southern Oklahoma fault system (Fig. 8). The Lower Pennsylvanian Post Oak Conglomerate, which rests on the Wichita Granite Group along the Wichita uplift, has zircons (~536 Ma) derived exclusively from the synrift granite (Figs. 3, 5, and 8). In contrast, the locally mapped Vanoss Conglomerate adjacent to the Arbuckle uplift has a detrital-zircon population (dominated by ages of the cratonic Superior province) derived almost exclusively from recycling of zircons from sandstones within the Cambrian–Ordovician passive-margin carbonate succession above the Arbuckle basement rocks (Figs. 4–8). These data document the dominance of localized proximal sources within the Wichita
was quickly overwhelmed by more regional dispersal systems, which received of the continent. The abrupt transition in the detrital-zircon populations from Paleozoic orogenic belts, including accreted terranes, around the margins of the Wichita and Arbuckle uplifts. The Wellington Formation is in the lower part of a cover succession above the onlapping basal conglomerates above the Wichita and Arbuckle uplifts. Symbol colors for rock units are explained in Figure 4.

Figure 8. Schematic block diagram (not to scale) of sample locations in the context of stratigraphic and structural settings. The Post Oak Conglomerate laps onto an erosion surface on the Wichita Granite Group within the Wichita uplift. The Vanoss Conglomerate laps onto an erosion surface that truncates the Paleozoic succession, including the Middle Ordovician carbonate succession with quartzose sandstone components, on the flanks of the Arbuckle uplift. The Wellington Formation is in the lower part of a cover succession above the onlapping basal conglomerates above the Wichita and Arbuckle uplifts. Symbol colors for rock units are explained in Figure 4.

and Arbuckle uplifts for sedimentary deposits that fringe the uplifts. The differences in the Post Oak and Vanoss samples demonstrate the significance of variations in the depth of erosional unroofing during the diachronous processes of uplift and sedimentation, consistent with different components of the fringing sediments having detrital-zircon populations from different parts of the basement and cover succession within the uplifts. In addition, the Vanoss samples confirm the importance of recycling of sediment from originally distant sources.

The detrital-zircon population of the Wellington Formation, which is stratigraphically above the syn-uplift clastic sediment (Fig. 8), contrasts strongly with those of the Post Oak and Vanoss, and most of the Wellington zircons could not have come from local sources within the Wichita and Arbuckle uplifts. Both the population of younger grains (673–329 Ma) and the proportions of various groups of older grains in the Wellington suggest supply of detritus from Paleozoic orogenic belts, including accreted terranes, around the margins of the continent. The abrupt transition in the detrital-zircon populations from the Post Oak and Vanoss upward to the Wellington indicates that the supply of detritus from local sources within the uplifts persisted for only a short time and was quickly overwhelmed by more regional dispersal systems, which received little or no sediment directly from the uplifts.

The locally derived ~535 Ma zircons in the Post Oak Conglomerate from the Wichita Granite Group have distinctive εHf, values (+4.7 to +10.1), that are consistent with mantle-derived juvenile magmas. In contrast, some other zircons of the same age in the Vanoss Conglomerate and Wellington Formation have εHf, values in the negative range, suggesting a different, presumably more distant source. The negative εHf, values are consistent with remobilization of older basement rocks, an attribute that suggests Gondwanan terranes. These results offer the possibility that ~535 Ma zircons from synrift mantle-derived magmas can be distinguished from remobilized basement rocks in accreted Gondwanan terranes on the basis of Hf data. Testing this concept will require focused sampling from several terranes and dispersal systems.

REFERENCES CITED


Pickup, J.M., 2012, Detrital zircon geochronology of Middle Ordovician siliciclastic sediment on the southern Laurentian shelf [M.S. thesis]: College Station, Texas A&M University, 120 p.