

Article

Heavy Mineral and Zircon Age Constraints on Provenance of Cenozoic Sandstones in the Gulf of Mexico Subsurface

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Abstract: Combined heavy mineral analysis and detrital zircon geochronology have enabled us to track detritus supplied by the ancestral river systems draining the North American continent into the deep subsurface of the Gulf of Mexico, in both the coastal plain and the offshore deep water areas. During deposition of the Paleocene–Eocene Wilcox Group, sandstones in the western part of the area are interpreted as the products of the Rosita system derived via paleo-Rio Grande material, with a large component of sediment shed from the Western Cordillera. By contrast, samples from wells further east have high proportions of zircons derived from the Yavapai-Mazatzal Province and are attributed to the Rockdale system with sediment fed predominantly by the paleo-Colorado or paleo-Colorado-Brazos. There is evidence that sediment from the Rosita system occasionally extended into the central Gulf of Mexico, and, likewise, data indicate that the Rockdale system sporadically supplied sediment to the western part of the basin. During the Late Eocene of the central Gulf of Mexico (Yegua Formation) there was a distinct shift in provenance. The earlier Yegua sandstones have a large Grenville zircon component and are most likely to have had a paleo-Mississippi origin, whereas the later Yegua sandstones are dominated by zircons of Western Cordilleran origin, similar to Wilcox sandstones fed by the Rosita system via the paleo-Rio Grande. The switch from paleo-Mississippi to paleo-Rio Grande sourcing implies there was a major reorganisation of drainage patterns during the Late Eocene. Miocene sandstones in the deepwater Gulf of Mexico were principally sourced from the paleo-Mississippi, although the paleo-Red River is inferred to have contributed to the more westerly-located wells.

Keywords: heavy minerals; zircon; Gulf of Mexico; Cenozoic; provenance



Citation: Morton, A.C.; Strickler, M.E.; Fanning, C.M. Heavy Mineral and Zircon Age Constraints on Provenance of Cenozoic Sandstones in the Gulf of Mexico Subsurface. *Minerals* **2024**, *14*, 779. <https://doi.org/10.3390/min14080779>

Academic Editor: Georgia Pe-Piper

Received: 12 June 2024

Revised: 15 July 2024

Accepted: 26 July 2024

Published: 30 July 2024



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1. Introduction

The Gulf of Mexico (GoM) Basin contains a voluminous accumulation of Mesozoic–Cenozoic sediment, hosting a large number of hydrocarbon accumulations. Extensive studies of the basin led by both industry and academia have enabled a thorough understanding of paleogeography, sediment supply patterns, stratigraphy, depositional environments and basin-fill architecture [1–3]. The GoM is an oceanic basin located between the North American plate to the north and the Yucatan block to the south. Sea-floor spreading began in the Middle Jurassic and continued for approximately 25 Myr. Spreading, which was asymmetric, created attenuated transitional continental crust beneath the northern part of the basin, with a fully oceanic crust further south in the basin centre. Deposition commenced with widespread thick salt deposits across much of the basin. Subsequent mobilization of this salt by sedimentary loading created complex gravity tectonic structures. By the end of the Mesozoic, thermal subsidence had created a deep basin floor, flanked by continental shelves. This basin is filled with a succession of Late Jurassic to Holocene strata, up to

20 km thick. The North American continent is estimated to have supplied nearly one-half of the sedimentary basin fill, with input from the northern and northwestern margins.

Deposition of the basin fill took place in seven phases. Middle-Late Jurassic evaporite and carbonate deposition took place in restricted to open marine conditions in a broad shallow basin. This was followed by progradation of sand-rich clastic sediment from the northern margins during the latest Jurassic and Early Cretaceous, succeeded by the development of a rimmed carbonate shelf in the mid-Cretaceous and then by mixed clastic and carbonate succession in the Late Cretaceous. In the Paleogene, there was renewed input of clastic sediment principally into the northwestern part of the basin, whereas, in the Miocene, progradation and basin fill were located further east, toward the central and northeastern part of the basin. Finally, during the late Neogene, under the influence of climatic and eustatic events, progradation took place along the central Gulf margin [1–3]. However, despite the prolonged history of investigations on the GoM, there remains debate concerning sediment provenance in the major depocenters [4], in particular concerning the origin of the sandstones in the deep-water areas where little data is currently unavailable.

In the early days of GoM studies, variations in non-opaque heavy mineral assemblages were used to interpret sand provenance [5–8]. However, these studies tended to concentrate on younger strata, because the application of heavy mineral analysis to the older parts of the succession proved difficult owing to the instability of many detrital species during burial diagenesis [9,10]. It has been shown that burial diagenesis has caused loss of provenance information from the Gulf Coast succession even at relatively shallow burial depths [11,12]. In order to counteract this problem, workers have recently concentrated on detrital zircon U-Pb age studies, because the stability of zircon means that provenance information is unlikely to be lost during diagenesis [13]. Furthermore, extensive geochronological work on North American basement terranes enables zircon crystallization ages to be readily traced back to their initial basement sources [14]. In recent years, detrital zircon dating has been extensively applied to the GoM, concentrating mainly on the Upper Paleocene–Lower Eocene Wilcox Group [4,15–22] but also on Oligocene and Miocene [4,20,23] and Pleistocene–Recent sandstones [20,24–28].

However, the majority of detrital zircon geochronology studies were carried out on samples from outcrops, apart from a small number of subsurface Wilcox and Miocene sandstones from the coastal plain [17,23]. To date, there is little published information on the deeply buried Cenozoic in the offshore part of the GoM. The only exceptions in the literature are a summary of information from 14 samples of Wilcox sandstones from five unspecified wells [29] and data from Miocene sandstones in the Green Canyon deep-sea fan [30].

Despite the undoubted value of detrital zircon dating in provenance studies of the GoM basin fill, heavy mineral suites also retain important provenance information even after extensive diagenetic modification. Ratios that compare the relative abundances of diagenetically stable minerals directly reflect provenance characteristics, especially if the minerals concerned have similar densities and by extension similar hydrodynamic behaviour [31]. In this paper, we adopt a dual approach, documenting heavy mineral and detrital zircon age data from sandstones in wells from the deepwater GoM and from the deep subsurface of the coastal plain (Figure 1). The sample set ranges in age from the Late Paleocene–Early Eocene Wilcox Group, through the Late Eocene Yegua Formation and into the Miocene. Heavy mineral data have been acquired from 42 Wilcox samples in six wells (Chinook Deep, Diamond Back and Shenzi Deep, offshore GoM; Allan Kovar, Urban #1 and Weatherby Gas Unit #2, onshore GoM), from 15 Yegua samples in two wells (Mid-Val #2 and Mid-Val #4, onshore GoM) and from 67 Miocene samples in six wells (Jedi, Myrtle Beach, Shenzi, Shenzi Deep, Stampede and Tubular Bells). Zircon data were collected from a subset of 11 samples (six from the Wilcox, two from the Yegua and three from the Miocene), comprising 707 individual age determinations. Both core and ditch cuttings samples were included in this study, with cores being analysed from the onshore wells (Allan Kovar, Urban #1, Weatherby Gas Unit #2, Mid-Val #2 and Mid-Val #4) and

ditch cuttings from the offshore region (Chinook Deep, Diamond Back, Jedi, Myrtle Beach, Shenzi, Shenzi Deep, Stampede and Tubular Bells). The aim of this paper is to extend the understanding of sediment transport routing [32] from the well-studied outcrops on the coastal plain into the deeper parts of the GoM basin.

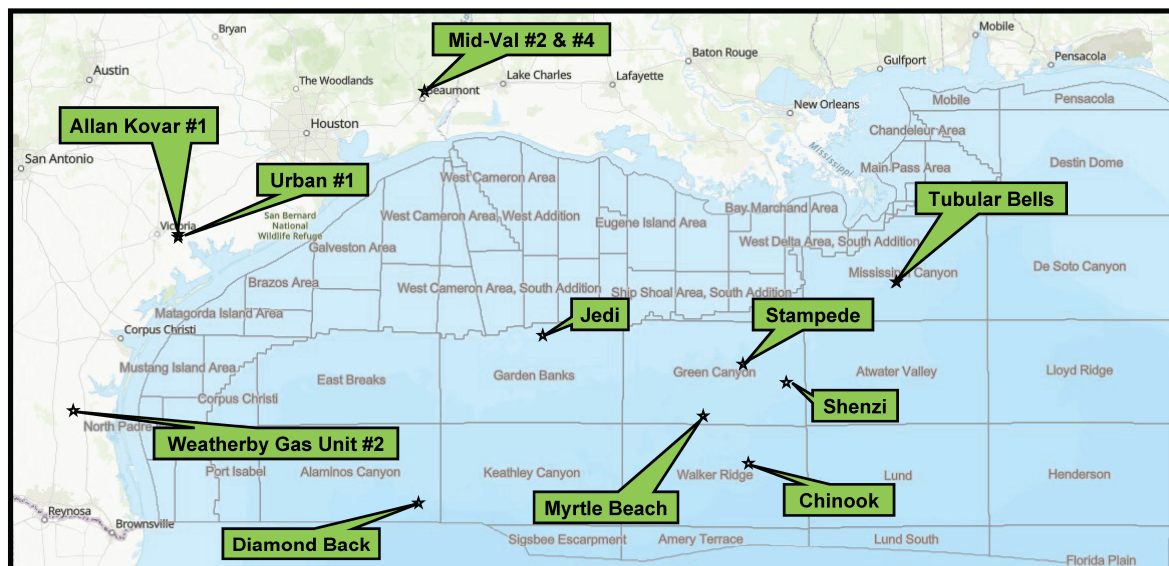


Figure 1. Location of the wells discussed in this paper.

