TEMPORAL EVOLUTION OF THE SEDIMENT ROUTING PATHWAY INTO THE DELAWARE BASIN, WEST TEXAS

A Thesis

by

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ABSTRACT

The Delaware Basin (DB), a sub-basin of the greater Permian Basin (PB), formed during the collision between the Gondwana and Laurentian plates in the Late Paleozoic. The basin is situated within the foreland of the Ouachita-Marathon (OM) fold-thrust belt, separated from the shallower Midland Basin (MB) by the Central Basin Platform (CBP) basement uplift. The complex structural geometries of the CBP, DB, and OM lead to uncertainties regarding the tectonic mechanisms driving formation of PB, and associated drainage and catchment pattern filling the basin. This research shows the siliciclastic paleodispersal patterns of the DB spanning pre- to post- OM deformation. As the first provenance study of the area to span this temporal range, the results from U-Pb detrital zircon geochronology, thin section petrology, heavy mineral analyses, and Kolmogorov-Smirnov statistical tests reveal four major drainage reorganizations that correspond to the regional tectonic events. Results indicate that Ordovician strata, previously interpretated as allochthonous, may have originated in Gondwana, and remained attached to North America after the breakup of Pangea in the Late Paleozoic. Mississippian strata of the Tesnus Formation were likely sourced from the distal Appalachian system during the initial collision phase, and transported axially along the Marathon-Ouachita fold-thrust belt. As collision continued, Pennsylvanian strata were sourced from alternating axial transport of distal material, and margin-perpendicular transport from Gondwanan sources. During the Cretaceous, sediment from the Cordilleran arc along the western margin of North America was transported east towards the Delaware Basin region.

DEDICATION

I would like to dedicate this thesis to my parents, Lu Gao and Guiqin Liu, who have walked alongside me during the past years. Even though they were physically far from me, they made their love and support known. This work, and all of my past accomplishments would not have been possible without them.

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CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professors Nicholas Perez and Michael Pope of the Department of Geology and Geophysics, and Professor Ping Chang from Department of Atmospheric Sciences.

Data collection was assisted by Chase Stanford, and data processing was assisted by National Petrographic Service Inc., and Dr. Katharina Pfaff at Colorado School of Mines, Ben Gremillion, Dominic Seidel, Cody Millet, and Chase Wittman of Texas A&M.

All other work conducted for this thesis was completed by the student independently.

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NOMENCLATURE

CBP	Central Basin Platform
DB	Delaware Basin
DZ	Detrital zircon
K – S	Kolmogorov – Smirnov
MB	Midland Basin
OM	Ouachita – Marathon
PB	Permian Basin
VB	Val Verde Basin

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I. INTRODUCTION

Southern Laurentia, west Texas, records a protracted sediment accumulation history spanning the initiation of the passive margin Tobosa Basin in the Early Paleozoic, and its subsequent partitioning during Mississippian-Pennsylvanian collision with Gondwana. The Permian Basin, situated in the foreland of the Ouachita-Marathon fold-thrust belt, records the stratigraphic record of multi-phase deformation associated with construction of Pangea. Potential topographic loads, such as the Central Basin Platform, contributed to flexural subsidence (Yang and Dorobek, 1995); however, the interaction between tectonic events and drainage evolution that delivered sediment to this basin remains unclear (Fischer and Sarnthein, 1988; Soreghan and Soreghan, 2013; Anthony, 2015). Provenance constraints (Figure 1) for the Permian Delaware Mountain Group (Soreghan and Soreghan, 2013; Anthony, 2015) modified prevailing interpretations (Figure 2) of northerly Ancestral Rocky Mountain basement uplift sources (Fischer and Sarnthein, 1988), suggesting contribution from Appalachian or Gondwanan sediment sources. The Pennsylvanian Haymond Formation was unlikely to have originated from the same parent rock as the Permian Delaware Mountain Group, revealing potential temporal changes in sediment sources (Gleason et al., 2007; Anthony, 2015).

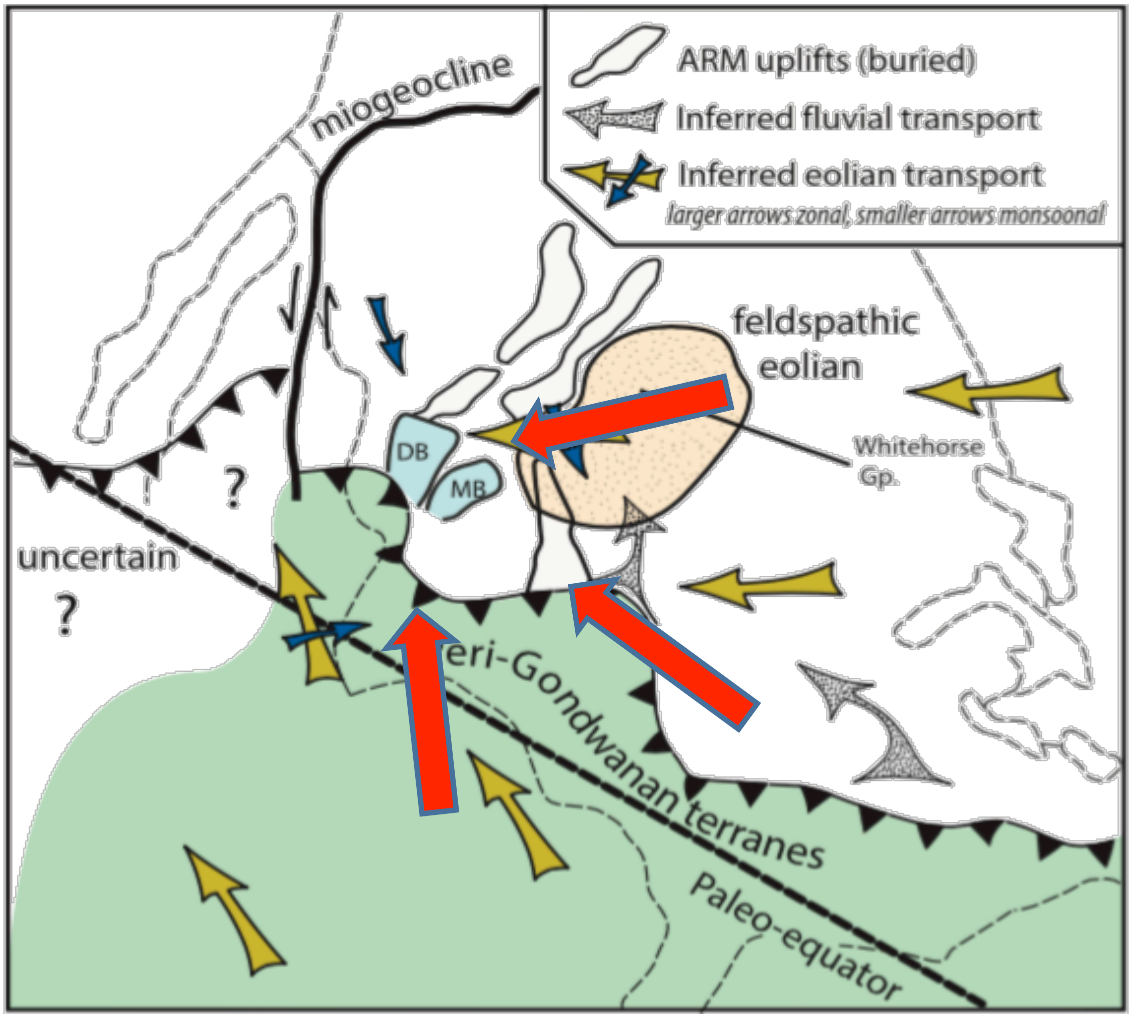

Figure 1 - Permian paleogeographic map of Southern Laurentia with inferred dispersal pathways and dominant wind directions. Red arrows indicate potential sediment pathways into the Delaware Basin. Modified from Soreghan and Soreghan (2013). DB is the Delaware Basin, and MB is the Midland Basin.

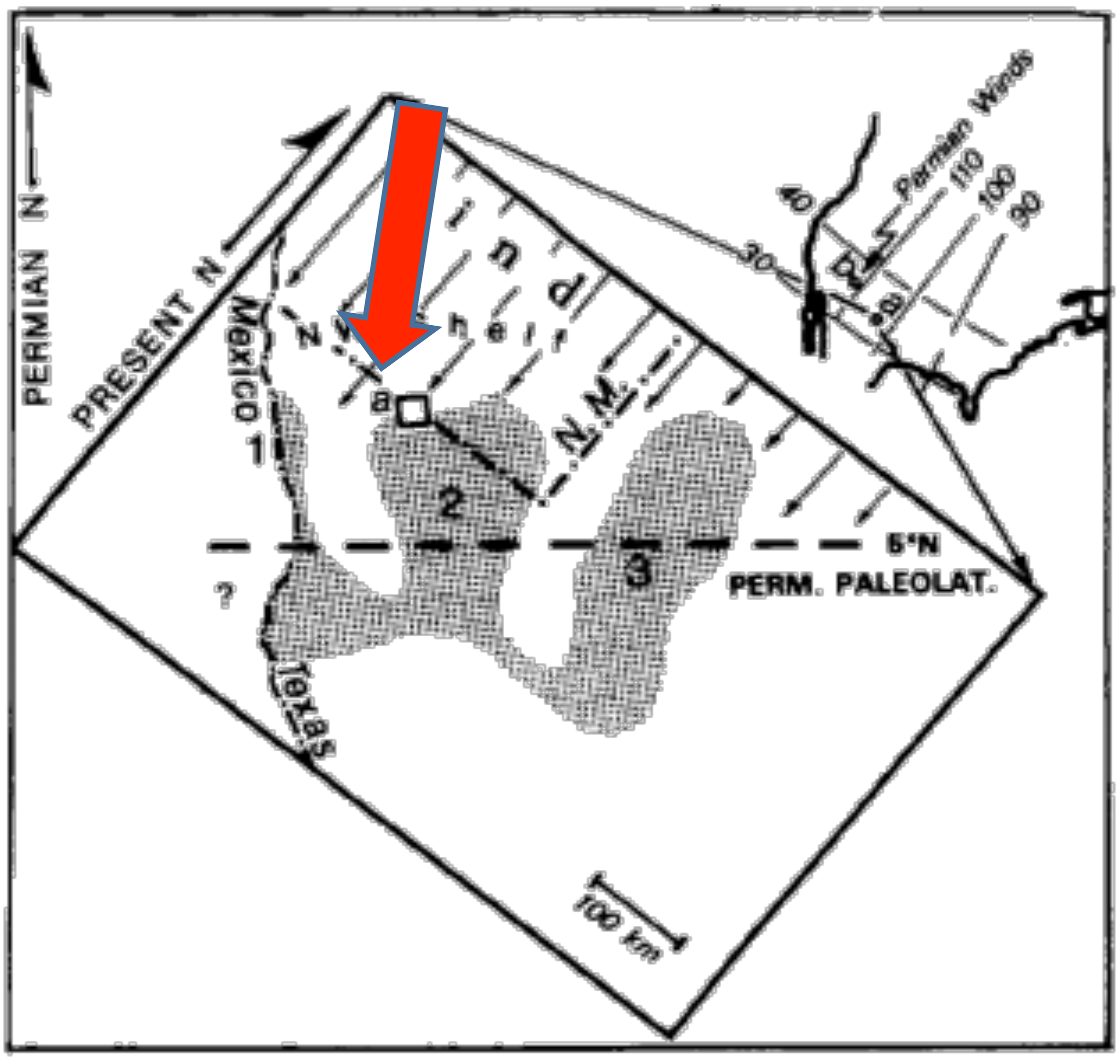

Figure 2 – Map showing Permian basin of west Texas with inferred paleo dispersal pathway. '2' is the Delaware Basin and '3' is the Midland Basin. Red arrow indicats proposed south-directed sediment transport pathway, carrying Ancestral Rocky Mountains sediment southward into the Delaware Basin. Modified from Fischer and Sarnthein (1988).

To understand the sediment source evolution of this foreland basin and its response to the transition from passive to active margin, detrital zircon U-Pb geochronology, thin section petrography, and heavy mineral analyses were utilized to characterize the provenance of 13 outcrop samples spanning the Precambrian to Cretaceous from the Marathon uplift to Guadalupe Mountains of west Texas (Figure 3 and Figure 4). This study builds upon previous results that focused on the Permian Delaware Mountain Group (Soreghan and Soreghan, 2013; Anthony,

2015) and the Pennsylvanian Haymond Formation (Gleason et al., 2007; Anthony, 2015) in order to investigate sediment transport pathways spanning pre- and post-collisional tectonic phases.

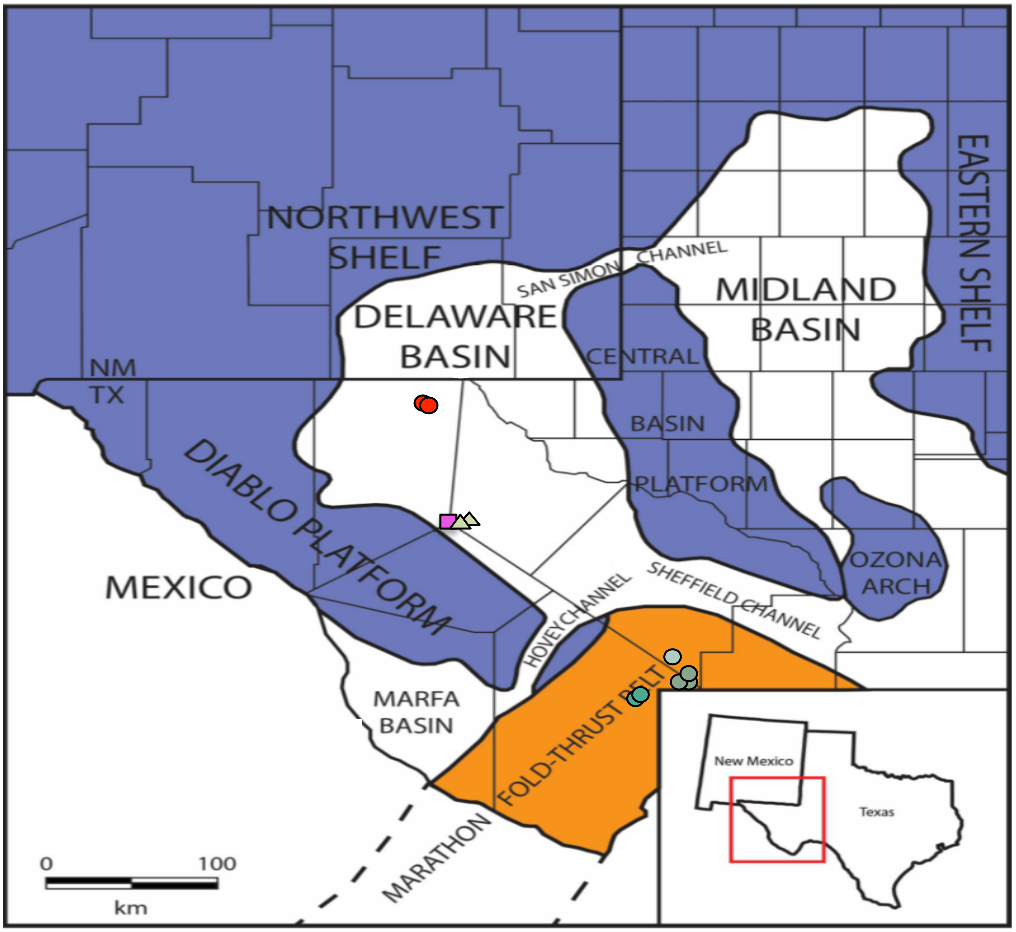

Figure 3 - Location map of outcrop samples collected in the Delaware Basin and Marathon Uplift region. Triangles indicate Mesozoic (Cretaceous) units collected in Van Horn, circles indicate Paleozoic (Ordovician, Mississippian, Pennsalvanian, and Permian) units. Ordovician, Mississippian and Pennsalvanian units were collected in Marathon region and Permian units were collected in Guadalupe Mountains area. Square indicates Precambrian unit, collected near Diablo Platform.

