



Eocene–Oligocene chronostratigraphy of ignimbrite flareup volcanic ash beds on the Gulf of Mexico coastal plains

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ABSTRACT

Sanidine ⁴⁰Ar/³⁹Ar dates and zircon U-Pb dates of middle Eocene to late Oligocene volcanic ash beds provide high-resolution geochronology for the northern Gulf of Mexico. The dates coincide with silicic volcanism generated as North America moved closer to the Pacific spreading axis. Ten new dates are reported, five for upper Eocene Jackson Group strata and five for Oligocene Catahoula Group strata. Dating is extended to south Texas and the Rio Grande Valley. Clusters of radiometric dates at ca. 34.1–34.5 Ma and at ca. 35.7–35.8 Ma indicate times of greater volcanic eruptive activity during the late Eocene. The ca. 34.1–34.5 Ma cluster occurs across the northern Gulf of Mexico from south Texas to Mississippi. Airborne volcanic ash plumes carried sanidine grains as coarse as 500 μm as much as 650 km away from the closest eruptive center, and grains to 150–200 μm occur in ash beds 600–800 km from the closest source. Volcanic ash bed dates do not correspond with any dated calderas in the southwestern United States. Long-distance transport of relatively coarse crystals has important implications for use of detrital mineral geochronology in paleodrainage studies. Early Rupelian dates of lower Gueydan Formation strata in the Catahoula Group are coeval to lower Vicksburg Group in the subsurface. The previous interpretation of a long-duration early Oligocene depositional hiatus in Texas is not supported and is replaced with the interpretation of early Oligocene nonmarine fan deposition in south Texas.

INTRODUCTION

Radiometric dating of volcanic ash is resolving a long-standing problem of obtaining accurate dates for outcropping Cenozoic strata in the northwestern sector of the Gulf of Mexico coastal plains. Strata younger than basal Paleocene Danian Stage contain few fossils capable of providing good age control (Fisher and McGowen, 1969; Fisher et al., 1970; Ewing, 1994). The strata are composed of clastic sediment containing abundant terrestrial plant debris that produced diagenetic conditions resulting in dissolution of most fossils used for biostratigraphic age determination. Reliable fossil-based age control is limited to several major marine incursions (Loutit et al., 1988). Other stratigraphic

units are dated by long-distance lithologic correlation of strata from deep-water basinal deposits or from the northeastern sector of the Gulf of Mexico (Loutit et al., 1988; Galloway et al., 2000; Brown and Loucks, 2009). Despite the absence of age-diagnostic marine fossils in the northwestern Gulf of Mexico outcrop belt, these middle Eocene to upper Oligocene strata contain volcanic ash beds that are suitable for radiometric dating (Fig. 1; Table 1).

The radiometric method of age determination remained largely unexploited for Gulf of Mexico coastal plains strata until Heintz et al. (2015) presented ⁴⁰Ar/³⁹Ar dates for a group of east Texas volcanic ash beds. That study also documented the presence of many layers of volcanic ash in upper Eocene and Oligocene strata and made observations on their regional occurrence. It is ironic that many radiometric age determinations are published for detrital zircons in Cenozoic strata of this region (Craddock and Kylander-Clark, 2013; Mackey et al., 2012; Wahl et al., 2016; Xu et al., 2017), but none were presented for ash bed phenocryst zircons. While dating of sanidine phenocrysts yields high-precision results, zircon phenocrysts also provide valuable high-resolution dating for Paleogene volcanic ash. In an area where most dating of formations is inferred and of low accuracy, radiometric dating of ash bed phenocrysts provides a great improvement in age control for outcrop strata that remain the major source of data for regional paleoenvironment, paleogeography, paleodrainage, and paleoclimate reconstructions.

The presence of volcanic ash in Eocene and Oligocene strata in the Texas coastal plains has been noted in many reports (e.g., Bailey, 1926; Renick, 1936; Russell, 1957; Callender and Folk, 1958; McBride et al., 1968; Grigsby and Dennis, 1991), and a few radiometric dates were produced as a byproduct of applied studies (Hurley et al., 1960; Corrigan, 1993; Guillemette and Yancey, 1996) or presented in a Master's thesis (Deux, 1970). In another part of the Gulf of Mexico coastal plains, Obradovich et al. (1993) reported on some Mississippi volcanic ash beds. The Obradovich et al. (1993) and Guillemette and Yancey (1996) studies presented the first dates using sanidine, obtained by using multiple grains of sanidine phenocrysts to obtain a single numerical date. Heintz et al. (2015) presented the first large study of Gulf of Mexico coastal plains ⁴⁰Ar/³⁹Ar radiometric dating on sanidine single crystals, coupling the geochronology data with major, trace, and rare earth element analysis of bulk ash samples on a large group of volcanic ash beds present in strata of the Brazos River Valley of Texas.