2. Analytical Methods

2.1. Conventional (Petrographic) Heavy Mineral Analysis

Core samples were gently disaggregated by use of a pestle and mortar, avoiding grinding action. Disaggregation was not necessary for ditch cuttings since this has already been achieved through the action of the drill bit. Following disaggregation, samples were immersed in water and cleaned by ultrasonic probe to remove and disperse any clay adhering to grain surfaces. The samples were then washed through a 63 μm sieve and resubjected to ultrasonic treatment until no more clay passed into the suspension. At this stage, the samples were wet sieved through the 125 and 63 μm sieves, and the resulting > 125 μm and 63–125 μm fractions were dried in an oven at 80 $^{\circ}\text{C}$. The 63–125 μm fraction was placed in bromoform with a measured specific gravity of 2.8. Heavy minerals were allowed to separate under gravity, with frequent stirring to ensure complete separation. The heavy mineral separates were mounted under Canada Balsam for optical study using a polarising microscope.

Heavy mineral proportions were estimated by counting 200 non-opaque detrital grains using the ribbon method [33]. Identification was made on the basis of optical properties, as described for grain mounts [34]. The presence of other components, such as diagenetic minerals, opaques and mica, was noted but not quantified. Determination of provenance-sensitive mineral ratios [31] was made on the basis of a 200 grain count per mineral pair unless this was not possible because of the scarcity of some of the mineral phases. The full set of heavy mineral and provenance-sensitive index data are given in Supplementary Data Tables available online.

2.2. Geochronology

U-Th-Pb zircon analyses were carried out using SHRIMP I and SHRIMP RG at The Australian National University (ANU) in Canberra, Australia. Detrital zircon grains were separated using standard crushing, washing, heavy liquid and paramagnetic procedures. Representative zircon grains were poured onto double-sided tape, cast into epoxy probe mounts together with chips of the reference zircons, sectioned approximately in half and polished. Scanning electron microscope (SEM) cathodoluminescence (CL) images were

made for all zircon grains at ANU. These were used to interpret the internal structures and to ensure that the SHRIMP spot was within a single domain of the grain, preferentially the youngest.

In each sample, between 46 and 71 grains were analysed. Each analysis consisted of four to five scans through the mass range, with a reference zircon analysed after every five unknowns. Errors in reference zircon calibration are given for each analytical session. Uncertainties for individual analyses are given at the 1σ level. SHRIMP analytical methods following [35]. The data were reduced using the SQUID Excel macro [36].

For grains older than c. 800 Ma and for those enriched in U, common Pb was corrected using the measured $^{204}\text{Pb}/^{206}\text{Pb}$ ratio. Correction for common Pb in grains younger than c. 800 Ma and those low in U and therefore radiogenic Pb was made using the measured $^{238}\text{U}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios following the ^{207}Pb correction method [35,37]. When the ^{207}Pb correction is applied, it is not possible to determine radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ ratios or ages. In these cases, therefore, the radiogenic $^{206}\text{Pb}/^{238}\text{U}$ age was used for the probability density plots. Probability density plots with stacked histograms were produced in AgeDisplay [38]. Zircon age data are presented in Supplementary Data Tables available online.

3. Wilcox Group Sandstones

3.1. Heavy Mineral Data

Heavy mineral assemblages in the Wilcox Group sandstones are comparatively limited in diversity, with four species comprising a mean of 91.8% (apatite mean 10.9%, garnet mean 10.7%, tourmaline mean 29.0% and zircon mean 49.2%). These four minerals are all stable or ultrastable under burial diagenetic conditions [39–41]. A further 6.3% is made up of three other stable or ultrastable minerals (anatase mean 1.0%, chloritoid mean 1.7% and rutile mean 3.6%). Present-day burial depths are all in excess of 14,000 ft (4267 m), and, consequently, the low diversity of the assemblages is ascribed to dissolution of unstable minerals during burial diagenesis, which is already known to be a major process in altering heavy mineral suites in the GoM region [11,12].

There is a marked difference in the abundance of garnet between the onshore and offshore wells. Garnet:zircon indices (GZi) in Diamond Back, Shenzi Deep and Chinook Deep are variable, but all are >14 , whereas values in Weatherby Gas Unit #2, Allan Kovar #1 and Urban #1 are rarely >0 (Figure 2). This is attributed to greater diagenetic modification in the onshore succession compared with offshore since garnet is known to be less stable than apatite, rutile, tourmaline and zircon during deep burial [39,40]. However, there is an anomalous relationship between burial depth and garnet depletion, since present-day burial depths for the Wilcox in the onshore wells are less than for the offshore wells (Figure 2). This may be partly related to the uplift of the onshore Wilcox, estimated to be between c. 1000 ft and c. 2500 ft [42,43], but the onshore successions remain anomalously depleted in garnet even after correction for the amount of uplift. The reason for the anomalously shallow depletion of garnet in the onshore area remains speculative, but one possibility is that it is related to the sample type. The onshore samples are all from cores, whereas those from offshore wells are from ditch cuttings acquired over a depth range. Consequently, ditch cuttings may sample lithologies that include lower-permeability sediments (such as siltstones or carbonate-cemented sandstones), which are more likely to have retained garnet.

In view of the evidence for variable diagenetic modification, provenance relationships are best explored using provenance-sensitive heavy mineral ratios [31]. These parameters compare the relative abundance of minerals that are stable in the context of the study and also have similar densities so that hydrodynamic fractionation is minimised. Given that GZi is compromised owing to variable garnet dissolution, and MZi (monazite:zircon) and CZi (chrome spinel:zircon) are uniformly low throughout, the only two parameters that can be used to identify differences in provenance are ATi (apatite:tourmaline) and RuZi (rutile:zircon). Both these parameters show significant variations (Figure 2).

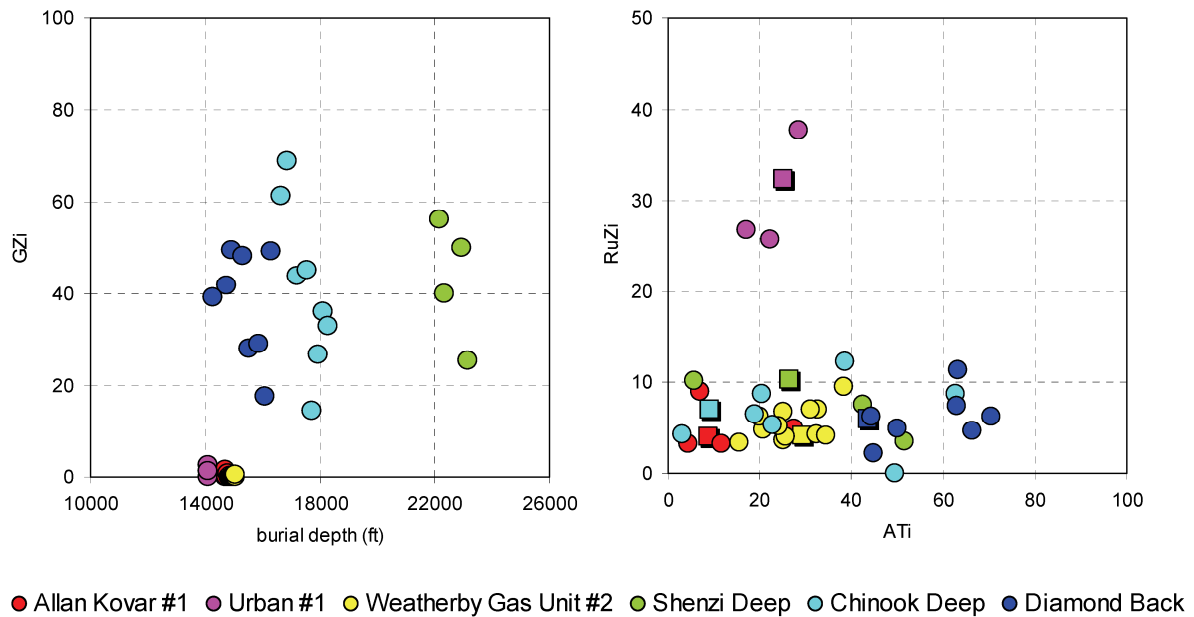


Figure 2. Relationships between burial depth and GZi and between ATi and RuZi in Wilcox Group sandstones from the GoM basin. Square symbols are samples with U-Pb zircon chronology data. Data from Allan Kovar #1, Urban #2 and Weatherby Gas Unit #2 are from core, whereas Shenzi Deep, Chinook Deep and Diamond Back are from ditch cuttings.