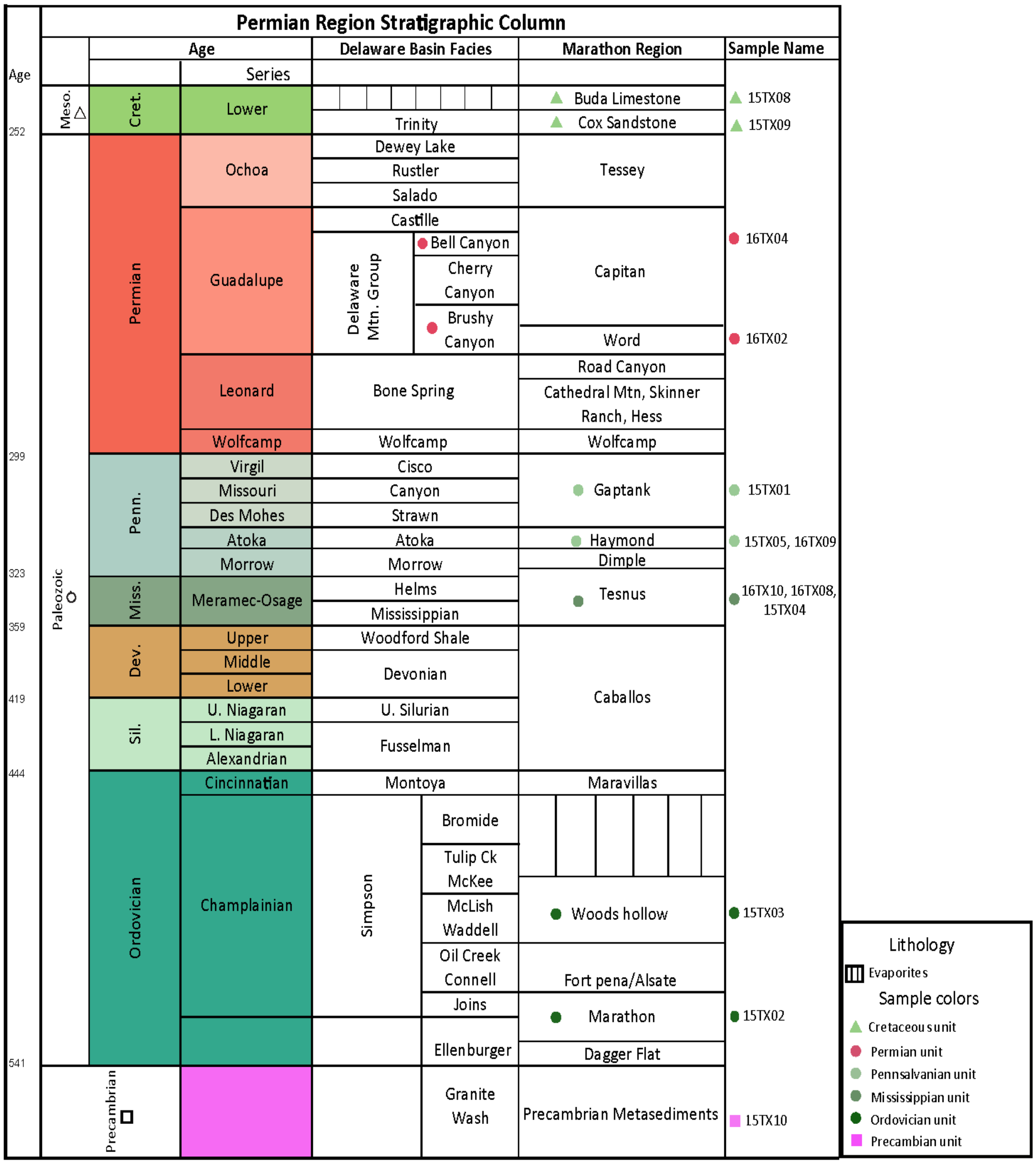

Figure 4 - Stratigraphy of the Delaware Basin and Marathon region. Unit sedimentology is indicated by the color with the legend on the right. Samples collected are presented in the stratigraphic location adjacent to each unit. Different colors indicating different age units.

The Taconic, Acadian, and Alleghanian orogenies, developed the structural and stratigraphic architecture of eastern Laurentia during the Ordovician to Mississippian. The Marathon-Ouachita orogeny of southeast Laurentia and Texas is the lateral equivalent of the Appalachian orogenic front, and occurred during the Mississippian-Pennsylvanian (Flawn, 1961;

Tauvers, 1987; McBride, 1988). This multi-phase collision developed a series of associated foreland basins and stratigraphic wedges, and accommodated terrane accretion. U-Pb detrital zircon ages from the Appalachian foreland basin documents the provenance changes in response to collisional phases (Park et al., 2010). The temporal change of DZ age spectra indicates the relationship between orogenic activities and foreland sediment accumulation, showing that in the Taconic clastic wedge, sediments were derived primarily from Grenville terranes. The Acadian clastic wedge consists of recycled Taconic-age sediments, indicating that orogenic activity exhumed and exposed pre-existing foreland basin sediments. Alleghanian siliciclastic sediments show a decrease in Paleozoic sediment input, indicating the orogenic hinterland consisted of deformed passive margin strata and Grenville basement. This study will investigate how the laterally equivalent tectonic setting of west Texas evolved, and compare those results to the coeval depocenters investigated by Park et al. (2010).

Permian and Jurassic units from the Colorado Plateau contain detrital zircons suggest a transcontinental sediment transport system that delivered Appalachian detritus to western North America via fluvial and aeolian systems (Gehrels and Dickinson, 2009). This study integrates the Delaware Basin drainage dispersal pathways into the proposed broader continental-scale drainage system to investigate whether it merged with the broader continental-scale network, or remained partitioned.

Cretaceous to Paleocene siliciclastic strata from the Western Canada Sedimentary Basin and Gulf of Mexico margin reveal reorganization of continental-scale drainage patterns (Blum and Pecha, 2014) that established the modern Mississippian drainage, although the driver of this remains unclear. These existing studies highlight Paleozoic to Cenozoic basin- and continental-scale sediment routing system that may change both rapidly and over protracted 10^2 Myr timeframes. The study presented here aims to understand the temporal evolution of Precambrian through Cretaceous sedimentation in the Delaware basin in order to describe the evolution of the basin. Results from this study constrain the transition from Gondwanan-derived sediment in Ordovician units, to Appalachian-derived sediments in Mississippian units, to mixed Appalachian and Gondwanan sediment sources in Pennsylvanian and Permian units, to western-derived sediments in the Cretaceous units.

II. BACKGROUND GEOLOGY

2.1 Basin overview

The Delaware Basin of west Texas is a part of the greater Permian foreland basin system, that formed as the result of the Ouachita-Marathon Orogeny (Yang and Dorobek, 1995). The Permian basin is one of multiple flexural intracratonic basins and associated basement uplifts that comprise the Ancestral Rocky Mountains that developed during the Pennsylvanian-Permian collision of Laurentia and Gondwana (Ye et al., 1996). The Delaware Basin formed on the western flank of the Permian Basin (Figure 3), spanning approximately 34,000 square kilometers and 12 counties in west Texas and southern New Mexico (Howard Weil Incorporated, 2012). The basin is composed mostly of Paleozoic sedimentary rocks, accommodating ~7.3 km of siliciclastic and carbonate sediments in the eastern portion, making the Delaware Basin one of the deepest intracratonic basins in North America (Hills, 1972). Gravity data indicates that a gravity high within the Delaware Basin (Figure 5) may correspond to the boundary between two sub-basins in the Delaware Basin (Adams and Keller, 1996). They suggest that this feature represents Precambrian granitic intrusion in the center of the basin.

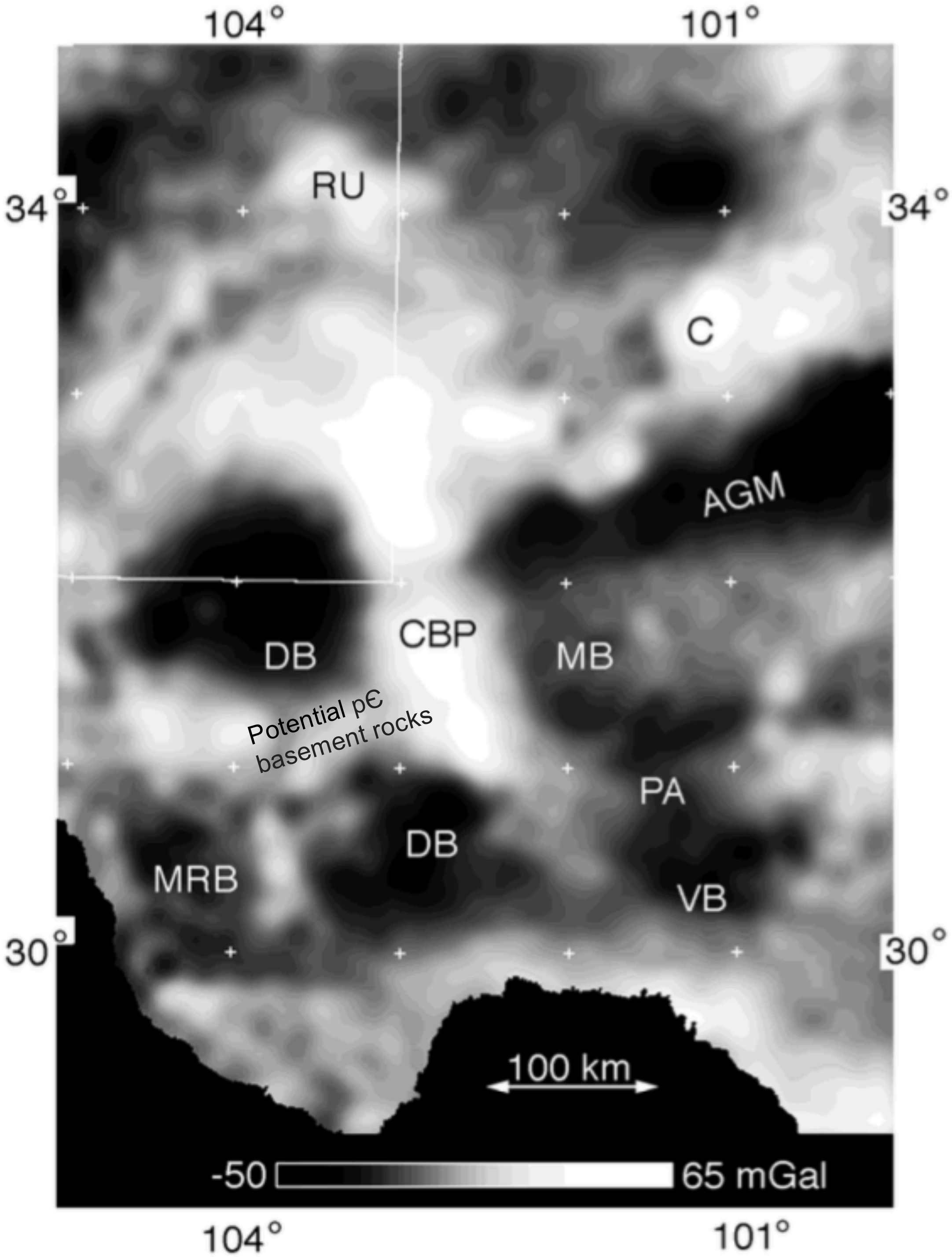

Figure 5 - Bouguer gravity anomaly map showing the complexity of the gravity field within the Delaware Basin. Abbreviated geological and geophysical features shown on the map: Delaware basin (DB), Midland basin (MB), Val Verde basin (VB), Marfa basin (MRB), Central Basin platform (CBP), Pecos arch (PA), Abilene gravity minimum (AGM), Crosbyton anomaly (C), and Roosevelt uplift (RU). Modified from Adams and Keller (1996).

2.2 Tectonic history

During the Early and Middle Paleozoic (Figure 6), the Permian Basin region was a topographic low referred to as the Tobosa Basin (Galley, 1958; Hills, 1972; and Adams and Keller, 1996), formed on a passive margin (Budnick, 1984; Hoffman, 1989), that records slow carbonate deposition with influxes of siliciclastic sedimentation (Robinson, 1980). Following a significant period of uplift and erosion during the Early Proterozoic, marine sedimentation began in the Late Cambrian and continued into the Early Ordovician (Keller, 1980). Sediment facies during this time include Ellenburger and Marathon Limestone marine carbonates, and Woods Hollow shale to the southeast (Galley, 1958). Prior to the basin deformation in the Late Paleozoic, sedimentation in this passive margin was periodically interrupted by erosional events associated with major sea level changes that resulted in subaerial exposure and produced regional unconformities (Galley, 1958; Keller, 1980).

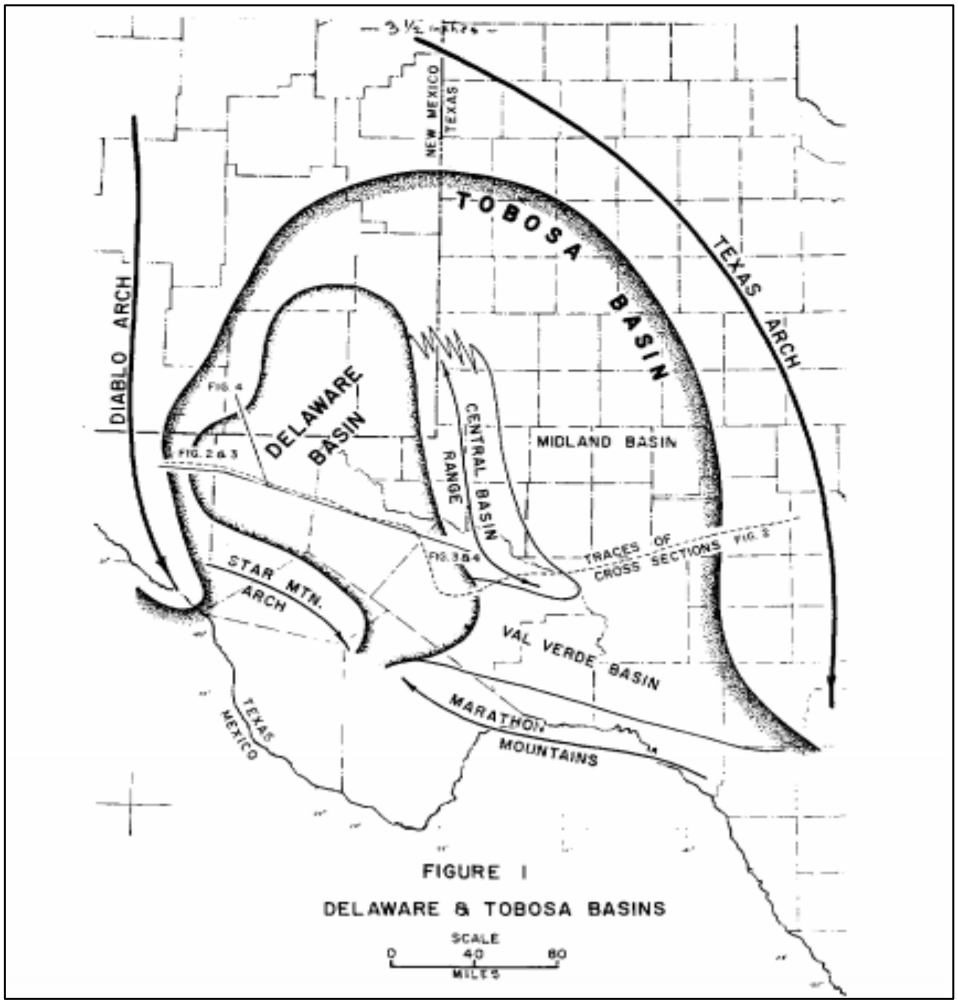

Figure 6 - Paleogeographic map of the Permain region during the early Paleozoic. Reprinted from Adams (1965).