These volcanic ash beds are derived from tephra produced by large volcanic eruptions from the western United States and Mexico (McBride et al.,

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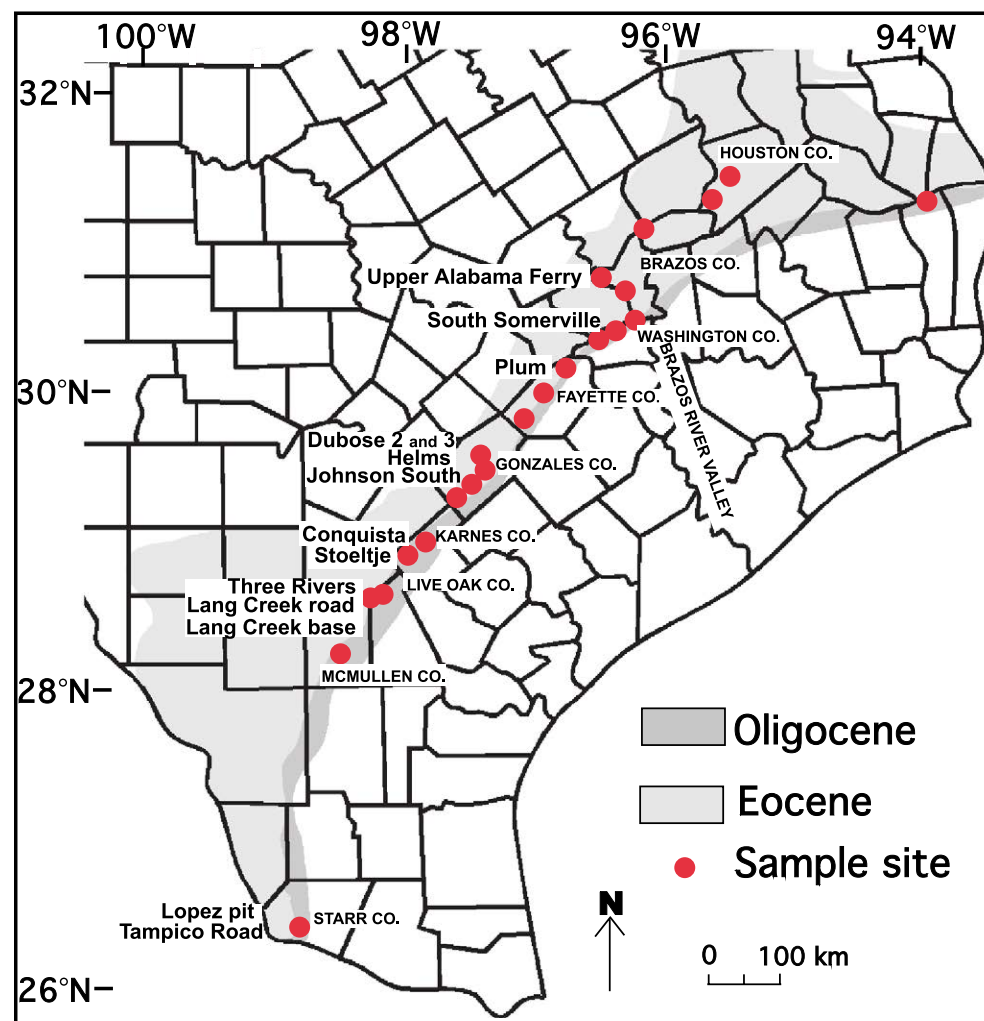


Figure 1. Location of volcanic ash beds sampled on the Texas coastal plains, southern United States for samples and locals cited in this study; unlabeled sample sites are reported in Heintz et al. (2015). Sample names are on the left, county names are on the right. Latitude and longitude were determined from Google Earth using the WGS84 datum. Co.—County.