Three heavy mineral provenance types can be recognised within the Wilcox Group. The samples from Urban #1 have low ATi and high RuZi, samples from Diamond Back have high ATi and low RuZi, and samples from Weatherby Gas Unit #2, Allan Kovar #1 and Shenzi Deep have low-moderate ATi and low RuZi. The succession in Chinook Deep has low RuZi throughout, but ATi is variable. The lower part has low-moderate ATi whereas the upper part has high ATi (Figure 3). The upward increase in ATi corresponds with upward-increasing GZi and higher chloritoid contents (Figure 3), indicating a significant shift in provenance within the succession. The same pattern (upward increases in ATi, GZi and chloritoid content) is also seen in the adjacent Shenzi Deep well (see Supplementary Data), indicating potential for heavy mineral subdivision and correlation of the Wilcox Group in this area.

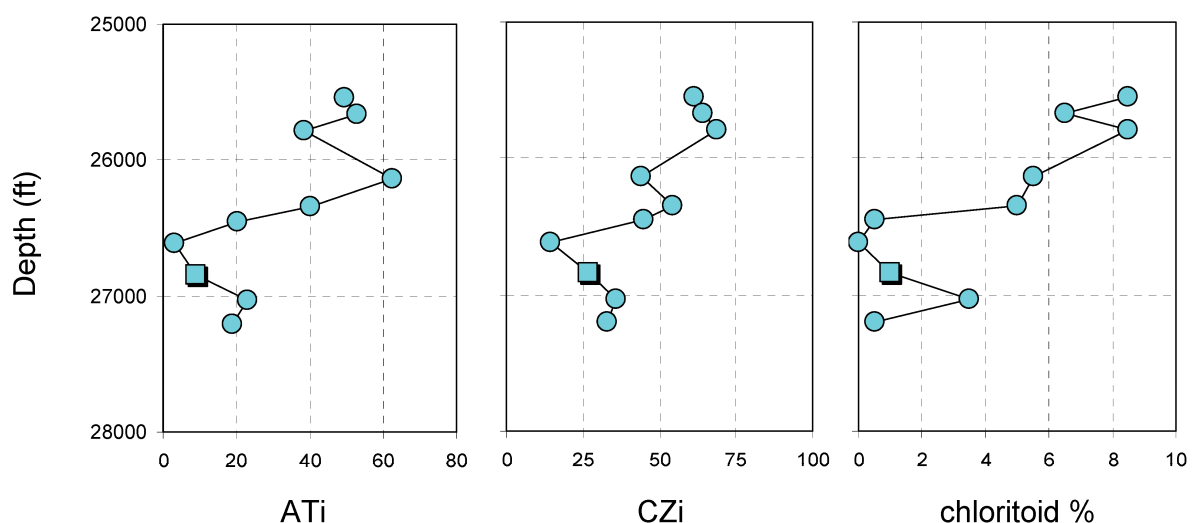


Figure 3. Stratigraphic variations in ATi, GZi and chloritoid content in Wilcox Group sandstones in Chinook Deep. The square symbol shows the sample with U-Pb zircon chronology data.

3.2. Zircon Geochronology

Zircon U-Pb age data have been acquired from six samples covering the range of heavy mineral assemblage types across the entire geographical range. Samples have been analysed from Shenzi Deep and Chinook Deep in the eastern part of the offshore area, from Diamond Back in the western part of the offshore area, and from Allan Kovar #1, Urban #1 and Weatherby Gas Unit #2 in the western part of the onshore area (Figure 4).

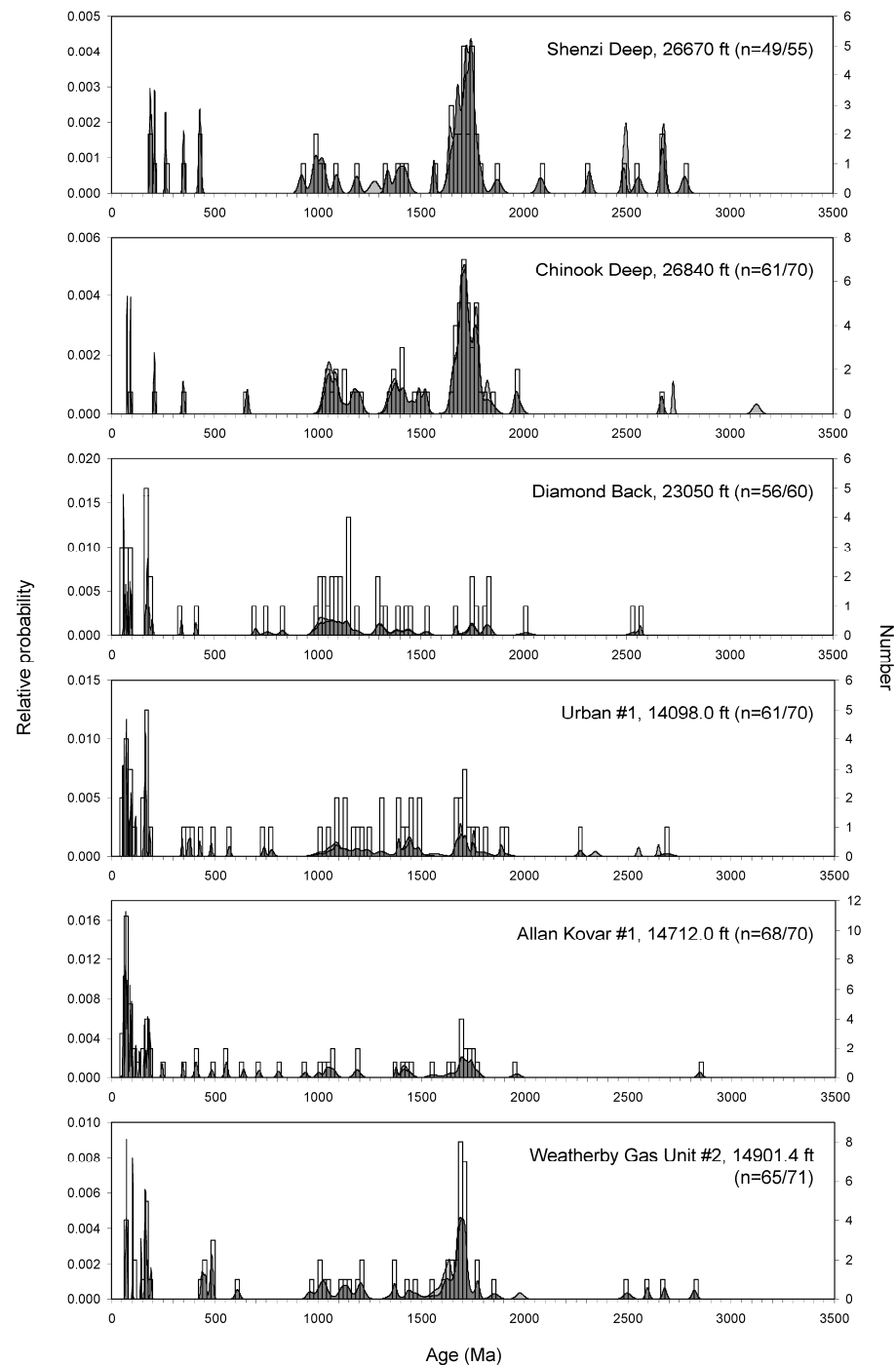


Figure 4. Wilcox Group zircon age spectra displayed as combined histogram-probability density plots. Dark grey = zircons with <10% discordance, pale grey = zircons with >10% discordance. 'n' = number of zircons with <10% discordance in the total zircon population. Data from Allan Kovar #1, Urban #2 and Weatherby Gas Unit #2 are from core, whereas Shenzi Deep, Chinook Deep and Diamond Back are from ditch cuttings.