During the Middle Mississippian, up to ~4000 m of Woodford and Barnett Shale were deposited to in northern Permian Basin (Galley, 1958; Hills, 1984, Kinley et al., 2008). To the southeast, >1,800 meters of sandstone and shale turbidites of the Tesnus Formation were deposited and are chronostratigraphically equivalent to the Barnett Shale (Ross, 1986). Initial collision began during the Mississippian, as Laurentia subducted beneath Gondwana (Figure 7), resulting in the progressive closure of Rheic Ocean (Murphy, 2006). Compressional stresses transmitted northward from the Ouachita – Marathon (OM) fold-thrust belt (Ye et al., 1996) potentially reactivated pre-existing extensional structures, and created multiple foreland basins, including the Permian Basin of west Texas, and the Ancestral Rocky Mountains of western North America (Ye et al., 1996). South of the study area and along the collisional margin, this continental collision accreted and uplifted multiple magmatic arcs, including six peri-Gondwana terranes: Caroline terrane, Suwanee Florida terrane, Yucatan/Maya terrane, Chiapas terrane, Coahuilla terrane, and Oaxaquia Acatlan/Mixteca terrane (Dickinson and Lawton, 2001; Vega – Granillo et al., 2008; Soreghan and Soreghan, 2013; Anthony, 2015). These terranes, caught between the Laurentia – Gondwana suture, represent possible sediment source areas for Late Paleozoic Delaware Basin sediments.

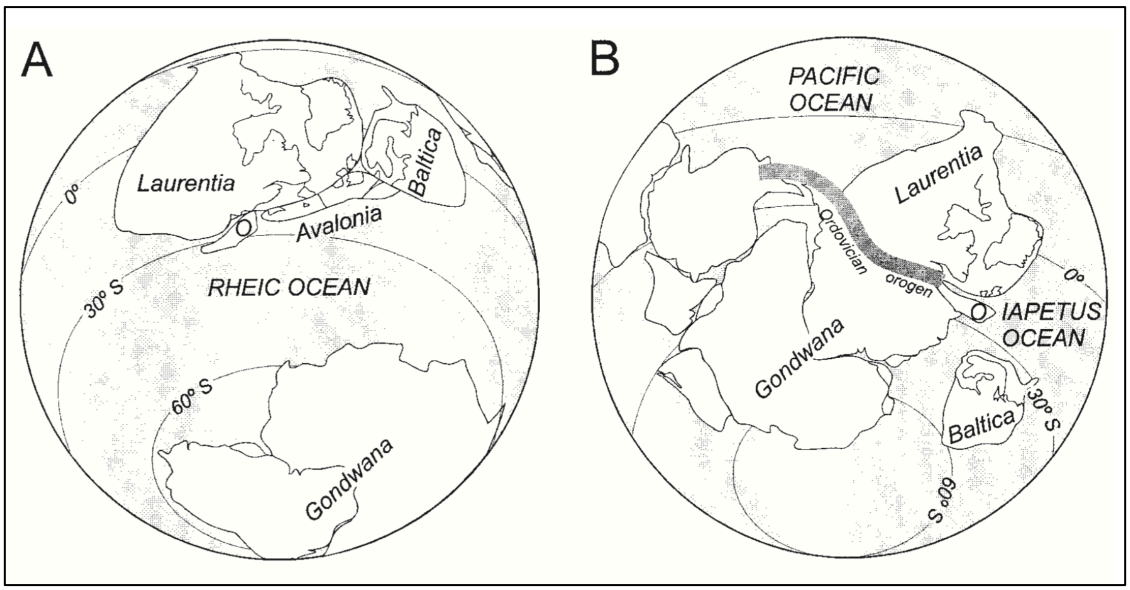

Figure 7 - Paleogeographic maps for Late Ordovician - Early Mississippian in the Gondwana and Laurentia region. A: Early Ordovician, Gondwana and Laurentia are separated by Rheic Ocean. B: Closure of Rheic Ocean is resulted in the collision between Laurentia and Gondwana during the Mississippian. Reprinted from Ortega- Gutiérrez et al. (1999).

Continued collision into the Pennsylvanian contributed to uplift of the northwest trending, basement-cored Central Basin Platform uplift, which partitioned the Tobosa Basin into the Delaware Basin to the west and the Midland Basin to the east. Topographic loading induced rapid subsidence in the eastern Delaware and western Midland basins, creating asymmetrical profiles and thickening of the Pennsylvanian to Early Permian deposits towards the Central Basin Platform (Yang and Dorobek, 1995). Uplift of the Central Basin Platform ceased during the Early Permian (Hills, 1984). Tesnus Formation deposition continued into the Early Pennsylvanian, and vertically graded into Dimple Limestone, deposited in the northwestern portion of the basin. Dimple Formation graded vertically gradually into Haymond Formation then Gaptank Formation, which consist of interbedded sandstone and distal shale deposition.

As the Delaware and Midland Basins subsided, carbonate platforms formed on the perimeter of the Permian Basin (Eastern Shelf, Northwestern Shelf, and Diablo Platform: Hartman and Woodard, 1971; Bozanich, 1979; Ward et al., 1986). These carbonate shelves were potentially traversed by siliciclastic depositional systems, transporting fluvial and aeolian material into the Delaware Basin during lowstand system tracts (Galley, 1958; Keller et al., 1980; Kocurek and Kirkland, 1998). By late Permian, the Captain reef complex acted as a sediment barrier, limiting the carbonate transport into the Delaware Basin and controlling the sedimentary facies of this time. During the Late Permian, deposition was controlled by minimal tectonic activity and prolonged sea level regression, leading to a thick evaporate deposition (Galley, 1958; Keller et al., 1980; Hills, 1984). A period of sedimentation hiatus took place during the Jurassic, and deposition resumed during the Cretaceous. The Delaware Basin was subsequently uplifted by Sevier and Laramide compressional events along western margin of North America during the Cretaceous, as well as Rio Grande Rift extension during the Cenozoic (King, 1948; Galley, 1958; Keller, 1980; Hills, 1984).

III. METHODS

3.1 Sample collection

Five Delaware Basin samples and eight Marathon Uplift samples (Figure 3) spanning Precambrian – Cretaceous (Figure 4) were collected from outcrops in west Texas. Upon cross examining Delaware Basin stratigraphic column of sandstone intervals and sandy limestones, and USGS Texas geologic maps, accessible public road cut locations in the desired geologic formations were selected. The sandstone units and sandy portions of limestone units include zircon grains that reflect crystallization age of deposition. Thirteen samples spanning the pre-collision to post-collision phase of the basin were selected to test the hypothesis that basin drainage system is affected by local tectonic events.

3.2 Sample preparation

All samples were prepared for analysis within the laboratories of the Department of Geology and Geophysics at Texas A&M University. Upon sample collection, ~5 kg samples were crushed using a jaw crusher, reducing hand samples to a pebble particle size. Each sample was fed into a disk mill with grinding steel plates to reduce the sample to consistent sand-sized grains. The material was sieved through a 1.4 mm Fisher Scientific Company USA standard testing sieve. Then, initial separation of dense minerals was completed using a Wilfley water table. Next, the sample was separated using bromoform (density: 2.89 g/cm^3). Prior to magnetic separation processes, a small fraction (~800-1000 grains) of all heavy minerals were randomly selected for heavy mineral analysis. A low strength hand magnet was used to remove ferromagnetic minerals and iron shavings from the disc mill prior to separating the samples with the Frantz Isodynamic separator. Remaining fraction underwent different magnetic fields with electric currents of 0.1 amperes, 0.5 amperes, 1.0 ampere, and 1.2 amperes. The magnet and tray are tipped forward at ~15-degree angle to advance the particle sliding. They are also tilted sideways with respect to horizon, which assists particle separation by weight as they slide down the tray through the separator. The magnetic fraction was set aside and non-magnetic fractions were prepared for the second round of heavy liquid separation using Methylene Iodide (MEI; density: 3.32 g/cm^3). Processed samples generally have a high fraction of zircon with small quantities of other minerals (apatite, hornblende, pyrite, etc). The accessory minerals were manually separated from the zircon fraction using a dental tool.

3.3 Laser ablation

The high purity zircon fraction from each sample was mounted on a strip of double-sided adhesive tape attached to a 5x20 mm glass slide for laser ablation at University of Houston ICP Analytical Laboratory under Dr. Joel Saylor, Dr. Thomas Lapen, and students' supervision. In addition to the processed samples, two standards with known ages are placed next to the samples for age correction. Zircon standards used include Plesovice (PLEIS); (330 Ma) and FC5z zircon; (1099 Ma) as primary and secondary standards, respectively. For each sample, 150 random grains were ablated using a Photon Machines Analyte 193 ArF excimer laser attached to a Varian 810 quadrupole mass spectrometer (Shaulis et al., 2010). The laser energy was set at 56% with a laser spot of 29.6 µm, with a wavelength of 193 nm during analyses. This process resulted in approximately twenty seconds of ablation, with eight seconds of background measurement and seven seconds of washout.

Three primary standards (PLEIS) and one secondary standard (FC5z) were ablated at the beginning of each sample's ablation run. One PLEIS standard was ablated after analyzing 10 unknown grains. Three PLEIS standard and one FC5Z standard were analyzed after analyzing a set of 30 grains. This process was repeated until 150 zircon grains were analyzed per sample. Data acquisition per grain lasts 45 seconds, which includes 10 seconds for laser to warm up, and 25 seconds of grain ablation, then 10 seconds of laser cool down. This process is repeated for each grain per sample, until the desired number are completed.

Once obtained, the isotopic data from ablation were uploaded into U-Pb tool, a data reduction program designed by PhD student Kurt Sundell at University of Houston. To achieve the statistical adequacy yet preserving the data integrity, age discordant cut off was set at 15% discordant, and Pb^{206}/U^{238} values were used if age variants were less than 600 Ma. Best ages were obtained from the U-Pb software and plotted in Isoplot 3.0 to create the probability density plots, and kernel density plots.

3.4 Heavy mineral

Heavy mineral analyses were conducted at Colorado School of Mines in their Automated Mineralogy Laboratory, which is equipped with a Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) device, an automated instrument for mineral and material analysis. It provides quantitative distribution of minerals with density greater than $2.89g/cm^3$. Thirteen heavy mineral fractions were extracted from the same detrital zircon separates post the heavy mineral Bromoform separation step, prior to the Frantz magnetic separation steps. The minerals extracted from these steps include chloride, apatite, hornblende, epidote, garnet, Al_2SiO_5 group, monazite, rutile, opx, cpx, olivine, and zircon. These raw data were then utilized to calculate two indices, because the ratio of minerals of different petrologic characteristics can indicate hydrodynamic conditions and mechanical abrasion during transport and deposition (Morton and Hallsworth, 1999) thus is a useful tracer of provenance shifts. The results from the heavy mineral analyses are compared against the interpretation of the detrital zircon analyses (Figure 8).

3.5 Point counting

All samples were mounted into thin sections on a glass slide, treated with blue epoxy for porous areas, and stained for potassium feldspar. Point counts were following the Gazzi-Dickinson methods to minimize the biasing due to the grain size variation (Dickinson, 1970; Gazzi et al., 1993; Ingersoll et al., 1984). Thin sections were point counted at Texas A&M using petrographic microscope with PELCON automated motorized stage at Dr. Nicholas Perez's lab. 400 grains greater than sand size (~0.0625 mm) were counted for each sample, following the Gazzi-Dickinson method, statistically minimizing the effect of grain size on modal composition (Ingersoll et al., 1984). Grain categories for normalization include monocrystalline quartz, polocrystalline quartz, chert, plagioclase feldspar, potassium feldspar, volcanic lithics, metamorphic lithics, sedimentary lithics, and plutonic lithics (Table 1). Depending on which part of the rock fragments intersecting the crosshair, fragments containing sand-sized crystals within a fine-grained matrix were either counted as the crystals or as lithics. Volcanic rock fragment within a sedimentary fragment were counted as Lv, instead of Ls. Quartz, feldspar, and lithics sub-categories were added and normalized to represent a consolidated framework and plotted on sandstone composition and provenance discrimination ternary diagrams (Dickinson et al., 1983) to provide source rock information. Additional categories tabulated but not included as framework grains include biotite, muscovite, diorite, porosity, matrix, cement, and miscellaneous minerals (Table 1) to document the distribution differences between all samples.

Table 1 - Categories used for petrographic point counts (framework grains are bolded) and grain parameters in normalization.

Categories		Mineral counted	Symbol
Quartz		**Monocrystalline quartz**	**Qm**
		Polycrystalline quartz	**Qp**
		Chert	**Qc**
Feldspar		**Plagioclase feldspar**	**Fp**
		Potassium feldspar	**Fk**
Lithics		**Sedimentary lithics**	**Ls**
		Volcanic lithics	**Lv**
		Metamorphic lithics	**Lm**
		Plutonic lithics	**Lp**
Miscellaneous		Biotite	Biot
		Muscovite	Musc
		Diorite	Dior
		Porosity	Φ
		Matrix	Matrix
		Cement	Cement
		Other	O
Normalization QmFLt plot			
Qm	=	Total monocrystalline quartz	Qm
F	=	Total Feldspars	(Fk + Fp)
Lt	=	Total Lithics	(Ls+Lv+Lm+Lp)

IV. RESULTS

Figures 8-11 present results (see supplemental files) from detrital zircon (DZ) U-Pb geochoronology, modal mineralogy from petrographic point counts, and heavy mineral compositions from thirteen samples. The DZ U-Pb geochronologic data (Figure 8) are displayed as probability distribution functions. The point count data (Figure 9 and Figure 10) constrain the percentage of monocrystalline quartz, feldspar (plagioclase, and potassium feldspar), and lithic fragments (volcanic and hypabyssal lithics, metamorphic lithics, sedimentary lithics, and plutonic lithics). Heavy mineral results (Figure 11) quantify the percentage of accessory minerals including pyroxene, olivine, hornblende, apatite, tourmaline, garnet, rutile, monazite, chlorite, and zircon.

4.1 U-Pb detrital zircon analysis

The Precambrian metasediments unit (15TX10) has a broad distribution of DZ ages, ranging from 1-2 Ga with a peak age of 1357 Ma. A high abundance of grains (57%) were observed in the 1300 – 1500 Ma age group. 21% of the zircon grains are within the 900 – 1300 Ma age group, and 25% of the grains are within the 1600 – 1800 Ma group.