1968; Heintz et al., 2015). This volcanic activity is related to the ignimbrite flareup across the southwestern portion of North America that occurred as the continent approached the Pacific spreading axis. This generated large amounts of high-silica magma and a corresponding increase in the frequency of large-magnitude silicic volcanic eruptions (Lipman et al., 1972; Ferrari et al., 1999, 2017; McDowell and McIntosh, 2012). In the northern Sierra Madre Occidental (northwestern Mexico), the ignimbrite flareup occurred from 36 Ma to 27 Ma (Ferrari et al., 2017). These eruptions generated ash clouds that spread

eastward over the continent to the Gulf of Mexico, depositing ash as far east as the state of Mississippi (Obradovich et al., 1993; Dockery et al., 2017). The Texas sector of the Gulf of Mexico coastal plain extends from 600 to 1200 km from the centers of greatest volcanic activity (McBride et al., 1968; McDowell and McIntosh, 2012). While many ash beds occur as thin layers, meter-thick ash beds (some now altered to bentonite) occur in the section.

Continued dating of Cenozoic Gulf Coast volcanic ash beds expands dating work on the Oligocene Catahoula Group (Fig. 2), a stratigraphic unit contain-

TABLE 1. SOUTH TEXAS VOLCANIC ASH SAMPLE LOCATIONS, BED THICKNESS, AND PHENOCRYST MAXIMUM DIAMETER

Ash bed	Location	Thickness (m)	Phenocryst maximum diameter (μm)
	Latitude ($^{\circ}\text{N}$), longitude ($^{\circ}\text{W}$)		
Tampico Road	26.352888 $^{\circ}\text{N}$, 98.758775 $^{\circ}\text{W}$	10	nd
Lopez pit	26.356187 $^{\circ}\text{N}$, 98.762236 $^{\circ}\text{W}$	1.5+	nd
Johnson Ranch caliche road	28.434718 $^{\circ}\text{N}$, 98.300229 $^{\circ}\text{W}$	1	200
Johnson Ranch badlands	28.432213 $^{\circ}\text{N}$, 98.301869 $^{\circ}\text{W}$	0.3	nd
Stoeltje pit	29.936063 $^{\circ}\text{N}$, 98.017836 $^{\circ}\text{W}$	0.25	nd
Three Rivers	28.595386 $^{\circ}\text{N}$, 98.223729 $^{\circ}\text{W}$	0–2	nd
Conquista (Sickenious west)	28.876347 $^{\circ}\text{N}$, 98.101288 $^{\circ}\text{W}$	3	200
Smiley	29.199341 $^{\circ}\text{N}$, 97.617346 $^{\circ}\text{W}$	0.8	nd
Johnson South (H.W. Johnson pit)	29.381600 $^{\circ}\text{N}$, 97.423961 $^{\circ}\text{W}$	1.5	200
Helms pit	29.484340 $^{\circ}\text{N}$, 97.370987 $^{\circ}\text{W}$	1.5	150
Dubose 3	29.488406 $^{\circ}\text{N}$, 97.325377 $^{\circ}\text{W}$	0.5	nd
Kennard (Dubose 2)	29.491020 $^{\circ}\text{N}$, 97.325610 $^{\circ}\text{W}$	0.25	nd
Plum	29.935115 $^{\circ}\text{N}$, 96.979841 $^{\circ}\text{W}$	1	150

Note: nd—not determined.

ing multiple tephra layers and large amounts of volcanic sediment in south Texas (Bailey, 1926; Renick, 1936; McBride et al., 1968). Sampling is extended to include upper Oligocene strata and expands the study area geographically to include south Texas and the Rio Grande Valley region (Fig. 1). A compilation of ten new $^{40}\text{Ar}/^{39}\text{Ar}$ -dated volcanic ash beds in the Texas coastal plains is presented in Figure 2. Sampling along the outcrop belt shows that volcanic ash beds are regionally extensive and occur in many horizons within Eocene and Oligocene strata. The recovery of late Oligocene volcanic ash indicates that the northwestern Gulf Coast contains a long-duration record of silicic volcanic activity. Reports of Eocene and Oligocene volcanic ash in the states of Louisiana (Chawner, 1936; Paine and Meyerhoff, 1968; Wrenn et al., 2004) and Mississippi (Obradovich et al., 1993; Dockery et al., 2017) point to regional distribution of volcanic ash beds that are currently dated only in Texas or Mississippi.