Both zircon spectra from the eastern GoM (Shenzi Deep and Chinook Deep) are dominated by a single peak in the 1600–1800 Ma, with subordinate groups in the 1000–1200 Ma and 1350–1550 Ma ranges. There is minor and sporadic representation in the Phanerozoic and the older Paleoproterozoic and Archaean.

The samples from further west in the GoM (Diamond Back, Allan Kovar #1, Urban #1 and Weatherby Gas Unit #2) have significantly larger proportions of Phanerozoic zircons < 300 Ma, which form between 18% and 47% of the populations compared with 4%–9% in Shenzi Deep and Chinook Deep. The Phanerozoic zircons fall into two main ranges, c. 55–105 Ma and c. 160–200 Ma (Figure 5), with particular peaks at 56–57 Ma (seen in all wells except Weatherby Gas Unit #2), 69–72 Ma (seen in all wells) and 160–175 Ma (seen in all wells). Older zircons mainly group in the 1000–1200 Ma, 1350–1550 Ma and the 1600–1800 Ma ranges. The latter group is especially common in the sample from Weatherby Gas Unit #2. The youngest zircons in Diamond Back, Allan Kovar #1 and Urban #1 constrain the maximum depositional age to the very latest Paleocene (57.7 ± 1.0 Ma, 57.8 ± 1.2 Ma and 58.5 ± 1.4 Ma in Diamond Back, 55.7 ± 0.9 Ma, 56.9 ± 1.0 Ma and 58.5 ± 1.0 Ma in Allan Kovar #1, and 54.1 ± 0.8 Ma and 55.8 ± 0.7 Ma in Urban #1).

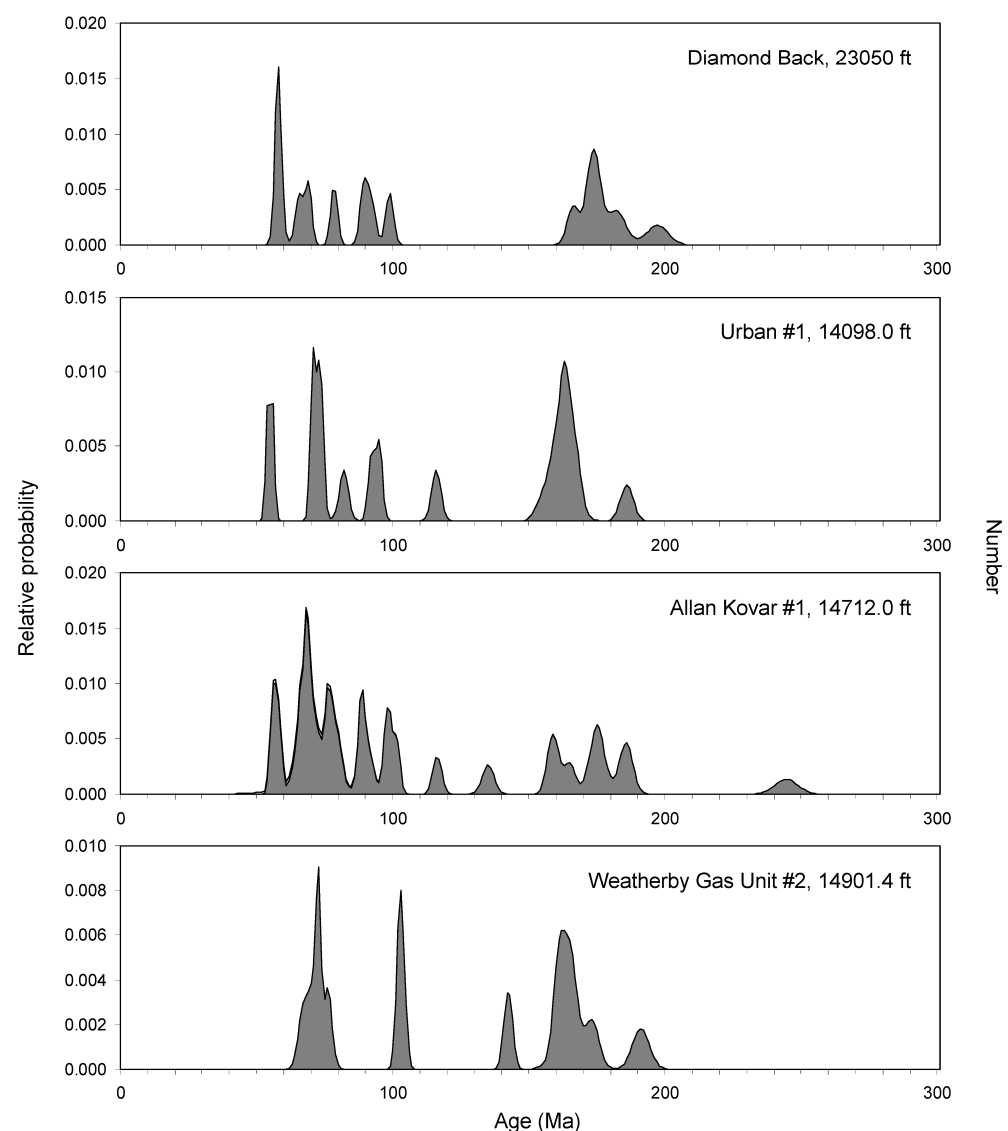


Figure 5. Zircon age distributions in the 0–300 Ma range in samples from the Wilcox Group in the western GoM.

3.3. Interpretation

Three main fluvio-deltaic systems fed the Wilcox coastal plain and associated deep-water fan deposits [2], comprising (from west to east) the Rosita system that occupies the Rio Grande Embayment, the Rockdale system in the Houston Embayment, and the Holly Springs system in the Mississippi Embayment (Figure 6). The Rosita system was fed by the paleo-Rio Grande River, the Rockdale system by, among others, the paleo-Colorado, paleo-Guadalupe, paleo-Red and paleo-Arkansas, and the Holly Springs by the paleo-Mississippi and paleo-Tennessee rivers. These paleo-river systems drained various parts of the North American continent, which comprises a series of well-defined terranes with known basement ages (Figure 6). Consequently, zircon age data enable the establishment of provenance relationships between sediments, the paleo-river system that deposited the sediment, and the basement terranes that initially sourced the detritus [18,20].