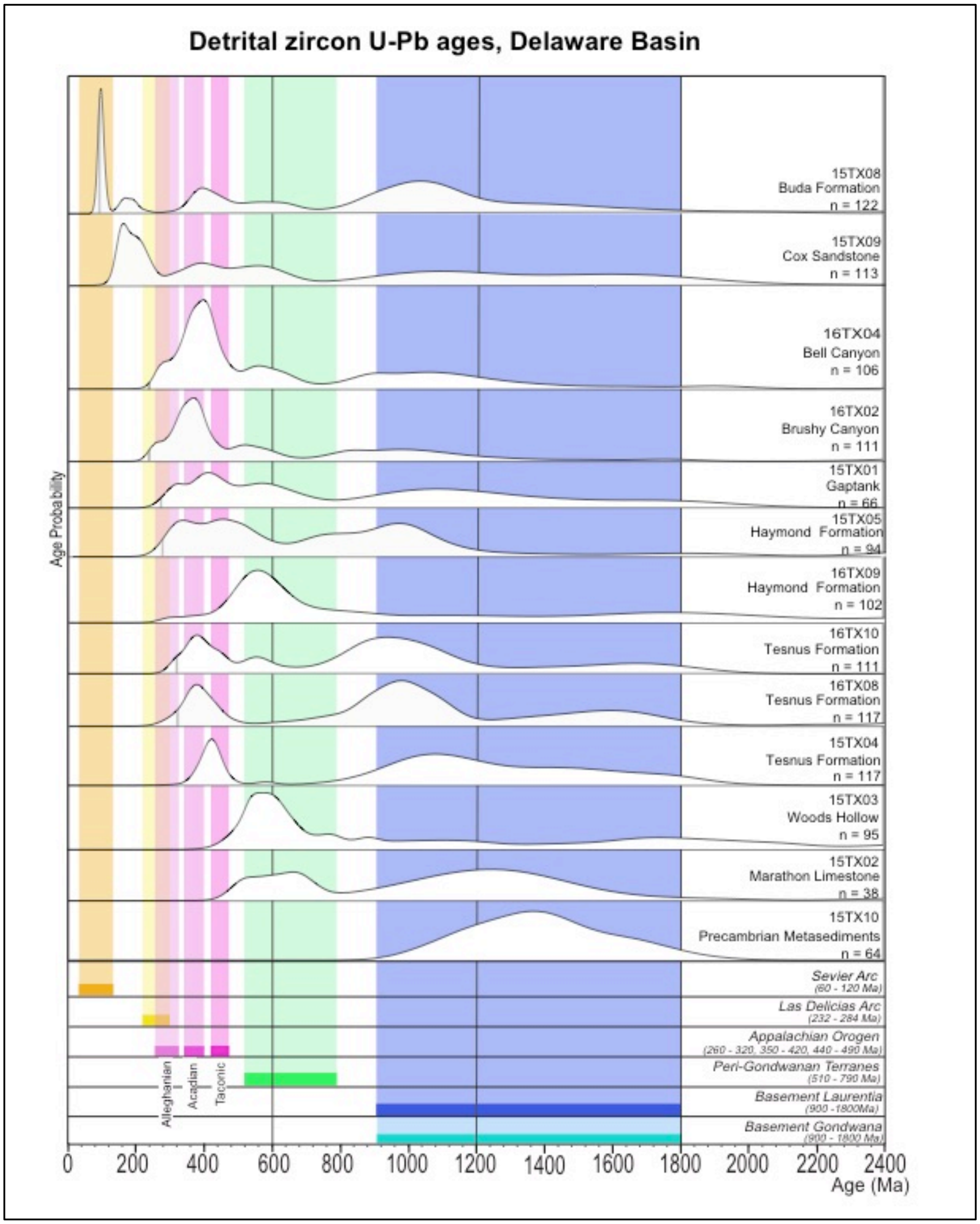

Figure 8 - Normalized probability density plot of U-Pb detrital zircon U-Pb ages from the thirteen samples collected from outcrop in the Delaware Basin and Marathon Uplift region. The number of concordant detrital zircon ages is listed for each sample ('n ='). Shaded color bars correspond to age ranges of potential source regions. Basement terranes synthetized from Livaccari and Perry (1993), William et al. (2004), Gleason et al. (2007), Parks et al. (2010), Gehrels et al. (2011), Soreghan and Soreghan (2013), and Anthony (2015).

Ordovician units

The two Ordovician units, the Marathon Limestone (15TX02) and the Woods Hollow Shale (15TX03), have different DZ signatures. The Marathon Limestone sample was collected from a marl interval in middle Marathon unit, and yielded few zircons (n=38). This sample has a bimodal distribution of DZ ages, with a range of zircons from 800 – 1600 Ma (70%) and another between 480 – 790 Ma. A majority of the zircon grains are found in the 900 - 1300 Ma and the 1300 – 1500 Ma age groups. A secondary group (16%) of the grains in the 510 – 680 Ma age group. The rest of grains are older than 1500 Ma.

The Woods Hollow Shale is dominated by a 510 – 680 Ma (34%) spectra, with a mode of ~580 Ma. 15% of the grains are in the 900 – 1300 Ma group, which contain. Only 9 grains occur in the 1600 – 1800 Ma age group and 4 grains in the 1300 – 1585 Ma group.

Mississippian units

The three Mississippian samples were all collected from the Tesnus Formation (15TX04, 16TX08, and 16TX10) in the Marathon region. All three samples are dominated by two main DZ groups: the abundance is highest (30 – 41%; weighted mean ~38%) in the 900 – 1300 Ma group. The second highest abundance (15 – 16%) is concentrated in 350 – 465 Ma group, with modes of 423, 387, and 367 Ma (respectively). The oldest Tesnus sample (15TX04) has DZ ages in 1300 – 1585 Ma groups and 1600 – 1800 Ma group (19% and 9%, respectively). The second oldest Tesnus sample (16TX08) has decreased contribution (9 – 11%) from 1300 – 1585 Ma and 1600 – 1800 Ma groups, and minor contribution (2%) in the 510 – 680 Ma group. The youngest Tesnus sample (16TX10) has a significant fraction (23%) observed in the 350 – 465 Ma group, whereas the 510 – 680 Ma, 1300 – 1585 Ma, and 1600 – 1800 Ma groups comprise 9 – 11%.

Pennsylvanian units

Two samples were collected from the Lower Pennsylvanian Haymond Formation (16TX09 and 15TX05), and one from the Upper Pennsylvanian Gaptank Formation (15TX01). The stratigraphically Lower Haymond Formation sample (16TX09) is dominated by 510 – 680 Ma (30%) grains, with a mode at 559 Ma. Remaining DZ spectra comprise relatively low abundance (4 – 13%) of the sample. The younger Haymond Formation sample has multimodal DZ spectra; 39% total in the 285 – 350 Ma and 350 – 465 Ma groups, 28% in the 900 – 1300 Ma group, with a mode of 1027 Ma, and 13 – 14 % in the 350 – 465 Ma and 510 – 680 Ma groups. The Gaptank Formation has a broad 900 – 1800 Ma age distribution representing 32% of the total grains in this unit. The remaining zircon grains occur in the following groups: 510 – 680 Ma, 350 – 465 Ma, and 285 – 350 Ma (11%, 10%, and 4% respectively).

Permian units

The two Permian units, the Brushy Canyon (16TX04) and the Bell Canyon (16TX02) formations collected near the Guadalupe Mountains, both have high abundance of 350 – 465 Ma zircons (33% and 36%, respectively) with modes of 387 and 389 Ma, respectively. The broad DZ group of 900 – 1300 Ma group compose 32% and 22%, respectively. 13% and 12% of zircons grains are in the 510 – 680 Ma group with modes of 508 and 537 Ma. An additional 11% of the grains occur in the 285 – 350 Ma group, with a mode of 286 Ma.

Cretaceous units

The Cretaceous Buda Limestone (15TX08) and Cox Sandstone (15TX09) formations have the highest zircon abundance in 900 – 1300 Ma group (35% and 25%, respectively). Age groups 350 – 465 Ma, 510 – 680 Ma, and 1300 – 1585 have similar percentages (9-11%) of zircons, modes of these groups are at 378 Ma, 1015 Ma (15TX08), 383 Ma, and 548 Ma

(15TX09). The Buda Limestone has relatively high abundance (14%) of 60 – 120 Ma group with a mode of 93 Ma.

Potential sediment sources

Detrital zircon U-Pb geochronologic results from this study were compared against basement terranes in Laurentia and Gondwana that were potential source areas of detrital material during sediment accumulation in the Tobosa and Delaware Basins. Although multiple potential source terranes have been identified, diagnostic spectra include Peri – Gondwana teranes (510 – 680 Ma) (Mueller et al., 1994; Dickinson and Lawton, 2001; Murphy et al., 2004; Sharrah, 2006; Soreghan and Soreghan, 2013), Appalachian terranes (350 – 465 Ma) (Krogh et al., 1993; Weber et al., 2006; Keppie et al., 2008), the Las Delicias Arc (232 – 284 Ma) (King, 1948; McKee, et al. 1988; Lopez et al., 2001; Gleason et al., 2007), and the Cordilleran arc (50 – 150 Ma); (Dickinson, 1981; Chen and Moore, 1982; Laskowkski et al., 2013;). Other groups may have been sourced either from Grenville basement Laurentia (0.9 – 1.3 Ga) (Dickinson and Gehrels, 2003; Gleason et al., 2007; Gehrels et al., 2011; Soreghan and Soreghan, 2013) or Sunsás basement (0.9 – 1.2 Ga) in Gondwana (Chew et al., 2011).

Paleoproterozoic (> 1825 Ma)

Potential Paleoproterozoic sediment sources occur in the Laurentian basement, such as the Superior – Wyoming Craton, the Mojave, and the Trans-Hudson terranes. The Superior – Wyoming Craton (> 2.5 Ga) includes multiple island arcs and accreted continental terranes (Park et al, 2010). The Mojave province of the southeastern Laurentia (2.1 – 2.3 Ga) encompasses igneous basement (Fedo et al., 2015). The Trans-Hudson terrane (1.8 – 2.0 Ga) is primarily composed of amalgamated metamorphic cratonic blocks as the result of collision between Superior and Wyoming provinces (Hoffman, 1989).

Late Paleoproterozoic (1600 – 1800 Ma)

Sediment sources for this age group is typical of the Yavapai - Mazatzal (1.6 – 1.8 Ba) basement province of the southwest Laurentia (Gleason et al., 2007). Grains of this age group are prevalent in the Pennsylvanian strata in the western Laurentia (Soreghan et al., 2008). 1.72-1.68 Ga zircons may also come from intrusive granitoids that stitched Yavapai terrane boundaries (Whitmeyer and Karlstrom, 2007).

Early Mesoproterozoic (1300 – 1600 Ma)

This range of zircon ages correlates with magmatic events associated to the formation of granite – rhyolite suites, and an amalgamation of scattered plutons overprinting the Yavapai – Mazatzal basement provinces (Gehrels and Dickinson, 2009). Some of the plutons likely took part of the formation of the Ancestral Rocky Mountain uplifts (Hoffman, 1989).

Mesoproterozoic (920 – 1300 Ma)

Grains of this age group typically are related to the Grenville Orogen of southern and eastern Laurentia (Lukert and Banks, 1984; Dickinson and Gehrels, 2003; Gleason et al., 2007; Park et al., 2010) or the Sunsás Orogenic belt on the Amazonian Craton in Gondwana (Chew et al., 2011). Grenville was formed as the result of multiphase continent – continent collisions with analogous orogenic events recognized in multiple continents (Moores, 1991; Park et al., 2010). The Sunsás orogenic belt formed as a result of collisional events with Laurentia during the formation of Rodinia along southwestern Amazonia (Teixeira et al., 2010; Chew et al., 2011).

Neoproterzoic – Early Paleozoic (510 – 790 Ma)

This range of zircon ages encompasses six-major Peri-Gondwana terranes formed as a result of Pan – African collisions associated with the closure of Neoproterozoic Ocean (Park et al., 2010). The accreted terranes include the Avalon, Carolina (southern Appalachians), Suwanee (Florida), Yucatan/Maya block, Chiapas, Coahuilla of Mexico, and Oaxaquia Acatlan/Mixteca (Heatherington et al., 1999; Wortman et al., 2000; Dickinson and Gehrels, 2003; Thompson et al., 2012; Soreghan and Soreghan, 2013).

Detrital zircons of 535 ± 10 Ma are commonly observed in Cambrian igneous rocks in the southern Oklahoma fault complex (Riggs et al., 1966; Dickinson and Gehrels, 2003; Gleason et al., 2007; Soreghan and Soreghan, 2013; Thomas et al., 2016). These rocks formed as a result of Late Paleozoic basement-cored uplift of the Wichita and Arbuckle Mountains.

Paleozoic (260 – 490 Ma and 232 – 284 Ma)

Two possible terranes, Appalachian orogenies east of the study area and Las Delicias Arc south of the study area, could both provide sediments into the Delaware Basin of this age range. The Appalachian orogenic system includes three distinct collisional phases: the Alleghanian (260 – 320 Ma), the Acadian (350 – 390 Ma), and the Taconic (440 – 490 Ma) orogenies (Dickinson and Gherels, 2003; Thomas, 2011). The synorogenic igneous rocks of the Appalachian fold thrust belt have an age range of 260 – 490 Ma (Park et al., 2010).

Local volcanic activities in the Las Delicias Arc contributed volcanic debris to the pre-existing Late Paleozoic marine sedimentation in the Las Delicias Basin (McKee, 1988). The Las Delicias arc of Coahuila is located in northwest Mexico and produced 232 – 284 Ma volcanic rocks (Lopez et al., 2001; Soreghan and Soreghan, 2013).

Early Mesozoic (60 – 220 Ma)

Sediments of this age group are consistent with ages of Cretaceous granitic plutons in the Cordillera magmatic arc (Chen and Moore, 1982; Ducea, 2001). The North American

Cordilleran orogenic system formed as a result of oceanic plate subduction beneath North Atlantic (Elison, 1991; Coney and Evenchick, 1994; Laskowksi et al., 2013).

4.2 Thin section petrology

Thirteen samples were point counted by the same operator (n = 400 grains) using the Gazzi-Dickinson method (Dickinson and Suczek, 1979, Ingersoll et al., 1984), where grains of 0.0625 mm or greater were tallied to constrain modal mineralogic compositions. Results from mineralogical data show that quartz compositions range from 16.9 – 87.6%, feldspars range from 1.3 – 51.8%, and lithic percentages range from 2.6 – 43.7%. Samples are predominantly lithic arenite, subarkosic, quartzarentic, or sublitharenitic (Figure 10).

Multiple complementary ternary diagrams were used to plot and compare the sample distribution, including QmFLt, QtFL, QmPK, and QpLvLs, where Qm is monocrystalline quartz, F is feldspar, Lt is total lithics, Qt is total quartz grains, P is plagioclase feldspar, K is potassium feldspar, Qp is polycrystalline quartz, Lv is volcanic lithics, and Ls is sedimentary lithics. Results (Figure 9 and Figure 10) are shown using the QmFLt ternary diagram.

Based on the different proportions of mineral assemblages, four stratigraphic groups were distinguished. The first group, consisting of the Precambrian basement (15TX04), Ordovician Marathon Limestone (15TX02), and Ordovician Woods Hollow Formation (15TX03), contain relatively low percentages of monocrystalline quartz (15 – 30%), and higher percentages of total lithic grains (39 – 49%). The second group consists of the three Tesnus samples (15TX04, 15TX08, and 16TX10) and the stratigraphically lowest Pennsylvanian Haymond Formation (16TX09). All samples have higher proportions of monocrystaline quartz (95.3 – 55%) than the first group, but there is a decrease in Qm proportion moving upsection. The third group consists of the Pennsylvanian Gaptank Formation (15TX01), Permian Bell Canyon (16TX04), and

Permian Brushy Canyon (16TX02) formations with relatively lower percentages (16 – 40%) of monocrystaline quartz and higher percentages of feldspar and lithic grains (16 – 60% and 38 – 61% respectively). The last group includes stratigraphically higher Pennsylvanian Haymond Formation (15TX05), Cretaceous Cox Sandstone (15TX09), and Buda Limestone (15TX08). Haymond Formation of this group is an outlier compare to other two samples that are stratigraphically close. This group has the most abundant quartz (70 – 93%) and relatively low amount of feldspar and lithic grains (4 – 20% and 3 – 10 %, respectively).