Obtaining dates on Catahoula Group volcanic ash is an important advance in dating Gulf Coast Cenozoic strata. Although the Catahoula Group, named and mapped as the Catahoula Tuff (Bailey, 1926; Renick, 1936; McBride et al., 1968), is known to contain large amounts of volcanic ash and glass shards and is considered to be deposited during the time of maximum silicic volcanic activity, the results of previous radiometric dating studies have been equivocal or unsatisfactory. Two attempts made to date outcrop rocks of the Gueydan Formation in the Catahoula Group include K-Ar determination on biotite extracted from “tuffaceous clay” by Deux (1970) and fission-track determinations on apatite extracted from sandstones by Corrigan (1993). Because these dates include some determinations that are much older than expected, they are considered unreliable for dating the time of ash deposition. A more recent report by Craddock and Kylander-Clark (2013) presented a date of 34.07 ± 0.8 Ma on detrital zircons in Catahoula sandstone of western Louisiana, an area where the formation is thin and irregularly preserved (Paine and Meyerhoff, 1968). This date is coeval with latest Eocene volcanic ashes dated by Heintz et al.

(2015), but the large uncertainty is consistent with either latest Eocene or early Oligocene deposition and only provides a maximum depositional age. The Catahoula Group dating presented here is consistent with expectations that Catahoula volcanic ash was deposited during peak silicic volcanic activity for western North America.

The high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ dates presented here on fine-grained, single crystals are made possible by relatively recent developments in multicollector, high sensitivity, ultra-clean mass spectrometers coupled with low-blank extraction systems. Previous $^{40}\text{Ar}/^{39}\text{Ar}$ dates of coastal plains Texas sandstone were based on analysis of multiple grains (e.g. Obradovich et al., 1993; Guillemette and Yancey, 1996), and not all of these determinations were presented in publication. Single-crystal dating is more accurate than multiple-grain analyses because spuriously young (argon loss) or old (inherited xenocrysts) crystals can be excluded in favor a discrete population of phenocrysts (e.g., Deino and Potts, 1992). Also, for samples that have experienced post-depositional reworking, this method can identify anomalously old detrital grains. In general, the youngest subpopulation of crystal ages is used to determine the age of deposition of the tephra layer. This method of choosing the most accurate age population is also utilized for U-Pb zircon dating. Methodological improvements (e.g., Mattinson, 2005; Schmitz and Schoene, 2007; Condon et al., 2015; McLean et al., 2015) in U-Pb dating by isotope dilution–thermal ionization mass spectrometry (ID-TIMS) have, in a manner analogous to improved Ar-Ar dating, greatly increased the utility of single-grain zircon analyses for high-resolution stratigraphic studies in Cenozoic sections.

The many undated beds of volcanic ash present in the stratigraphic section provide an opportunity to determine a high-resolution chronostratigraphy for Eocene–Oligocene strata throughout the Gulf Coast region, independent of lithostratigraphic correlation–based dating. Radiometric dating provides a direct tie to the paleomagnetic time scale as well. Reliable high-resolution dating