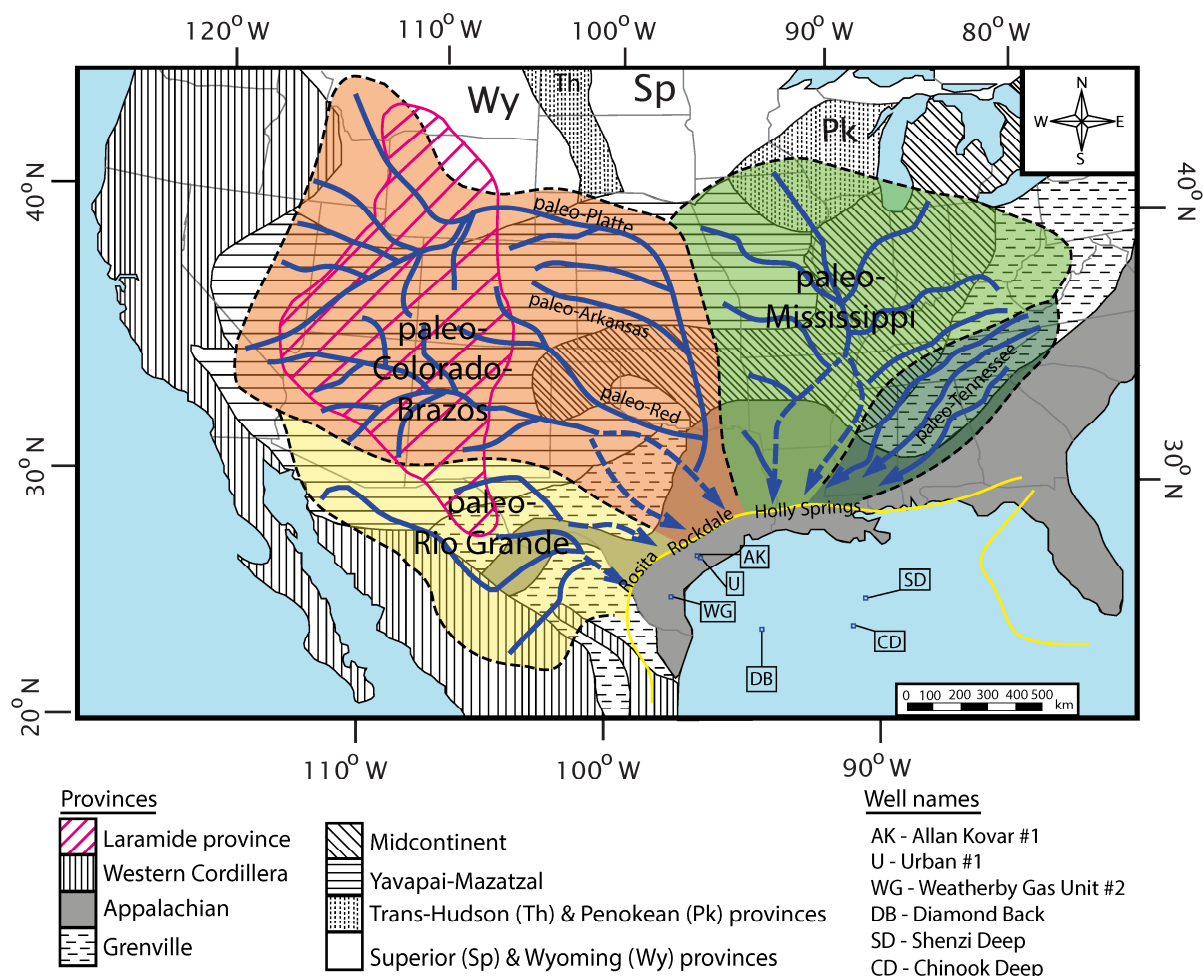


Figure 6. Paleodrainage reconstruction for the Wilcox Group in the GoM adapted from Galloway et al. [2] and Blum et al. [20], showing locations of the wells discussed in this paper. Terrane base map is from Blum et al. [20]. The yellow line is the Paleocene shelf margin.

Mackey et al. [17] published a numerical breakdown of zircon age data from the Wilcox Group in southwest Texas, attributing zircons to the various basement terranes of North America. This approach was also followed by Craddock and Kylander-Clark [4] in their study of the Cenozoic of Louisiana. We adopted the same approach in the current study, using the boundary conditions proposed by Mackey et al. [17], with the zircon age breakdown shown in Figure 7. By comparison with the zircon age data previously acquired from the Wilcox [18,20], the samples from Allan Kovar #1, Urban #1 and Diamond Back are most likely to represent sediment fed by the Rosita system derived via paleo-

Rio Grande material, in common with the Wilcox of southwest Texas [17], with a large component of sediment shed from the Western Cordillera. The samples from Shenzi Deep and Chinook Deep, by contrast, have high proportions of zircons derived from the Yavapai-Mazatzal Province and are therefore attributed to the Rockdale system with sediment fed predominantly by the paleo-Colorado or paleo-Colorado-Brazos.

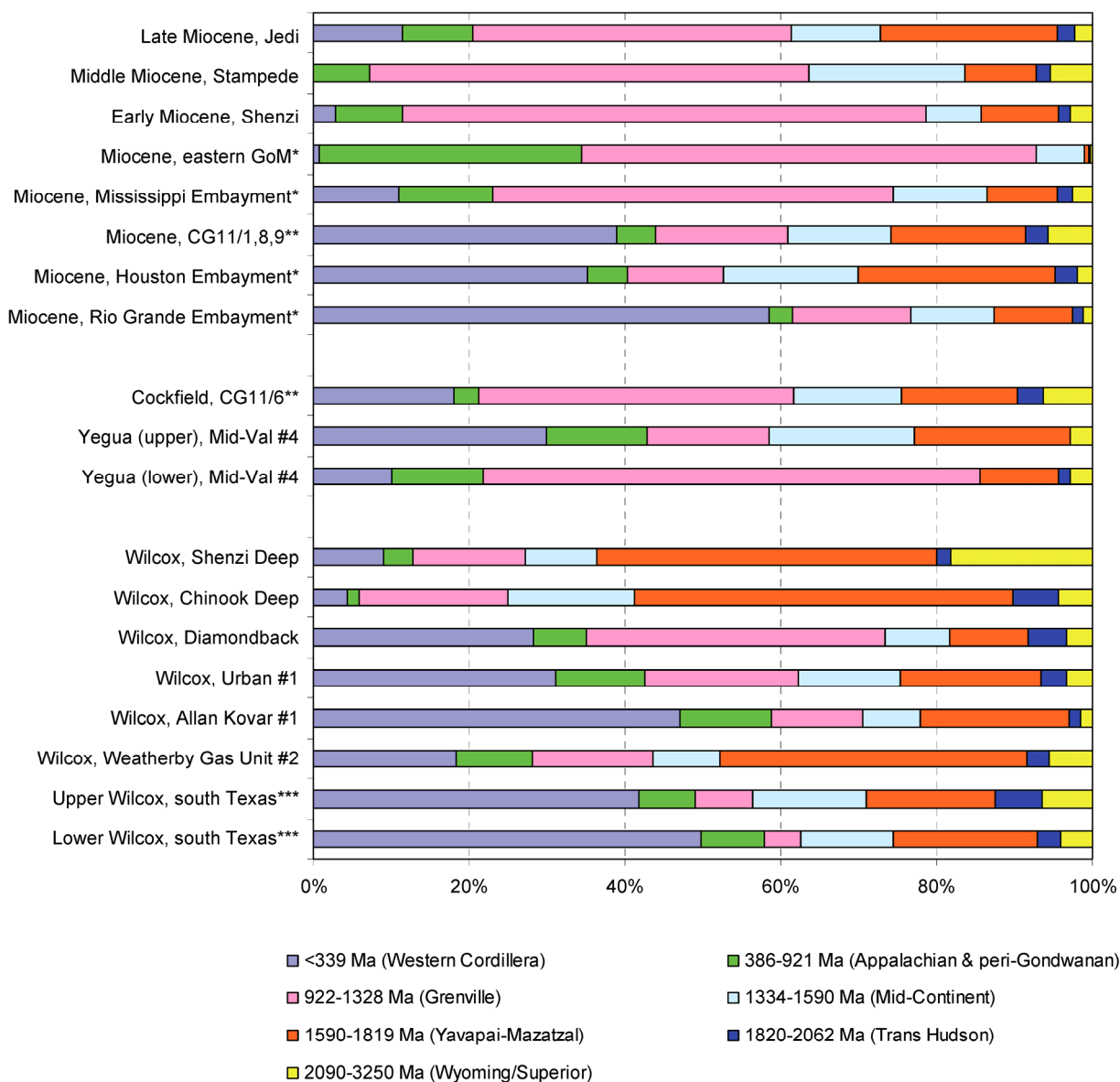


Figure 7. Zircon populations in Wilcox, Yegua and Miocene sandstones broken down into the specific age groups defined by Mackey et al. [17]. *—data from Xu et al. [23]; Rio Grande Embayment is compiled from samples GOM2–7; Houston Embayment is compiled from samples GOM8–13; Mississippi Embayment is compiled from samples GOM14–15; Eastern Gulf of Mexico is compiled from samples GOM16–19. **—data from Craddock and Kylander-Clark [4]. ***—data from Mackey et al. [17].

Heavy mineral data (concurrent changes in ATi, GZi and chloritoid content) suggest that the upper part of the succession in Chinook Deep has a different provenance to the lower part (Figure 4) and has similar characteristics to those seen in Diamond Back. Although it was not possible to acquire zircon data from the upper part of Chinook Deep owing to the low recovery of zircons (due to small sample sizes), the heavy mineral data suggest that this part of the succession was fed by the Rosita system by analogy with Diamond Back. Heavy mineral data also indicate that differences can be recognised

within the sediment fed by the Rosita system despite the general similarity in zircon age spectra. For example, Urban #1 has much higher RuZi than the other wells, implying a relative increase in supply from rutile-bearing lithologies (predominantly metamafic and metapelitic rocks) [44]. Diamond Back and the upper part of Chinook Deep have relatively high ATi, whereas Allan Kovar #1 has low ATi. This is interpreted as indicating that Diamond Back and Shenzi Deep have higher proportions of first-cycle sediment whereas Allan Kovar #1 has a higher proportion of weathered (and potentially recycled) detritus since apatite is highly unstable under weathering conditions [39,45].

Zircon age data from Weatherby Gas Unit #2 are somewhat anomalous in paleogeographic terms since this well is the furthest west in the data set and would be expected to have sediment with paleo-Rio Grande characteristics. In fact, it bears much closer resemblance to sediment of paleo-Colorado or paleo-Colorado-Brazos origin on the basis of the high proportion of zircons attributable to the Yavapai-Mazatzal Province (Figure 7). This suggests that the Rosita delta temporarily received sediment from north of the paleo-Rio Grande catchment. One of the Lower Wilcox samples (Z4) analysed by Mackey et al. [17] has similar characteristics to the Weatherby Gas Unit #2 sample (see Figure 5 in [17]), indicating that the atypical provenance features seen in Weatherby Gas Unit #2 are not an isolated occurrence within the Rosita system.