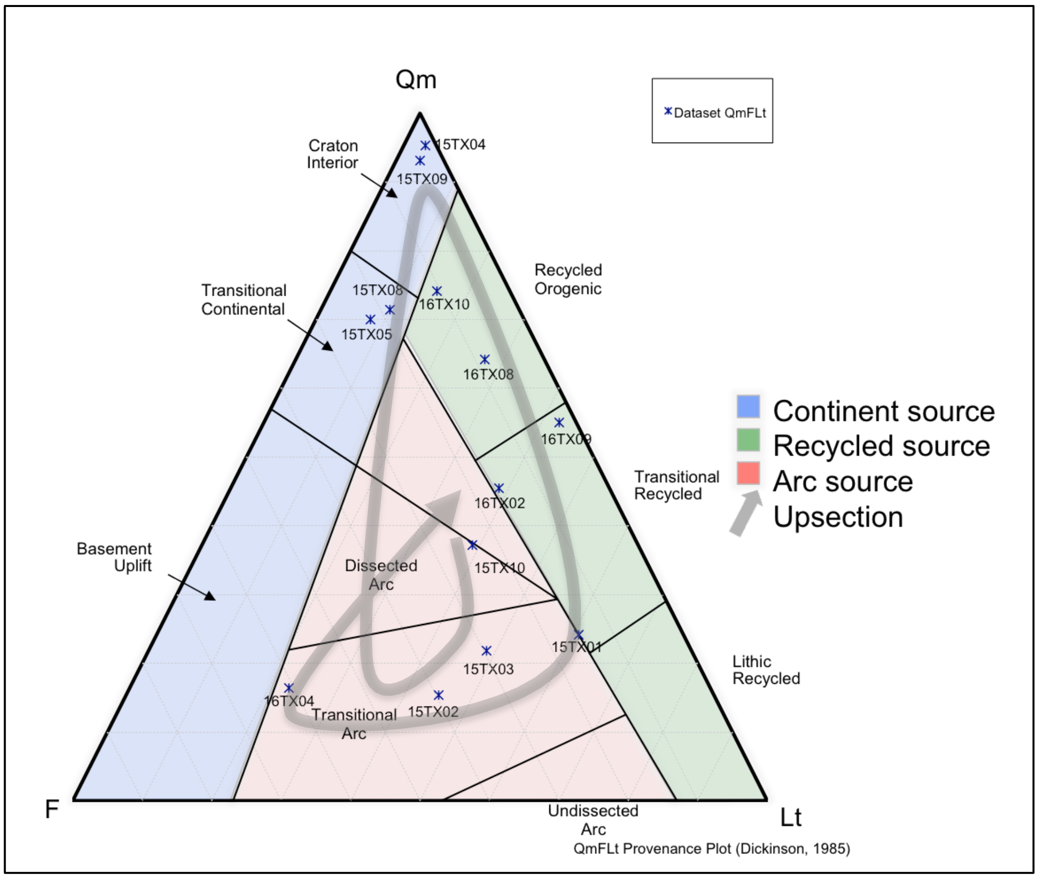

Figure 9 - Ternary diagram of sandstone petrographic results plotted on QmFLt diagram. Qm: monocrystalline quartz, F: feldspar and plagioclase summed; Lt: total lithic fragments. Light grey arrow indicates an upsection increase in maturity until Tesnus Formation when a decrease in maturity to Bell Canyon samples in the Delaware Basin samples, followed by a decrease in maturity. Colored areas indicating different interpreted source terranes: Red: arc sourc; blue: continent source; green: recycled source.

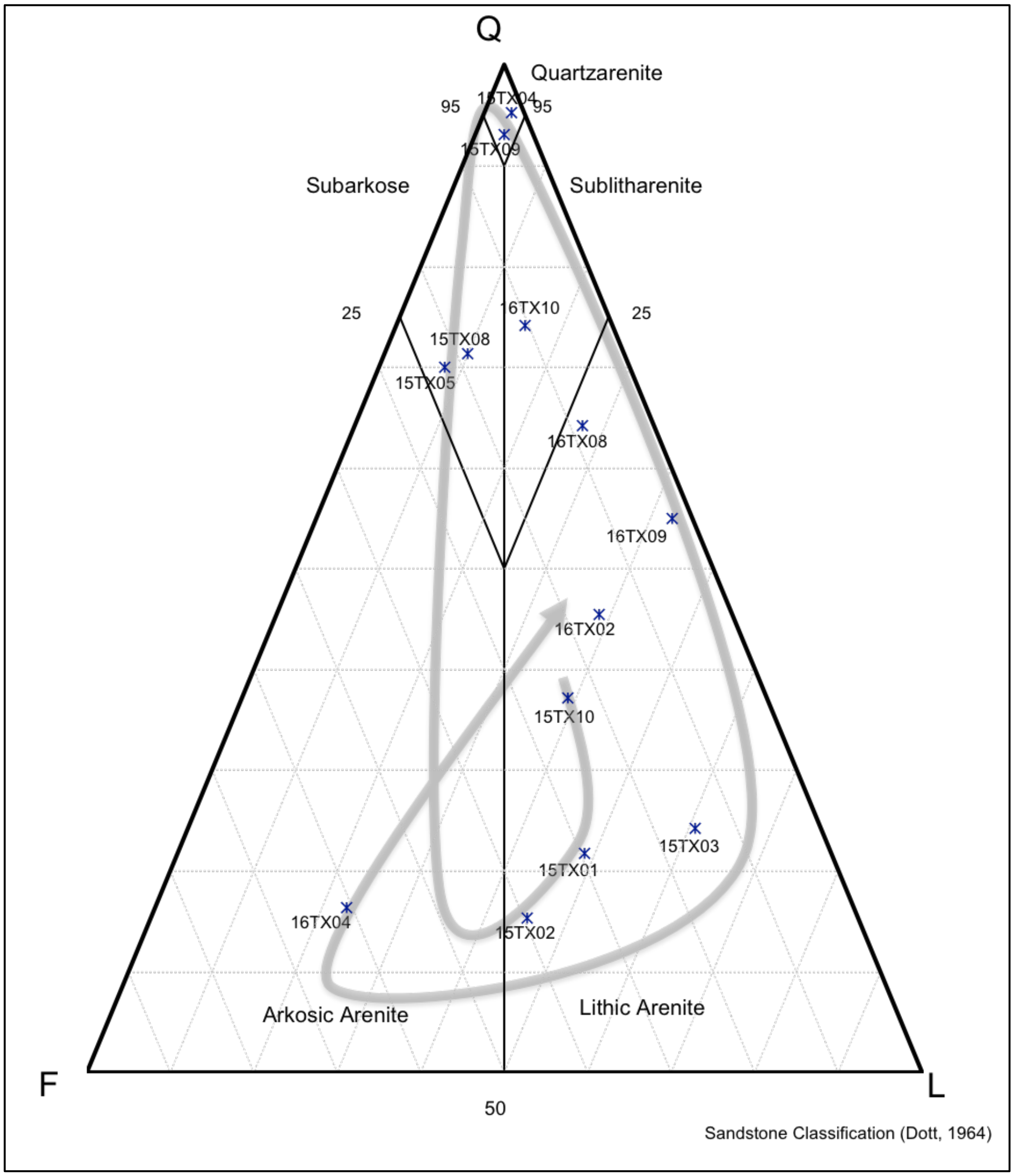

Figure 10 - Ternary diagram of sandstone compositional diagram. Gray arrow indicates the upsection changes in lithology.

4.3 Heavy mineral analysis

Heavy minerals (density > 2.89 g/cm^3) are accessory phases in siliciclastic rocks and constitute a small volumetric proportion of each sample. Their composition can reveal the interplay between the sediment sources, transport processes, and burial associated compactions (Morton, 1991; Lihou and Mange-Rajetzky, 1996; Morton and Hallsworth, 1999; Bush et al., 2016).

Heavy minerals analyzed include chlorite, apatite, hornblende, epidote, tourmaline, garnet, Al_2SiO_5 group, monazite, rutile, orthopyroxene, clinopyroxene, olivine, and zircon (Figure 11). From these raw mineral counts, multiple index ratios were calculated, including ZTR (zircon - rutile - tourmaline; Hubert, 1962; Morton and Hallsworth, 1999), ATi (apatite – tourmaline index; Morton and Hallsworth, 1999). The ZTR index quantifies the presence of stable minerals, where high ZTR index suggests the sample is more mature and likely recycled and low ZTR index indicates that the sample was first cycle deposit. The ATi compares relatively unstable apatite phase with the stable tourmaline phase. High ATi values are interpreted as evidence for proximal sediment sources, or shallow burial depth (Morton, 1984; Smale and Morton, 1987; Milliken, 1988; Morton and Hallsworth, 1999). The index ratios among all the samples, ZTR ranges between 5.27 – 93.07%; the ATi index ($\frac{a*100}{a+t}$) ranges between 0 – 96.05 %.

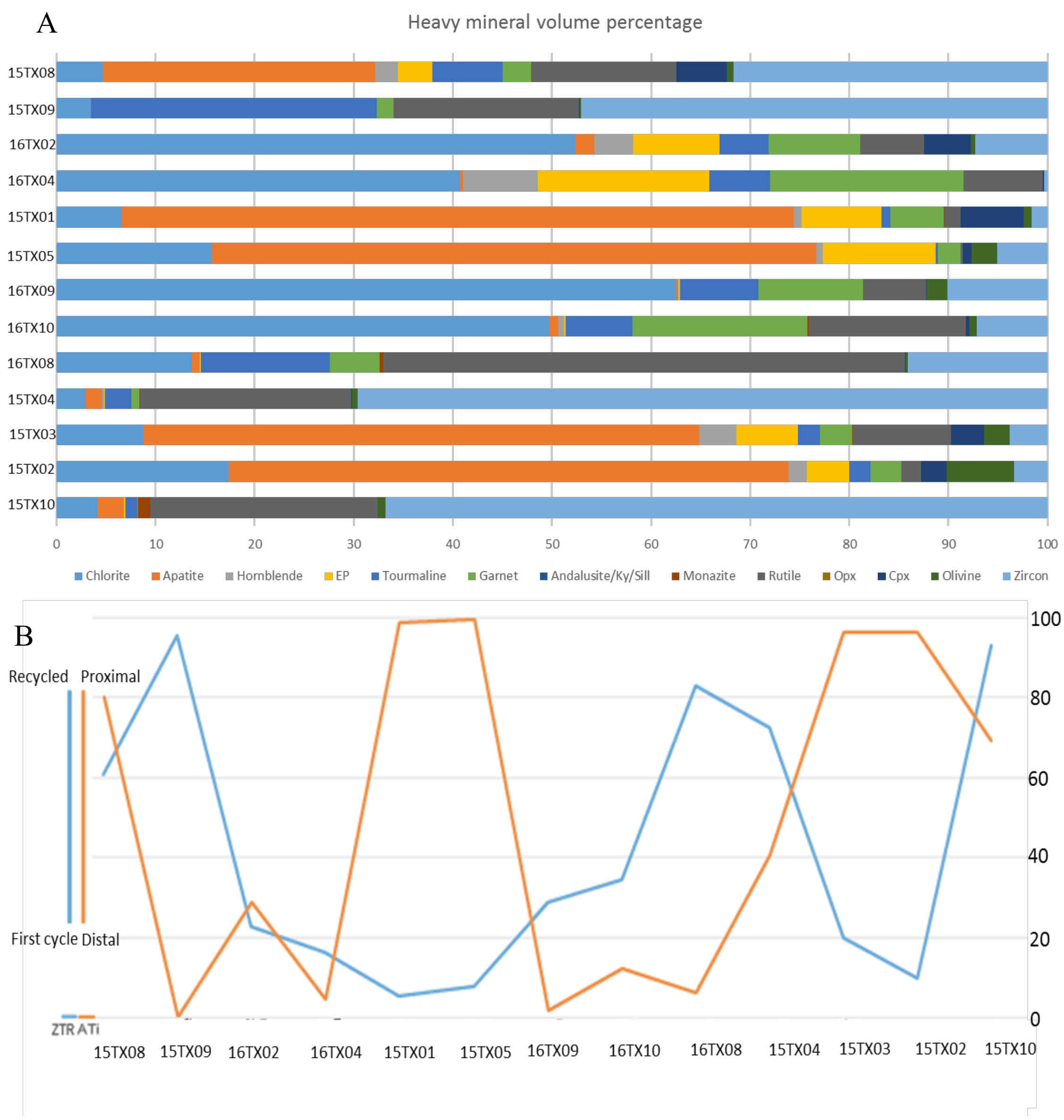

Figure 11 - Heavy mineral (ρ> 2.89g/cm^3) distribution from Delaware Basin region samples, plotted in stratigraphic order. A) Percentage relative abundance chart. B) Heavy mineral indices. ZTR - zircon, tourmaline, and rutile index (zircon + tourmaline + rutile). High value of ZTR ratio indicate recycled sediments, whereas low account of ZTR volume percentages represent first cycle sediments. ATi- apatite – tourmaline index [100 * apatite count /(total apatite + tourmaline)]. High account of ATi ratio indicate that the provenance source is proximal to catchment location, whereas low account of ATi indicate a distal provenance source.

The heavy mineral mass percentage chart shows 7 groups based on heavy mineral results. The Precambrian unit (15TX10) is dominated by zircons (66.8%; mean of all samples = 20.6 %) and rutile (22.9%; mean of all samples = 13%). The two Ordovician units, Marathon Limestone (15TX02) and Woods Hollow Shale (15TX03), both have high proportions of apatite (56.4%, 56.1% respectively; mean of all samples = 21.3 %), a relatively low abundance of zircon (3.4 - 3.8%), and relatively high abundance of olivine (2.58 - 6.75%; mean of all samples = 1.8%). The stratigraphically lowest Mississippian Tesnus Formation sample (15TX04) is characterized by high percentages of zircon (69.6%) and of rutile (21.33%). The two younger Tesnus Formation samples (16TX08, 16TX10), and the stratigraphically lowest Pennsylvanian Haymond Formation sample (16TX09), share similar heavy mineral assemblages: relatively high abundance of tourmaline (7 - 13%; mean of all samples = 6.3%), and garnet (6 – 17%; mean of all samples = 6.2%), whereas chlorite is variable (14 – 62.5%; mean of all samples = 21.7%). The Pennsylvanian Haymond (15TX05) and Gaptank (15TX01) formations both have low abundance of zircon (1.6 - 5.1%), high percentage of apatite (61 - 67%), and relatively high concentration of epidote (8 - 11%; average of all samples = 1.7%). The two Permian samples Bell Canyon (16TX04) and Brushy Canyon (16TX02) both contain high volumes of garnet (10 - 19.5%), epidote (9 - 17%), and chlorite (41 - 52%). The two Cretaceous units, Cox Sandstone (15TX09) and Buda Limestone (15TX08) each have relatively high proportion of zircon grains (32 – 47%) and rutile grains (15 – 18%). Although Cox Sandstone has higher amount of tourmaline (29%), the Buda Limestone has higher percentage of apatite (27.5%).