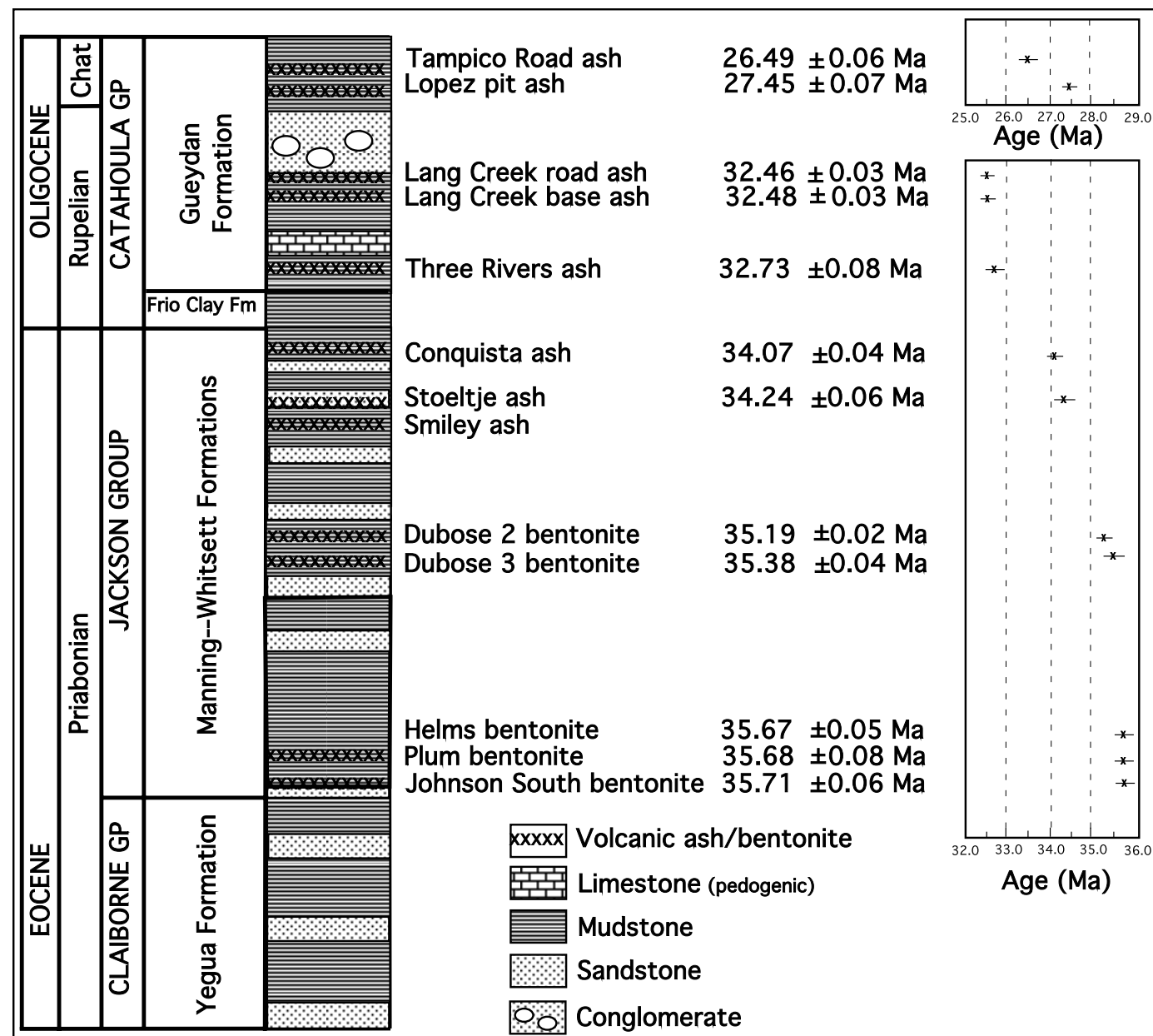


Figure 2. Radiometric dates for south and south-central Texas and the Rio Grande Valley. All are new except for the Conquista and Dubose 2 dates previously reported by Heintz et al. (2015). All dates shown are reported at 95% uncertainty level. Chat—Chattian; Gp—Group; Fm—Formation.

is beneficial for all studies involving geologic history, and improves paleogeographic and paleodrainage reconstructions and calculations of rate change of geologic processes. The present study is a contribution of a program started in 2012 with a focus on obtaining radiometric dates and glass geochemistry of single-event volcanic ash beds present in the Texas coastal plains. This program is producing high-resolution dating for Eocene and Oligocene shelf deposits of the northern and western Gulf Coast. This dating can be applied to document a detailed record of cyclic sediment deposition (Yancey and Heintz, 2015) and climate history during a time of cooling and drying in North America (Yancey et al., 2003).

■ $^{40}\text{Ar}/^{39}\text{Ar}$ DATING OF VOLCANIC ASHES

Samples of Gulf Coast volcanic ash are from layers easily identified as being volcanic ash, either by their distinctive white color or by the presence of abundant volcanic glass shards. Layers containing coarse glass shards (i.e., as large as 500 μm) are good candidates for dating provided they also contain sanidine. Excellent candidates for radiometric dating are volcanic ash beds deposited in marine strata or lignites that have planar lower and upper boundaries and show little evidence of post-deposition disturbance. Volcanic ash deposited in nonmarine environments is usually reworked and requires further evaluation to determine acceptability for dating. Although volcanic ash in the Catahoula Group is reworked in all areas examined during this study, samples collected in the Three Rivers area of Live Oak County, Texas, have provided useful dates, including a sample from the large channel fill illustrated by McBride et al. (1968).

Sample collection consists of taking a 5–10 kg sample from an outcrop with preference for material from the base of the volcanic ash bed. In addition to systematic sampling of volcanic ash exposures, the work incorporated samples of opportunity obtained during previous field work. Processing large samples is necessary to recover sufficient material for dating, as the ashes are commonly dominated by volcanic glass. Lab processing, as described by Guillemette and Yancey (1996), removes clay and silt from the sample to produce a sand-size concentrate of minerals. Microscopic examination of the concentrate determines if there is a significant component of phenocryst grains, followed by a decision on whether to attempt radiometric dating on the sample. Samples meeting the criteria for dating were analyzed for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology at the New Mexico Geochronological Research Laboratory at New Mexico Tech. Analytical methods are similar to those reported by Heintz et al. (2015). The $^{40}\text{Ar}/^{39}\text{Ar}$ data are presented in Table 2. Information on irradiation, instrumentation, and analysis is summarized here and provided in the Supplemental Document¹. All age assignments were made without stratigraphic knowledge, thereby eliminating potential bias during data reduction.