4. Yegua Sandstones

4.1. Heavy Mineral Data

The data set from the Late Eocene Yegua Formation is more limited than either the older Wilcox or younger Miocene sandstones, comprising samples from two adjacent wells east of Houston, Mid-Val #2 and Mid-Val #4 (Figure 1). Heavy mineral assemblages are limited in diversity, with just three minerals (apatite, tourmaline and zircon) forming over 93% of the populations. Rutile is the only other relatively common phase, with a mean value of 5%. These minerals are all ultrastable in burial diagenetic conditions [39,40], suggesting that diagenetic modification of the suites is advanced.

Despite the likely loss of provenance information due to diagenesis, the heavy mineral data indicate the presence of two distinct sand types. Based on variations in rutile:zircon (RuZi) and apatite:tourmaline (ATi), two distinct data clusters are evident, one (in the upper part of Mid-Val #4) with high RuZi and moderate ATi, and the other (in Mid-Val #2 and the lower part of Mid-Val #4) with high ATi and low-moderate RuZi (Figure 8).

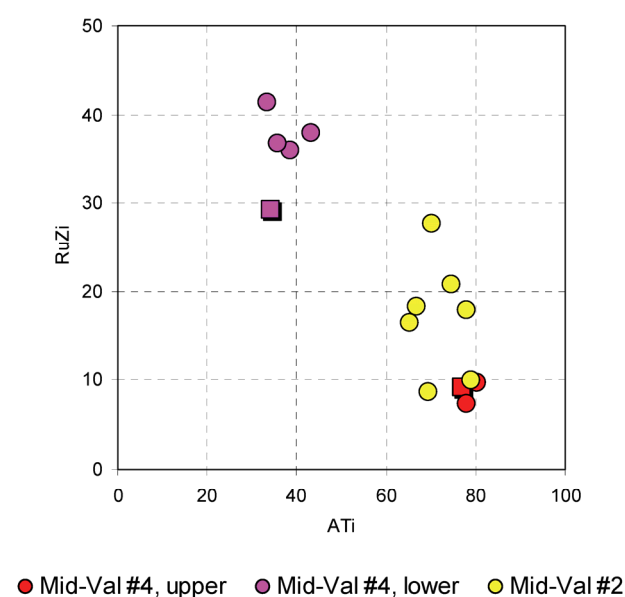


Figure 8. ATi-RuZi plot of Yegua sandstones in Mid-Val #2 and #4 showing the presence of two distinct provenance types. Square symbols are samples with U-Pb zircon chronology data. All data are from core.

4.2. Zircon Geochronology

The two different heavy mineral provenance types are also distinguished on the basis of detrital zircon geochronology. The high ATi, low/moderate RuZi sand type found in the upper part of Mid-Val #4 is dominated by young (Phanerozoic) zircons sourced from the Western Cordillera, with subordinate representation of zircons associated with the Appalachian and Peri-Gondwanan, Grenville, Mid-Continent and Yavapai-Mazatzal provinces (Figures 9 and 10). Following the criteria considered to be the most reliable basis for estimating maximum depositional age (the mean age of the youngest zircons overlapping at 2σ) [46], the data confirm the latest Eocene or younger age (<37.1 Ma) for the Yegua Formation (36.6 ± 0.8 Ma, 36.9 ± 0.6 Ma, 37.3 ± 0.6 Ma, 37.3 ± 0.5 Ma, 37.6 ± 0.8 Ma).

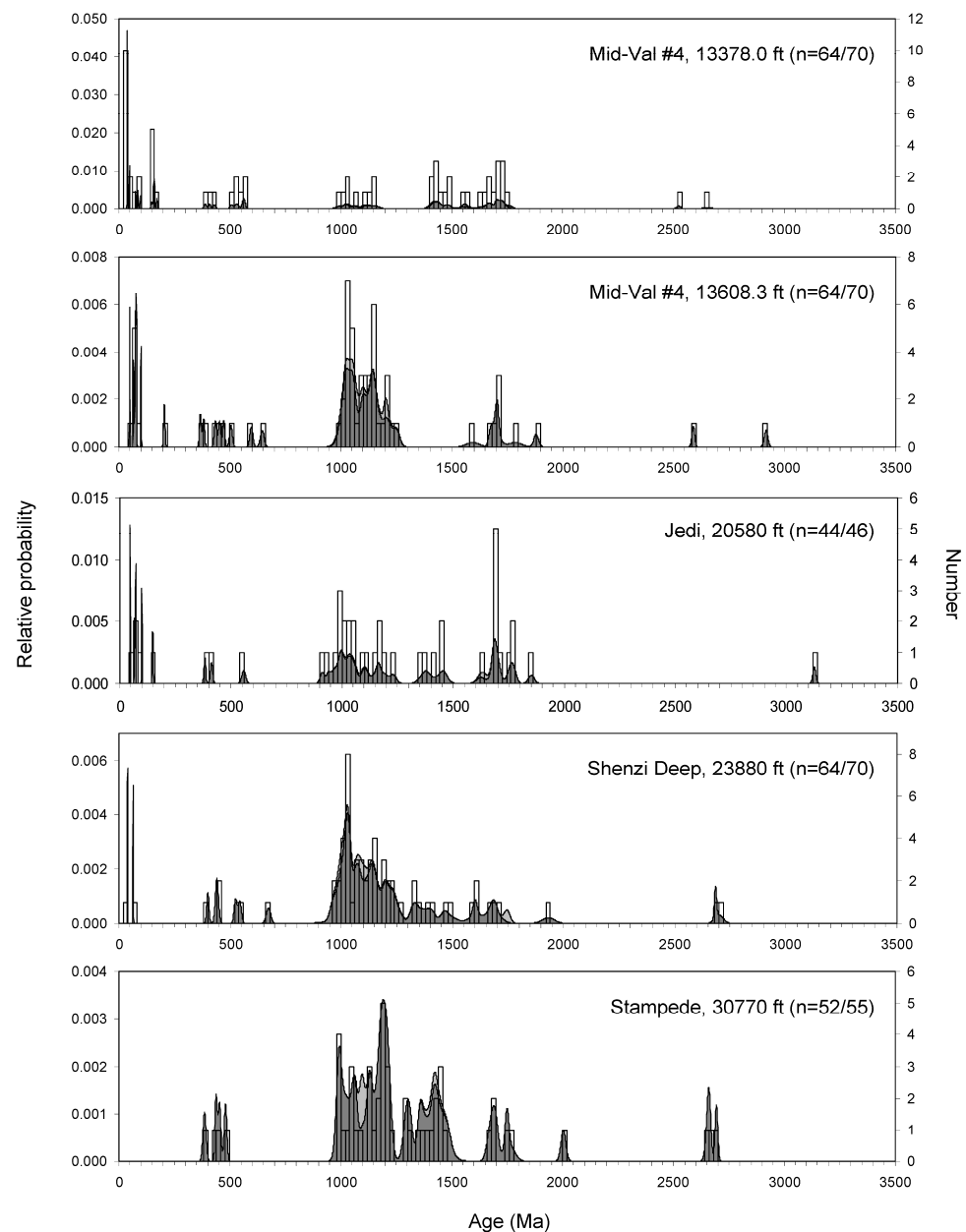


Figure 9. Yegua and Miocene age zircon spectra displayed as combined histogram-probability density plots. Dark grey = zircons with $<10\%$ discordance, pale grey = zircons with $>10\%$ discordance. 'n' = number of zircons with $<10\%$ discordance in the total zircon population. Data from Mid-Val #4 are from core, whereas Jedi, Shenzi Deep and Stampede are from ditch cuttings.