4.4 Kolmogorov-Smirnoff statistical test

In addition to visual comparison of the three datasets, the Kolmogorov-Smirnoff (K-S) statistical test was used to compare datasets of all samples. The K-S statistical method tests the hypothesis of whether two samples are drawn from parent populations with the same distribution, and yields a value P, which is inversely proportional to the confidence value. With $p < 0.05$, the test fails, suggesting that there is a >95% confidence level that the two zircon populations are not derived from the same source (Burrett et al., 2014). The K-S test determines the dissimilarity among pairs of cumulative distribution functions, here applied to distributions of detrital zircon U-Pb ages (Barbeau et al., 2006; Vermeesch, 2013; Vermeesch and Garzanti, 2015; Saylor and Sundell, 2016). Low values of dissimilarity suggest the two samples are similar, which may suggest the two samples were sourced from similar sediment sources. Results of the K-S test can be transformed into 'disparities' and plotted as Euclidean distances in a multidimensional scaling map (Figure 12). In an MDS map, samples that plot close to each other are more similar than samples that plot farther apart. We use this technique to complement and test interpretations derived from visual inspection of DZ U-Pb geochronology results.

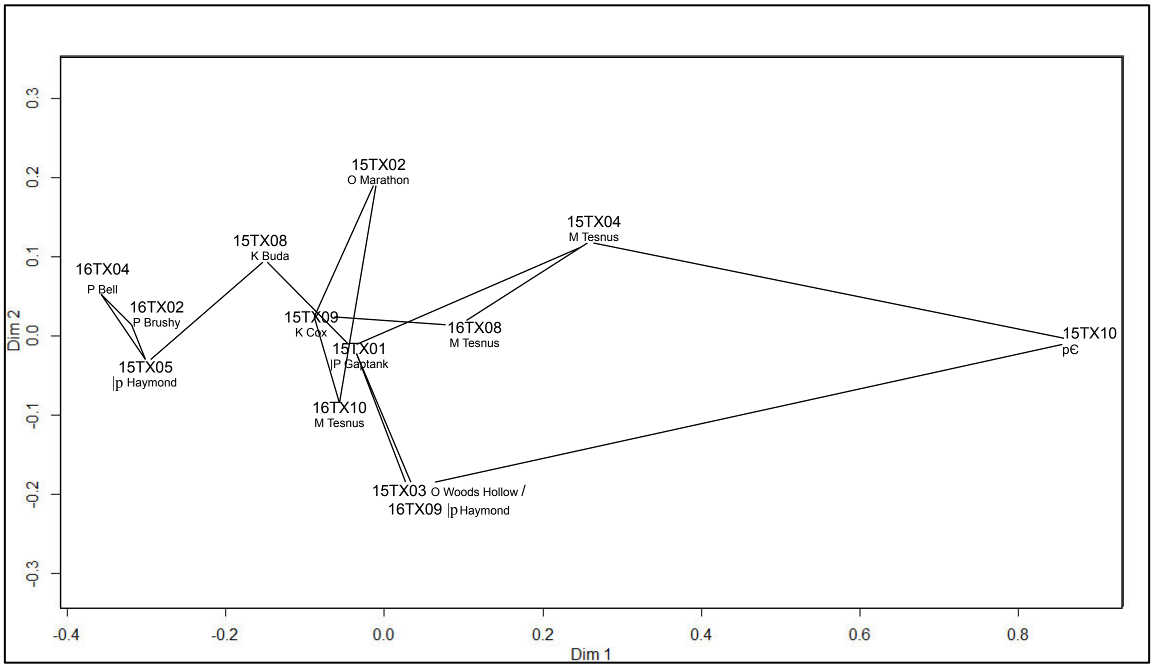

Figure 12 - Multidimensional scaling (MDS) plot for all Delaware basin detrital zircon samples, generated following methods outlined by Vermeesch (2013). Circles indicate different groups of proposed similarity.

V. PROVENANCE INTERPRETATIONS

Below, the results from multiple provenance proxies, detrital zircon U-Pb geochronology, heavy mineral distributions, and modal mineralogy from petrographic point counts are integrated to establish the provenance history of Paleozoic – Cretaceous rocks of west Texas. Four diagnostic DZ U-Pb age spectra are emphasized that uniquely identify contribution from specific sediment source areas. These ages include Peri-Gondwanan terrane (510 – 790 Ma), Appalachian orogenic provinces of eastern North America (440 – 490, 350 – 420, 260 – 320 Ma), Las Delicias Arc (232 – 284 Ma) in Mexico, and Cordilleran Arc of western North America (60 – 120 Ma). Each provenance technique contributes complementary information of sediment source areas. Point count data indicates samples that are more quartz, feldspar, or lithic rich, which may indicate levels of maturity or tectonic setting of source area. Heavy mineral analyses determine the abundance of accessory mineral phases, and can be used to indicate which sample was likely sourced from relatively local or distal sources, or are consistent with first cycle or recycled sediment. Detrital zircon geochronology highlights diagnostic terranes based on U-Pb crystallization age. The K-S test is used to support interpretations that were made by visual inspection.

Results from the Precambrian sample are not interpreted as a provenance result, but instead constrain the composition of a potential sediment source for younger strata. The 510 – 680 Ma DZ signature in the two Ordovician units (15TX02 and 15TX03) is most consistent with ages observed in Peri – Gondwanan sources, but also overlaps the 535 Ma signature in Wichita and Arbuckle Mountains. From heavy mineral results, the presence of high apatite and olivine percentages, and low ZTR values suggest first cycle sediment, and high ATi ratio is consistent with derivation from a proximal igneous source. These results, combined with feldspathic litharenite point count results, are indicative of an arc source, likely sourced from Peri – Gondwanan terranes and arcs situated to the south. I interpret siliciclastic sediment in Ordovician units of the Marathon uplift region as likely transported northward from southern Peri-Gondwanan terranes.

The three Mississippian Tesnus Formation samples (15TX04, 16TX08, and 16TX10) are characterized by changes in all three proxies. These samples have similar sublitharenite – litharenite point count results with higher quartz and decreased lithics and feldspar content, consistent with recycled orogenic provenance. High mineral counts of rutile, garnet, and tourmaline suggest a shift to sediment sourced from metamorphic rocks, whereas low ATi and high ZTR indices are consistent with sediment that is likely more recycled from a distal source. Syndepositional zircons occur in the stratigraphically younger Tesnus units (16TX08 and 16TX10), constraining the weighted mean of the youngest three grains yields maximum depositional age to ~339±51 Ma. All three samples share similar detrital zircon signatures: the reduction in Peri-Gondwana terrane DZ (2-10% in these samples compared to 30-40% in previous samples), and they plot as a group MDS map (Figure 12). The 350 – 465 Ma DZ spectra are most consistent with rocks derived from the Appalachian Orogeny. These provenance results suggest that by the Mississippian, the Delaware Basin was receiving sediments recycled mainly from Appalachian fold-thrust belt and foreland basin rocks to the east.

The stratigraphically lowest Pennsylvanian Haymond Formation sample (16TX09) has zircon ages between 300 – 700 Ma, a distribution that is similar to the older Ordovician Marathon (15TX02) unit. Heavy mineral results show the low ATi index, and abundance of tourmaline, garnet, and rutile. This suggests the Haymond unit received sediment from a source that was distal and underwent medium grade metamorphism. Heavy mineral assemblages between the Ordovician Marathon Formation (15TX02) and the Pennsylvanian Haymond Formation (16TX09) are different however: 15TX02 has a high olivine and apatite signature and a lower proportion of garnet, tourmaline, rutile, and chlorite, whereas 16TX09 has higher concentrations of garnet, tourmaline, rutile, and chlorite, and very low amount of olivine and apatite. The two aforementioned minerals have lower mechanical strengths, therefore are easier to breakdown in the recycling process. Thin section point count of 16TX09 reveal a lithic arenite and indicates the sample is consistent with a recycled orogen source. K-S statistical analysis (Figure 12) demonstrates that the two samples (16TX09 and 15TX02) plot on top of each other with a 96% similarity. All three provenance techniques support that this Haymond Formation sample is likely recycled from the Ordovician Marathon unit.

The remaining Pennsylvanian samples, the upper Haymond Formation (15TX05) and Gaptank Formation (15TX01), show a shift in DZ spectra, with 305 – 469 Ma group that is most consistent with the DZ signature of the Appalachian Orogeny (350 – 465 Ma). Syndepositional zircons (weighted mean of 3 and 4 grains respectively) have yielded maximum depositional age of ~312 and 309 Ma of 15TX05 and 15TX01 respectively. Heavy mineral results indicate increased apatite, epidote, garnet, and chlorite content. Low ZTR and high ATi ratios are consistent with proximal first cycle sediment sources. Low monocrystalline quartz content and associated heavy mineral assemblage changes indicate a shift from recycled sediment source to a proximal, low-grade metamorphic, continental source. Although results from the three provenance proxies may appear contradictory, these results are interpreted as evidence for a change to mixture of distal Appalachian sediment and proximal Las Delicias Arc and Gondwanan sediment during the Late Pennsylvanian.

The Permian units, Brushy Canyon and Bell Canyon Formation samples (16TX02 and 16TX04, respectively), show high proportions of zircon age groups: 320 – 460 Ma (30 – 35%), 900 – 1300 Ma (22 – 32%), and 521 – 680 Ma (13 – 14%) corresponding to Appalachian orogeny (350 – 365 Ma), Grenville terrane (900 – 1300 Ma), and Peri – Gondwanan terranes (520 – 680 Ma). The weighted mean of 3 and 2 syndepositional zircons in these two samples, constrain maximum depositional ages of these two units to ~278 ± 42 and 275 ± 41Ma, respectively. High garnet, rutile, epidote, chlorite, tourmaline counts, low monocrystalline quartz abundances and high ATi ratio suggest a distal low-grade metamorphic source. These results, combined with arkosic point count results are indicative of a recycled arc source, likely with a mixture of sediment source, with majority of sediments from the distal Appalachian orogeny and a portion of grains from Gondwana and basement Laurentia, similar to the Pennsylvanian. Like the Pennsylvanian units, the Permian units indicate a mixture of Appalachian sediment to the east and Gondwanan sediment to the south or southeast.

The Cretaceous units, the Cox Sandstone and Buda Limestone (15TX09 and 15TX08, respectively), introduced two new age groups (90 - 150 Ma and 140- 221 Ma, respectively) in addition to previously described groups. These young dates are most consistent with the Cordilleran Arc of western Laurentia. Thin section point count reveal subarkose continental source, consistent with Cordilleran source interpretation. Older groups were produced by sediment recycling, as indicated by the high ZTR ratio count in both units. Sample 15TX09 has very low ATi ratio indicating a distal source, potentially with a south-, southeast- directed sediment pathway from the Sevier Arc north of the Delaware Basin. 15TX08 has syndepositional grains with a weighted mean of 92 ± 14 Ma, and the ATi index suggests a proximal source. Therefore, during this time, the Delaware Basin Buda Formation experienced sedimentation sourced from the west or northwest of the Delaware Basin. During the Cretaceous, Cordilleran grains are the dominant DZ signature. Syndepositional age grains were observed in this sample, indicating that the maximum depositional age of the unit is ~94 Ma, which is consistent with existing stratigraphic framework of the unit (Bilodeau and Lindberg, 1983).

Integrating thin section point counts, heavy mineral analyses, and detrital zircon U-Pb geochronology, can differentiate between first-cycle and recycled sediment characteristics, proximal and distal sediment sources, and may identified the location of sediment sources. The results define four major shifts in provenance and sediment transport direction through the Paleozoic-Mesozoic of west Texas Delaware Basin region: a north-directed sediment transport system during the Ordovician; a west-directed sediment transport pathway during the Mississippian; a mixture of proximal southern and distal eastern sources during the Pennsylvanian and Permian; and an east / northeast directed sediment transport system during the Cretaceous.

VI. DISCUSSION

Multiple changes in composition and provenance of sediments in west Texas are recognized based on integration of results from detrital zircon U-Pb geochronologic, petrographic point counts, and heavy mineral analyses. The interpretations suggest catchment and sediment transport network reorganization during sediment accumulation in the Delaware Basin.

6.1 Temporal evolution of Marathon and Appalachian depocenters

The Marathon-Ouachita fold-thrust belt and Permian Basin system were tectonically and temporally correlative with the Appalachian fold-thrust belt/foreland basin system along the eastern North American margin during the Mississippian-Permian. However, it remains unclear if the two regions developed similarly during the collision, and how the pre-collisional sediment sources of the Marathon region compare with the collisional basin filling during the Ordovician Taconic Orogeny. Fifteen sandstone samples in the southern and central Appalachian Basin from Upper Ordovician to Mississippian strata real the sediment provenance evolution during the Appalachian orogenies (Park et al., 2010). Comparison of detrital zircon U-Pb geochronologic results from the Ordovician strata from the Appalachian region (Park et al., 2010) and this study in the Delaware Basin data show differences in age spectra between two regions (Figure 13). Basement (1-2 Ga) ages dominant Ordovician samples (~97%) from the Appalachian Basin, whereas they represent a smaller proportion (~38%) in the Delaware Basin. However, no Paleozoic grains are observed in the Ordovician Finscalte Formation from Virginia, and only three Paleozoic grains are observed in the Ordovician Oswego Formation from West Virginia, whereas Neoproterozoic-Paleozoic ages (510-790 Ma) dominate Ordovician samples in this study. Although Peri-Gondwanan were accreted during the Taconic Orogeny, it is possible but unlikely for sediments from those terranes bypassed the local Appalachian foreland basin, but were deposited in the distal Delaware basin across the continent. Instead, it is more likely that these detrital zircons were sourced from Peri-Gondwana terranes south of Delaware Basin during the Ordovician. The differences between DZ spectra from Appalachian and Marathon samples indicate that the two regions were received sediment from disconnected and different catchments.

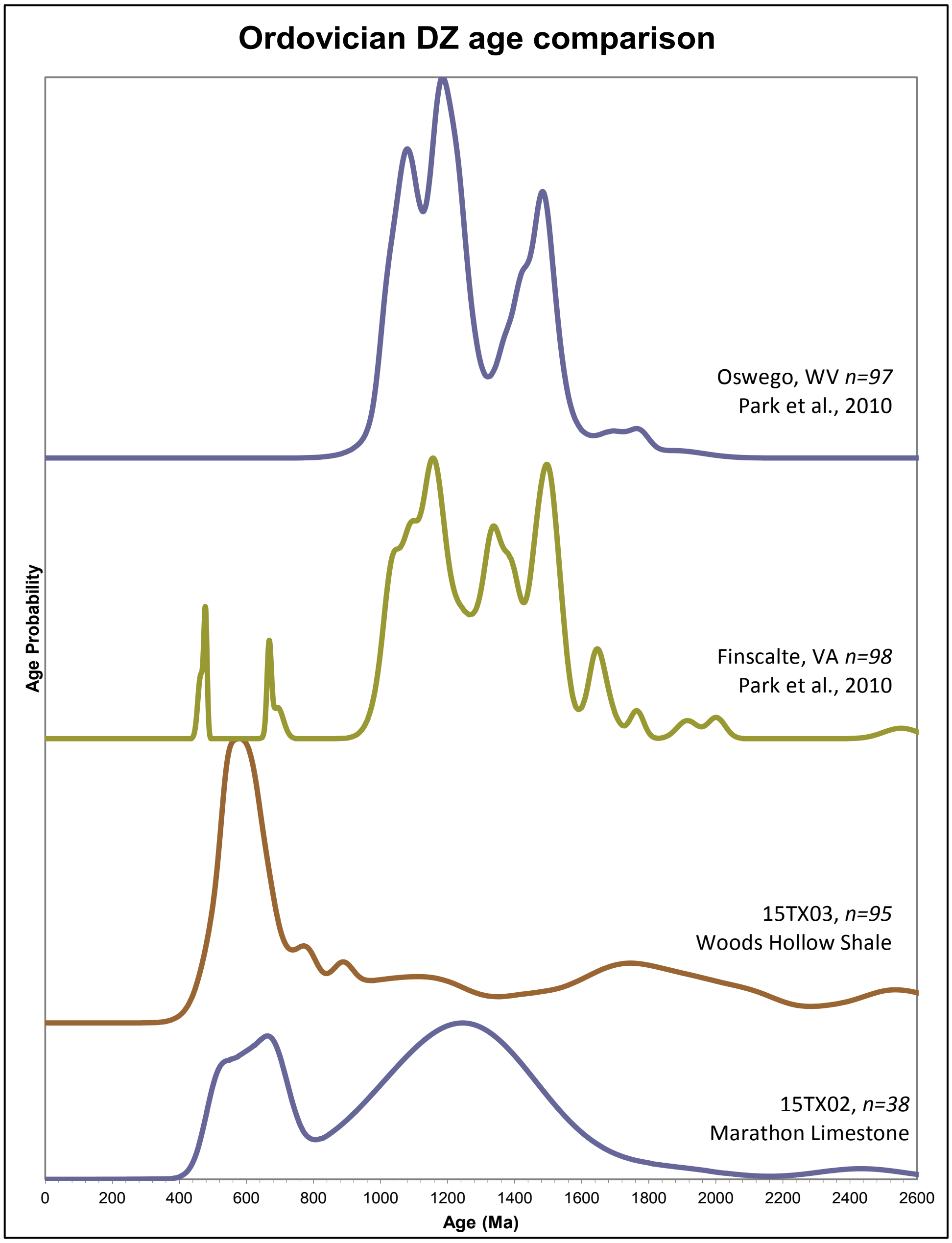

Figure 13 - Comparison detrital zircon probability density plot of Ordovician age detrital zircon samples from the Delaware Basin region (red and blue) and Appalachian Basin (green, and purple) in virginia region from Park et al. (2010).

The Mississippian Tesnus Formation samples have abundant Paleozoic detrital zircons, and detrital zircon characteristics between the Appalachian and Delaware Basin units are similar (Figure 14). Both regions have two groups of zircon ages: one of Paleozoic (300-700 Ma) and another of Precambrian basement (900-2000 Ma), suggesting the two geographically distant basins were likely sourced from a similar catchment and drainage system during the Mississippian. This similarity supports the interpretation that a west – flowing Appalachian-sourcing drainage system and transported detritus transcontinentally into the Delaware Basin. The change from a locally sourced Ordovician provenance transitioning into regionally sourced Mississippian strata suggests a potential drainage reorganization occurred during this time period.

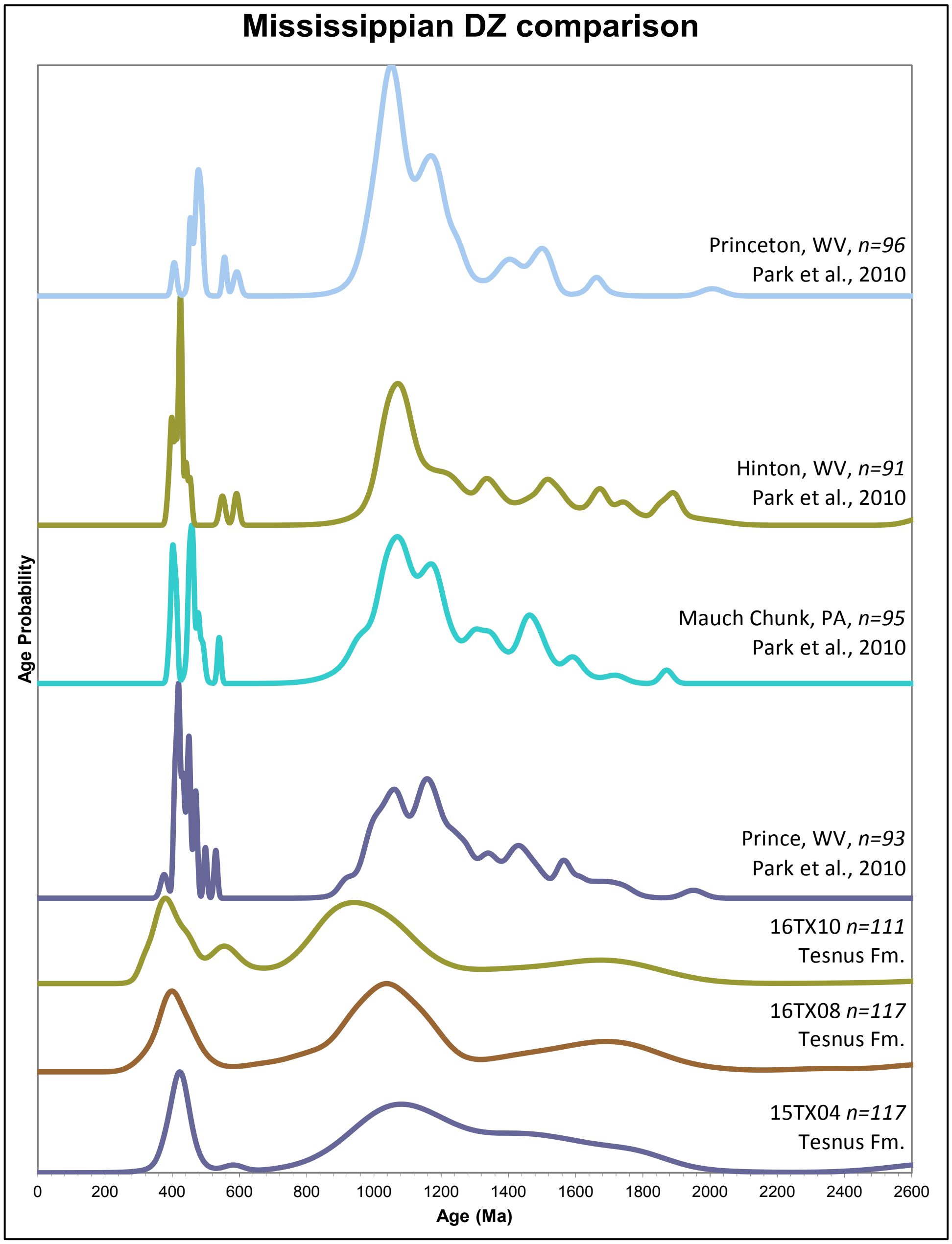

Figure 14 – Comparison detrital zircon probability density plot of Mississippian age detrital zircon samples from the Delaware Basin region (blue, red, and green) and Appalachian Basin (purple, cyan, orange, and light blue) from Park et al. (2010).

6.2 Comparison of the Permian rocks of the Colorado Plateau and Delaware Basin

With a general understanding of the sediment sources into the Permian Basin region during the Paleozoic, a broader question arises with regard to the regional drainage system. How does the sediment routing pathway I propose for southern Laurentia contribute to the overall drainage system proposed for the rest of North America?

A transcontinental paleoriver system was proposed during the Permian to Jurassic, to transport Appalachian-derived sediments westward (Dickinson and Gehrels, 2003). Eolianite samples from the Cedar Mesa and Coconino Formations contain an abundant Paleozoic mode, with secondary Grenvillian peaks, and zircons consistent with Peri-Gondwanan assemblages and metamorphic basement terranes from North America. The four separate age peaks of the detrital grains in their eolianite samples correspond with the known ages along the Appalachian – Ouachita flank of Laurentia supercontinent, indicating that a transcontinental scale drainage system formed during the Permian. Four out of their ten eolianite samples contain a total of 49 grains whose ages range from 158 Ma to 261 Ma, corresponding to detrital grains from the eastern Mexico magmatic arc (232 – 284 Ma). The north directed paleowind system confirm that these arc-derived sediments were transported from a southern source, and mixed with westward flowing paleorivers (Dickinson and Lawton, 2001; Dickinson and Gehrels, 2003).

In contrast, the Delaware Basin samples in this study have different DZ distributions during the Permian (Figure 15), with 350 – 600 Ma zircons constituting the main group in Delaware Basin units, with 900 – 1300 Ma zircons forming a subordinate constituent. Conversely, the Colorado Plateau samples have a dominant amount of zircons of 900 – 1300 Ma and subordinate constituent from 350 – 600 Ma. This could be explained by the geographic location of two study areas, as the Delaware Basin is located closer to the Mexico magmatic arc, this signature may be diluted with increasing distance from northeast Mexico. This shows that the mixed drainage interpretation during the Permian age in the Delaware Basin fits within the continental scale drainage system. 15 – 20% of Colorado Plateau samples have zircon ages greater than 1600 Ma, which do not occur in the Delaware Basin samples. Grains of 1350 – 1500 Ma represents 8% of the zircons in Colorado Plateau units, which are absent in Delaware Basin units. Whereas Colorado Plateau units lack 800 – 900 Ma zircons, these zircons constitute 11% of the Delaware Basin samples. These differences between datasets indicate that there is drainage disconnect between the Delaware Basin and the Colorado Plateau.

The gravity anomaly map (Figure 5) shows the complexity of the gravity fields of the Permian Basin region. The Delaware Basin is separated by a gravity high in the basin center, which represents one of many basement features that may have acted as barriers to sediment transport throughout the Ancestral Rocky Mountains. The Permian samples in this study are unable to conclude the drainage pattern near the Marathon uplift region, and it remains unclear whether the southern Delaware Basin region had a similar sediment provenance.

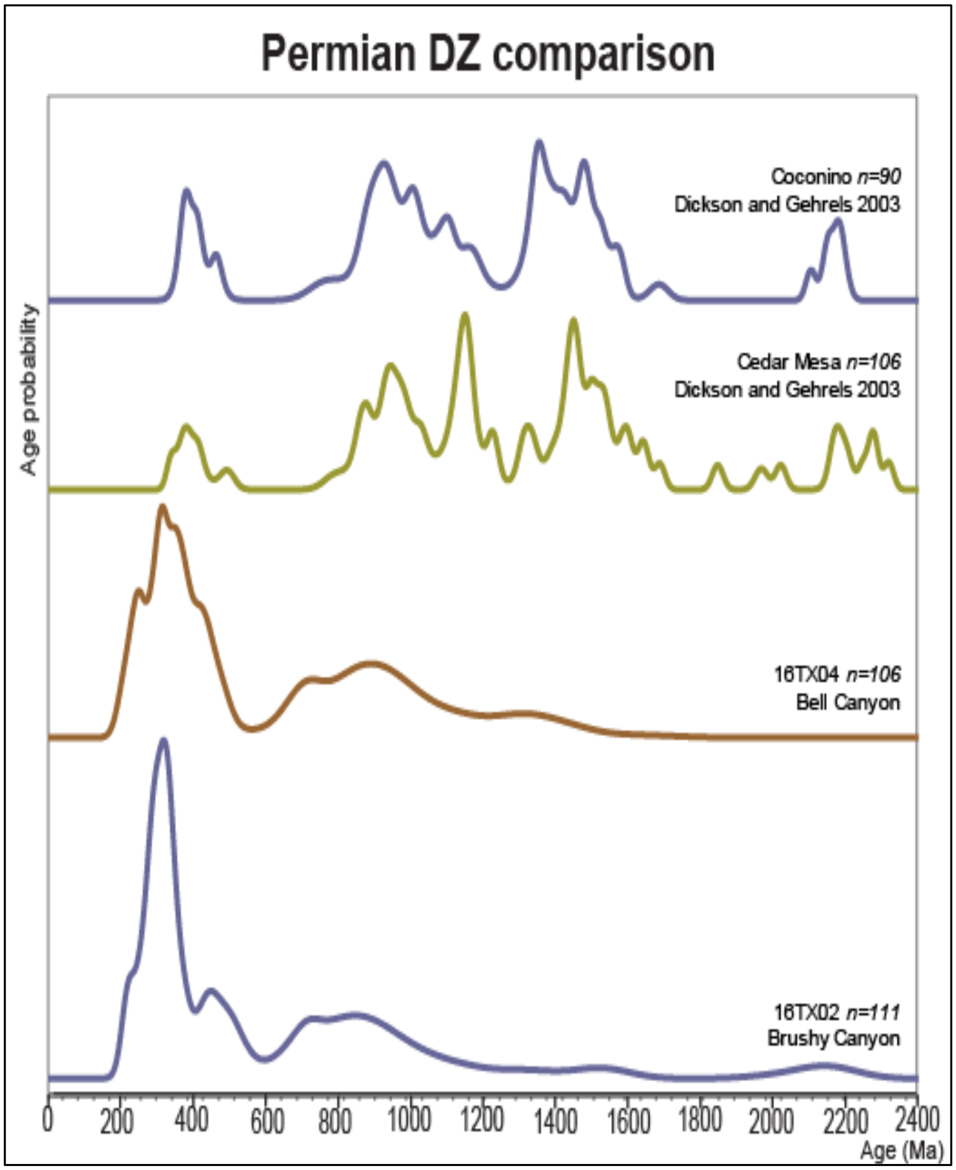

Figure 15 - Comparison detrital zircon probability density plot of Permian age detrital zircon samples from the Delaware Basin region (blue and red) and Colorado Plateau (green, purple, cyan, and orange curves) from Dickinson and Gehrels (2003).

6.3 Provenance and drainage shifts spanning tectonic events

Results from this study span pre-, syn-, and post-collisional phases of the southwestern Laurentian margin during the Paleozoic-Mesozoic amalgamation with Gondwana and subsequent breakup of Pangea, thus constraining the sediment transport dynamics across a continental margin at long time scales. Four provenance changes are interpreted based on results from thirteen samples presented here, and may be related to the major tectonic events in Laurentia. During the Ordovician, provenance results suggest dominantly Peri-Gondwanan and Grenville sources, suggesting a north – directed sediment transport system. Ordovician deposition in the Marathon region was previously interpreted as occurring along the continental slope of a passive margin phase facing the Rheic Ocean that separated Gondwana from Laurentia (Figure 7) (McBride, 1972; Hickman et al., 2009).

Biostratigraphy data of the Ordovician Maravillas Formation in the Delaware Basin region show a mix of fauna, including a primary group of graptolite and a secondary group of marine fauna, including corals, brachiopods, bryozoans, trilobites, and gastropods (Ellison, 1941; Wallis, 1958; Berry, 1960 McBride, 1972). The graptolites of this region correspond to those of Australia and Britain and this succession is not recognized anywhere else on North America (Wallis, 1958), highlighting difficulties in correlating Ordovician rocks in the Marathon region with equivalent units from other parts of North America.

Plate reconstructions suggest a large spatial distance between Laurentia and Gondwana, 60º of latitude (Scotese, C.R., and Barrett, S.F., 1990). The spatial distance across the Rheic Ocean is unlikely to have been transversed by depositional systems sourced from Gondwana and delivering sediments to Laurentia. Instead, the provenance results argue for Ordovician rocks in the Marathon uplift being allochthonous, accreted to Laurentia during the Marathon-Ouachita collision, and remaining attached after breakup of Pangea. This interpretation of an amalgamation between Gondwana and Laurentian terrane during the closure of Rheic Ocean and final assembly of Pangea, is consistent with provenance results from Kuiper et al. (2017), who suggest that Gondwanan crustal material may also remain attached offshore eastern North

America. Thus, the Ordovician rocks do not represent a pre-collisional sequence of Laurentia, but instead may have been originally deposited in Gondwana.

The Mississippian marks the onset of collision. Provenance results indicate that Mississippian samples were likely sourced from the distal Appalachian Orogeny, suggesting a transcontinental west-directed sediment transport system that was bounded by the collisional margin (Figure 16). This orogen-parallel transport signature is similar to Cretaceous deposition in the Magallanes Basin (Fosdick et al., 2014), and also is observed in the Appalachian foreland basin (Park et al., 2010). At the onset of collision, mountain building may contribute to margin-parallel sediment transport, potentially separating the detrital record of mountain building from the position of deformation.