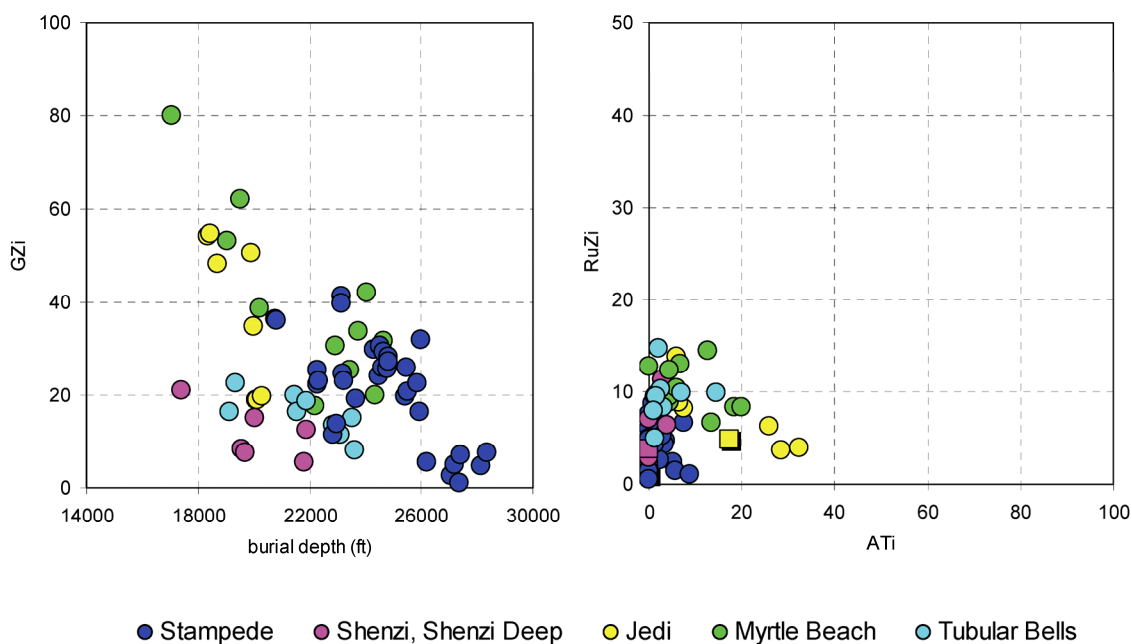


Figure 10. Heavy mineral parameters in Miocene sandstones from Jedi, Myrtle Beach, Shenzi, Stampede and Tubular Bells. Square symbols are samples with U-Pb zircon chronology data. All data are from ditch cuttings.

By contrast, the high RuZi, moderate ATi population in the lower part of Mid-Val #4 is rich in zircons from the Grenville Province, with only minor representation of the Western Cordillera, Appalachian and Peri-Gondwanan, Grenville and Yavapai-Mazatzal provinces (Figures 9 and 10).

4.3. Interpretation

Heavy mineral provenance data indicate that there was a provenance change within the analysed interval in Mid-Val #4 and that the entire cored interval in Mid-Val #2 is genetically related to the upper part of Mid-Val #4. The zircon population in the upper part of Mid-Val #4 resembles those present in Wilcox sandstones deposited by the Rosita system in the western GoM, and suggests that the Western Cordillera was the dominant source for this part of the Yegua Formation. The high ATi, low-moderate RuZi heavy mineral assemblage found in the upper Yegua is similar to the Wilcox in Diamond Back, which also has a zircon population indicative of a Rosita system origin.

The lower Yegua in the Mid-Val area has a large Grenville zircon component and is most likely to have had a paleo-Mississippi origin [18,20]. The switch from paleo-Mississippi to paleo-Rio Grande sourcing implies there was a major reorganisation of drainage patterns in the GoM during the Late Eocene.

Craddock and Kylander-Clark [4] noted that there was a marked increase in Grenville sourcing in the Claiborne Group (which includes the Yegua-equivalent Cockfield Formation, Figure 10) compared with the underlying Wilcox and overlying Cenozoic sandstones in Louisiana. The increased Grenville supply in the Clairborne Group [4] is confirmed by the new data from the Yegua Formation.

5. Miocene Sandstones

5.1. Heavy Mineral Data

The Miocene data set comprises samples from five wells in the deepwater GoM (Jedi, Myrtle Beach, Stampede, Shenzi/Shenzi Deep and Tubular Bells; Figure 1). Heavy mineral assemblages are somewhat more diverse than in the older Cenozoic, but, nevertheless, zircon and tourmaline remain the most abundant phases, forming 48.5% and 21.2% of the populations, respectively. The main differences compared with the older sandstones

are that garnet is more abundant (15.5%) and apatite is considerably less common (1.1%). Garnet proportions vary widely, from 46.5% down to 0.9%, and this variation is interpreted as at least partly controlled by garnet dissolution during deep burial. This relationship is demonstrated by the plot of burial depth against GZi (Figure 1), which shows that the most deeply buried sandstones have the lowest GZi.

There may also be a provenance control on GZi since values in Jedi and Myrtle Beach are higher at the same depth compared with Shenzi and Tubular Bells (Figure 10). However, the ATi-RuZi plot shows that all of the data cluster tightly together with low values of both indices, suggesting there was little difference in provenance between the wells. The only significant difference is that ATi values are slightly higher in some Jedi samples, and some Tubular Bells samples show the same trend, although to a lesser extent (Figure 10).

5.2. Zircon Geochronology

All three Miocene zircon spectra are dominated by the Grenville-age component, especially those in Shenzi and Stampede (Figure 9), which contain 67% and 56% of zircons of this age, respectively. There are differences in the structure of the Grenville component between the two wells; in Shenzi, the c. 1000 Ma peak is dominant, whereas Stampede has a bimodal structure with peaks at c. 1000 Ma and c. 1200 Ma. These two peaks are closely coincident with the ages of orogenic pulses in the Grenville Province [47], with the former matching the Ottawa (1020–1080 Ma) and Rigolet (980–1010 Ma) and the latter matching the Elzevirian (1190–1250 Ma) and Shawinigan (1140–1190 Ma). There is also a difference between the abundance of the Mid-Continent component, which is better represented in Stampede than in Shenzi. The spectrum in Jedi is also rich in the Grenville-age component but is less well represented than in Stampede and Shenzi (41%). The other main difference is that zircons of Yavapai-Mazatzal affinity are more common in Jedi (23%) than in Shenzi and Stampede (9%–10%).

5.3. Interpretation

Heavy mineral data indicate the Miocene sandstones in Jedi, Myrtle Beach, Shenzi, Stampede and Tubular Bells have similar provenance to one another, all having low ATi and low RuZi. However, Jedi and Myrtle Beach are subtly different in having slightly higher ATi. Low ATi values generally imply extensive weathering during sedimentation history, since apatite is unstable in such conditions. The most likely explanation for the uniformly low ATi is that the sandstones are predominantly recycled. The subtle differences within the data set probably indicate that Jedi and Myrtle Beach contain slightly more first-cycle detritus than Shenzi, Stampede and Tubular Bells.

By comparison with the extensive zircon data set on Miocene sandstones onshore GoM [23], the zircon age spectra in Jedi, Shenzi and Stampede compare closely with those found in the Mississippi Embayment and are markedly different to those seen in the Rio Grande and Houston embayments to the west, and to the eastern GoM (Figure 10). The Mississippi Embayment zircon data have been interpreted as indicating a large contribution from Appalachian terranes towards the east, to account for the abundant Grenville-age grains and the increase in the Appalachian-Ouachita component [23]. The Appalachian-Ouachita component was derived either from the Paleozoic fold-and-thrust belt in the Appalachian terranes or from the Ouachita Mountains [23]. In addition, the presence of Cordillera Magmatic Province, Midcontinent and Yavapai-Mazatzal components indicates an important western U.S. influence [23]. There is a strong similarity between the Lower Miocene of the Mississippi Embayment and the Wilcox Group to the north, interpreted as indicating the Lower Miocene sandstones were either recycled from the Wilcox or originated from the same drainage area [23]. The evidence from the heavy mineral data for extensive weathering suggests that Wilcox recycling is a more likely origin for the Miocene sandstones in the offshore GoM, although it is possible that the low ATi resulted from prolonged weathering during alluvial storage during the Miocene sedimentation cycle.

The presence of two main peaks within the Grenville-age zircon group in Stampede is mirrored by zircons derived by the paleo-Mississippi during Wilcox deposition [18,20]. This indicates that recycling from adjacent Wilcox sandstones, or derivation from the same source area, is a likely origin for the Miocene in Stampede. However, the unimodal pattern in Shenzi, with a c. 1000 Ma peak, could indicate derivation from the Ouachita Mountains, where zircons of this age are dominant (see sample GOM75 of Blum et al. [20] Figure 13).

The zircons in Jedi have slightly higher proportions of western Cordillera and Yavapai-Mazatzal zircons compared with Shenzi and Stampede (Figure 10), confirming the heavy mineral evidence for a subtly different provenance. The data indicate that at least some of the Miocene detritus in Jedi was supplied through the paleo-Red River, where western Cordillera and Yavapai-Mazatzal components are better represented than in the Mississippi Embayment (Figure 10). This is compatible with the geographical location of Jedi, which is further west than Shenzi and Stampede (Figure 11). In this regard, it is noteworthy that Miocene sandstones from the Mississippi Embayment [4] have similar zircon characteristics to those from the Houston Embayment [23] (Figure 10), implying that the paleo-Red River sporadically contributed sediment to the paleo-Mississippi. Alternatively, the higher proportions of western Cordillera and Yavapai-Mazatzal zircons may be related to the recycling of Wilcox sandstones.