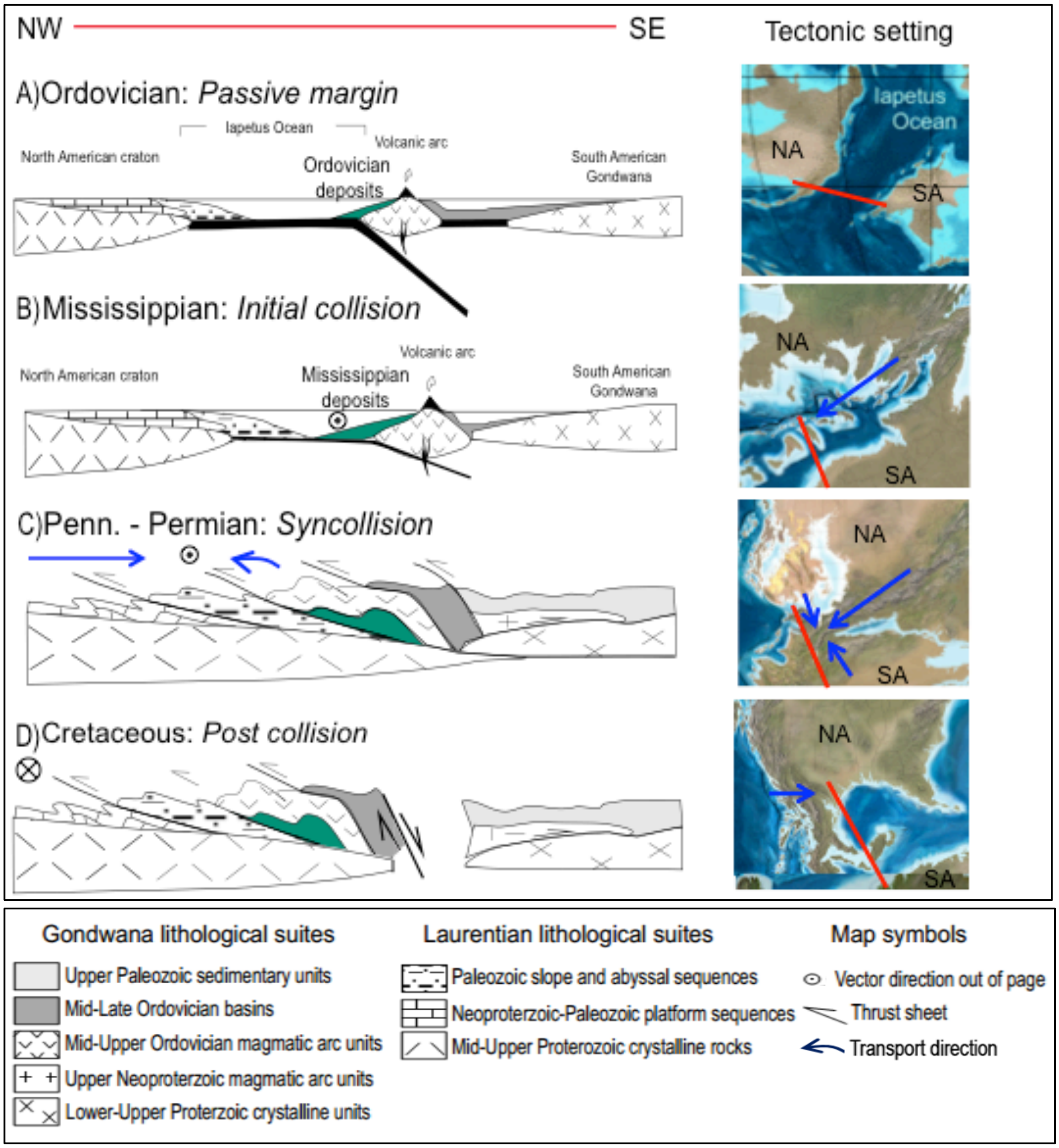

Figure 16 - Cross section (left) and map (right) view of the tectonic settings of Laurentia and Gondwana terranes. Red line indicates location of schematic cross section, and blue arrows indicate proposed sediment transport direction on map and cross section views (Modified from Vega-Granillo et al. 2008; and Ron Blakey, http://jan.ucc.nau.edu/rcb7/nam.html).

During the syncollisional phase of the Delaware Basin in the Pennsylvanian and Permian time, drainage patterns changed over a relatively short period. Provenance results suggest a mixture of west-, and north-directed sediment transport pathways, different from the previously interpreted west-directed sediment drainage system (Figure 17). New north-, northwest-directed sediment transport is consistent with recycling of material uplifted, deformed, and eroded from the growing Marathon-Ouachita fold-thrust belt. Continued regional deformation associated with the collision is recorded in the detrital sediment signature as competing west-directed, axial, Appalachian-derived systems and approximately north-directed, transverse, Gondwanan-derived system.

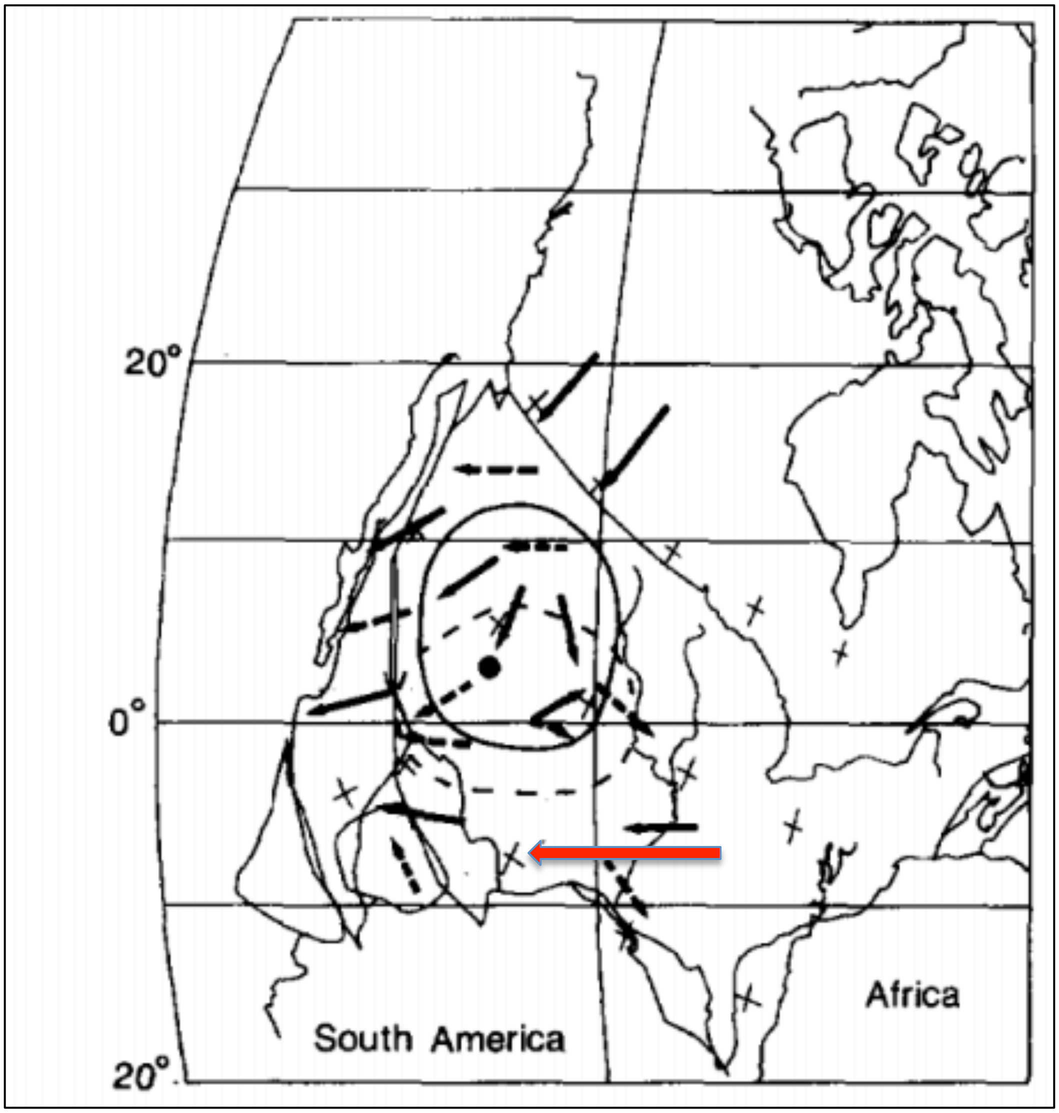

Figure 17 - Predicted wind directions in western Laurentia during Late Carboniferous and Early Permian. Red arrow indicates the paleowind direction into the Permian Region. Large dot indicate the junction of Colorado, New Mexico, Arizona, and Utah. Modified from Parrish (1988).

During the Cretaceous, Appalachian-derived sediments were transported eastward into central North American plate (Figure 18) (Finzel, 2014; Blum and Pecha, 2014). However, results from Delaware region Cretaceous samples reveal different zircon characteristics and a final change to an east – directed sediment dispersal pathway, likely sourced from the Cordilleran arcs of western Laurentia. Subduction was initiated in the Late Jurassic in response to the subduction of the Farallon Plate, and caused reversal of drainage patterns towards the east (Coney and Evenchick, 1994). As the main active thrust belt system of North America during this time of deposition, the Cordilleran thrust belt and retro arc system extend from the northwestern United States into northwestern New Mexico. Syndepositional detrital zircons (94 ± 11Ma) observed in Cretaceous age units indicate that arc material associated with Cordilleran collision was transported rapidly into the Delaware Basin. The large proportion of Cretaceous ages in the west Texas region from Cretaceous strata confirm the main sediment source was the Cordilleran arc, resulting in an east-directed drainage pattern that differed from the previously transported systems of the study area and from coeval drainage pathway in other parts of North America.

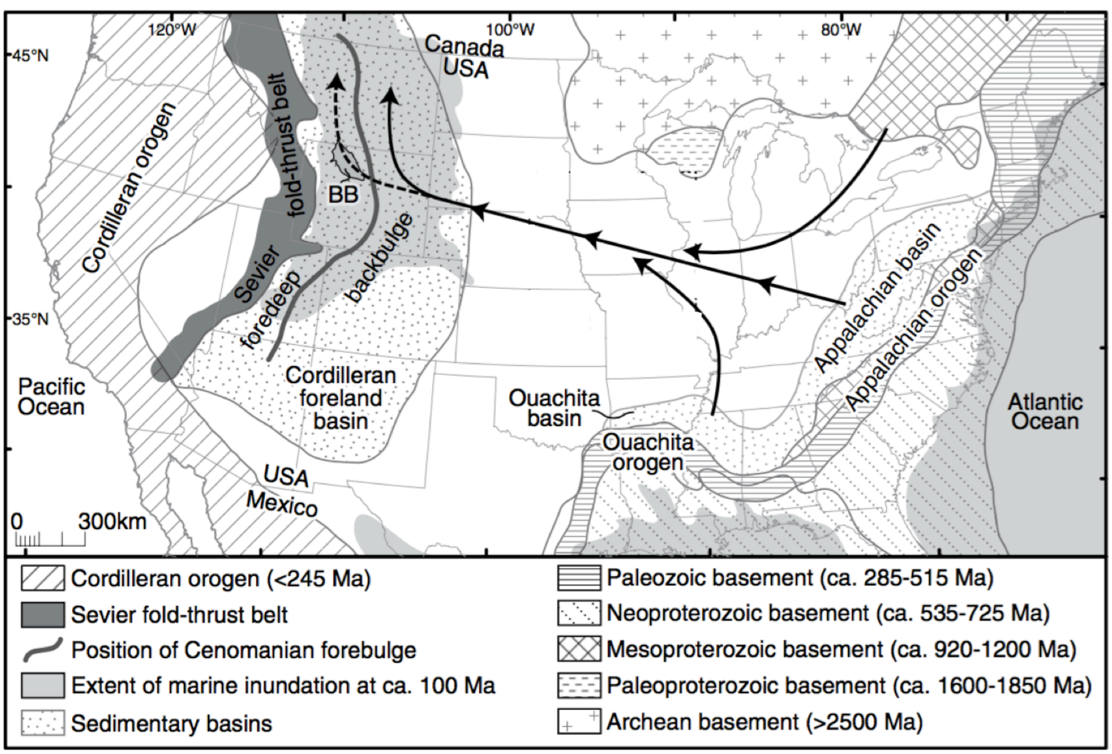

Figure 18 - Dominant sediment transport systems during Middle Cretaceous, arrows indicating the west-/ northwest-, directed sediment transport directions, reprinted from Finzel (2014).

VII. CONCLUSION

Utilizing sandstone modal mineralogy, heavy mineral analyses, and detrital zircon U-Pb geochronology, this study defines the provenance of multiple units and inferred their paleodrainage pattern of the Delaware Basin region of west Texas.

1. U-Pb ages of detrital zircons collected in the Ordovician unit contain abundant zircons of 400-800 Ma, corresponding to Gondwanan terranes. New provenance constraints presented here, coupled with existing biostratigraphy correlations, argue for an allochthonous source and show potential evidence of a piece of Gondwana preserved in Laurentia after the final closure of the Rheic Ocean and breakup of Pangea.
2. Provenance results indicate sediment transport directions during initial collision in the Mississippian drove orogen-parallel axial sediment transport, delivering sediment from the Appalachian Orogen to the Marathon region. Continued collision induced complex mixing patterns, with continued axial transport mixed with recycled Marathon fold-thrust belt sources delivered to the Marathon region via orogen perpendicular sediment transport.
3. Comparison of DZ data from this study with study by Park et al. (2010) show that the dominant age peak (400 – 800 Ma) in Ordovician units in Delaware region is almost completely absent in Ordovician units in Appalachian Basin, indicating during the Ordovician, drainage system was different between the two depocenters. In the Mississippian, dominant peaks (300 – 700 Ma, 900 – 1200 Ma, and 1400 – 1900 Ma) were similar between the two depocenters, indicating that the two locations potentially shared the same continental scale drainage system in the Mississippian. This comparison

is consistent with the interpretation of an allochthonous sediment source in the Ordovician, and a transcontinental scale drainage system in the Mississippian.

4. Comparison of DZ data from Permian strata from this study with coeval strata in the Colorado Plateau area (Dickinson and Gehrels, 2003) indicates different concentrations of similar age spectra (350 – 600 Ma, 900 – 1300 Ma). This may be explained by dilution of sediment sources associated with different distances between these depocenters and the source terrane. However, significant differences in DZ spectra reveal that the Colorado Plateau has 800-900 Ma, 1350-1500 Ma, and >1600 Ma detrital zircons, that do not occur in Delaware Basin samples. The 200-300 Ma zircons observed in Delaware Basin region are not observed in Colorado Plateau samples. This data comparison shows that the two regions are disconnected in their drainage systems.
5. Maximum depositional ages are constrained for the following formations: Mississippian Tesnus Formations (16TX08; 339 ± 51 Ma and 16TX10; 339 ± 51 Ma), Pennsylvanian Haymond Formation (15TX05; 312 ± 47 Ma), Pennsylvanian Gaptank Formation (15TX01; 309 ± 46 Ma), Permian Brushy Canyon (16TX02; 278 ± 42 Ma), Permian Bell Canyon (16TX04; 275 ± 41 Ma), and Cretaceous Buda Formation (15TX08; 94 ± 11Ma).

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