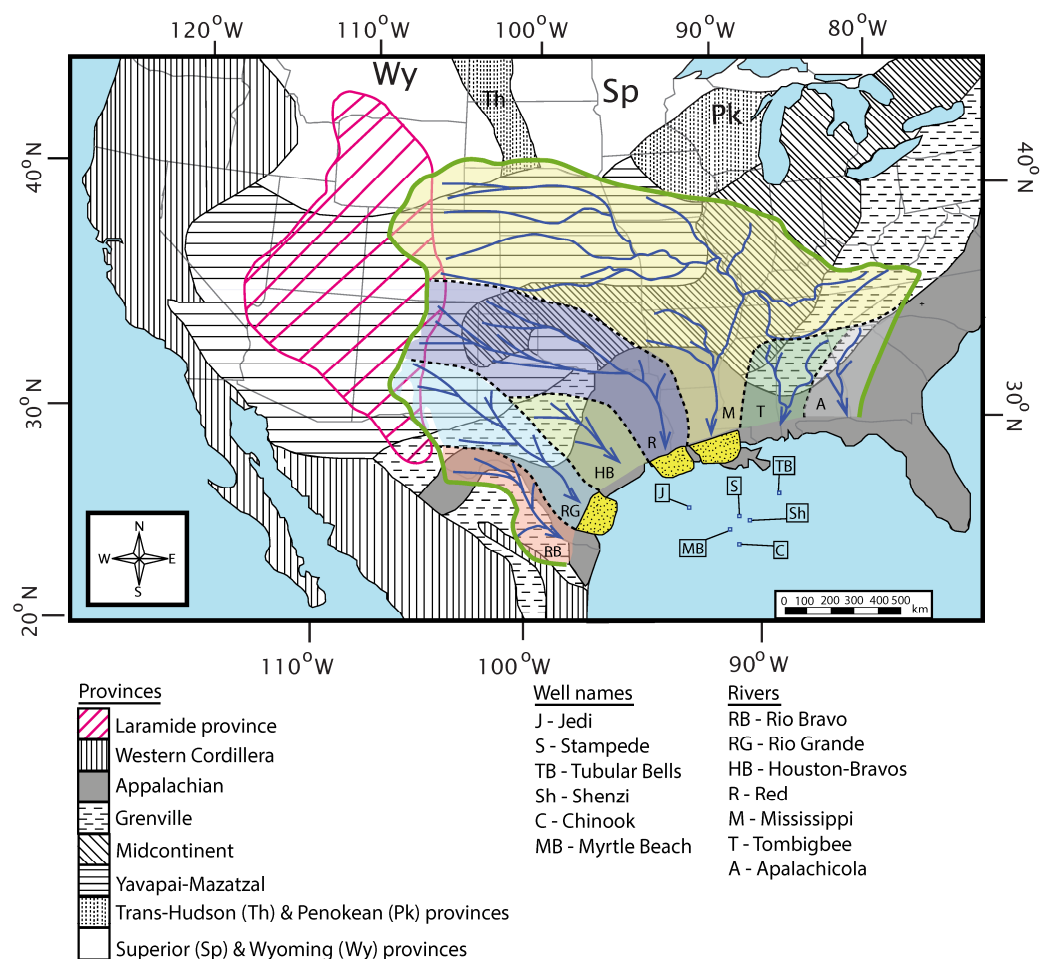


Figure 11. Miocene paleodrainage into the GoM, adapted from Galloway et al. [2] and Xu et al. [23], showing the locations of wells discussed in this paper. Terrane base map is from Blum et al. [20].

6. Conclusions

New heavy mineral and zircon geochronology data from Paleocene-Miocene sandstones have extended the understanding of sediment pathways from the Gulf Coast outcrops into the deep subsurface both in the onshore and offshore GoM.

In the Paleocene–Eocene Wilcox Group, sandstones in Allan Kovar #1, Urban #1 and Diamond Back are interpreted as the products of the Rosita system derived via paleo-Rio Grande material (Figure 6), in common with the Wilcox of southwest Texas [17], with a large component of sediment shed from the Western Cordillera. By contrast, samples from wells further east (Shenzi Deep and Chinook Deep) have high proportions of zircons derived from the Yavapai–Mazatzal Province and are attributed to the Rockdale system with sediment fed predominantly by the paleo-Colorado or paleo-Colorado–Brazos. Heavy mineral data from the upper part of the succession in Chinook Deep are similar to those from Diamond Back, indicating that sediment from the Rosita system sporadically extended into the central GoM. Likewise, the Rockdale system is inferred to have sporadically supplied sediment to the western part of the basin, since a high proportion of zircons in Weatherby Gas Unit #2 are attributed to a Yavapai–Mazatzal provenance implying transport via the paleo-Colorado or paleo-Colorado–Brazos.

Evidence from the Mid-Val area (central GoM) indicates there was a distinct shift in provenance during the deposition of the Yegua Formation in the Late Eocene. The earlier Yegua sandstones have a large Grenville zircon component and are most likely to have had a paleo-Mississippi origin. By contrast, the later Yegua sandstones are dominated by zircons of Western Cordilleran origin, similar to Wilcox sandstones fed by the Rosita system via the paleo-Rio Grande. The switch from paleo-Mississippi to paleo-Rio Grande sourcing implies there was a major reorganisation of drainage patterns in the GoM during the Late Eocene.

Miocene sandstones in the deepwater GoM were principally sourced from the paleo-Mississippi (Figure 11), although the paleo-Red River is inferred to have contributed to the more westerly-located wells (Jedi and Myrtle Beach).

Zircon geochronology has also provided constraints on maximum depositional age for some Wilcox and Yegua sandstones, on the basis of the mean age of the youngest zircons overlapping at 2σ [45]. The youngest zircons in the Wilcox of Diamond Back, Allan Kovar #1 and Urban #1 constrain the maximum depositional age to the very latest Paleocene (57.7 ± 1.0 Ma, 57.8 ± 1.2 Ma and 58.5 ± 1.4 Ma in Diamond Back; 55.7 ± 0.9 Ma, 56.9 ± 1.0 Ma and 58.5 ± 1.0 Ma in Allan Kovar #1; and 54.1 ± 0.8 Ma and 55.8 ± 0.7 Ma in Urban #1). Deposition of the Yegua in Mid-Val #4 took place in the latest Eocene (<37.1 Ma) on the basis of the five youngest zircons (36.6 ± 0.8 Ma, 36.9 ± 0.6 Ma, 37.3 ± 0.6 Ma, 37.3 ± 0.5 Ma and 37.6 ± 0.8 Ma).

Although heavy mineral assemblages have been heavily modified through the dissolution of unstable minerals during burial diagenesis, the application of the provenance-sensitive ratio method has added value to the interpretation of the provenance of Paleocene–Miocene sandstones in the GoM. For example, differences can be recognised between Wilcox sandstones that are all attributed to derivation via the Rosita system on the basis of their zircon populations. Diamond Back (and the upper part of Chinook Deep) has high ATI , implying much of the detritus is of first-cycle origin. Sandstones in Urban #1 have much higher $RuZi$ than the other wells, implying a relative increase in supply from rutile-bearing lithologies. Finally, Allan Kovar #1 has low ATI , suggesting it contains a higher proportion of weathered (and potentially recycled) detritus. Likewise, heavy mineral data readily distinguish the two zircon provenance types found in the Yegua sandstones of the Mid-Val area and confirm a genetic relationship between the upper Yegua and Wilcox sandstones in Diamond Back. Heavy mineral assemblages in the Miocene sandstones have uniformly low ATI , implying prolonged weathering either through recycling or during alluvial storage in the Miocene depositional cycle. The difference in provenance identified on the basis of detrital zircon data is supported by a subtle change in ATI .

Stratigraphic variations in provenance-sensitive heavy mineral parameters, such as those seen in the Wilcox of Chinook Deep and the Yegua of Mid-Val #2 and #4, indicate that the method has potential lithostratigraphic value, at least on a local basis, in common with many other hydrocarbon-bearing basins [48,49].

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/min14080779/s1>, supplementary data tables.

Author Contributions: Conceptualization, A.C.M., M.E.S.; formal analysis, A.C.M., C.M.F.; writing, A.C.M.; writing, review and editing, M.E.S., C.M.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article and Supplementary Materials.

Acknowledgments: We are grateful to the Hess Corporation for permitting the publication of the heavy mineral and zircon geochronology data discussed in this report, and to Paula McGill (HM Research Norway) for drafting Figures 6 and 11.

Conflicts of Interest: Author M.S. was employed by the company Hess. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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