Sanidine mineral separation using standard magnetic and heavy liquid methods was conducted at the New Mexico Geochronology Research Laboratory on mineral concentrates provided by Texas A&M University. The crystals were irradiated at the TRIGA reactor in Denver, Colorado, in three separate

irradiations that varied from 16 to 32 h (Supplemental Document [footnote 1]) along with Fish Canyon sanidine interlaboratory standard FC-2 with an assigned age of 28.201 Ma (Kuiper et al., 2008). Ages are calculated with a total ^{40}K decay constant of $5.463 \times 10^{-10}/\text{a}$ (Min et al., 2000).

After irradiation, at least six crystals of FC-2 from multiple monitor holes were analyzed. Both monitors and sample crystals were fused with a CO_2 laser and the extracted gas was cleaned for 30 s with a SAES NP10 getter operated at 1.6 A and a SAES D50 getter operated at room temperature. The gas was analyzed for argon isotopes using a Thermo Scientific ARGUS VI multicollector mass spectrometer equipped with five Faraday cups and one compact discrete dyonode (CDD) ion counting multiplier. Details of the collector configuration are provided in the Supplemental Table (footnote 1). All data acquisition was accomplished with New Mexico Tech Pychron software (http://www.bgc.org/about_bgc/mission.html), and data reduction used Mass Spec software (ver. 7.875, http://www.bgc.org/about_bgc/mission.html) written by Alan Deino at the Berkeley Geochronology Center in Berkeley, California. Extraction line blank plus mass spectrometer background values are averages of numerous measurements interspersed with the unknown measurements. Blank values are generally small compared to sample gas quantities and are provided for each irradiation in the Supplemental Table (footnote 1).

The preferred eruption ages are generally defined by the youngest group of dates that either form or nearly form a Gaussian distribution as defined by the mean square of weighted deviates (MSWD) value of the selected dates. The reported age is the inverse variance weighted mean of the selected crystals, and the error is the weighted error using the inverse variance as the weighting factor. This error is multiplied by the square root of the MSWD for $\text{MSWD} > 1$. J-factors that monitor neutron dose during irradiation were determined by laser fusion of Fish Canyon sanidine grains and have uncertainties between 0.01 and 0.02%. This uncertainty is propagated into the weighted mean age error that is reported at 2σ precision.

■ U-Pb DATING OF VOLCANIC ASHES

Paleogene high-silica volcanic ash deposits are also amenable to dating with zircon phenocrysts. The sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ ages are expected to be more precise for Cenozoic rocks, but both of these systems are subject to complications resulting from the incorporation of xenocrystic grains older than the volcanic event producing the ash bed or with the possible loss of radiogenic daughter isotopes from the crystal. Zircon is much more resistant to diagenetic or other secondary alteration than sanidine and can be used for dating where alteration has damaged or destroyed feldspar grains in a sample. The use of both mineral systems from the same sample allows for greater quality control on checking for presumed xenocrystic grains and secondary alteration, permitting a more robust age interpretation. Same-sample $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine combined with U-Pb zircon dating is presented for four samples to demonstrate agreement of the U-Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ dating systems within their respective analytical errors. The U-Pb data are presented in Table 3.

Table 1. Summary of age data and analytical methods and instrumentation.

Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ results									
Sample	Lot	Ion	n	MSWD	Age(Ma)	$\pm 2\sigma$	Comments (ACA sample/notes)		
Cambodia/Ceylon/Fm	63231	NM-271E	12	2.9	32.71	± 0.09	Cambodia/Ceylon/Fm		
Dubois 3	63951	NM-279A	18	1.1	35.38	± 0.04	GC02		
Holmes	63961	NM-279A	21	1.3	35.67	± 0.05	GC03		
Johnson South	63960	NM-279A	6	0.8	35.71	± 0.06	GC04		
Sankey	63962	NM-279A	2	0.8	34.42	± 0.17	GC05		
Lang Creek Road	63954	NM-279A	14	2.1	32.46	± 0.03	BJ02		
Lang Creek base	63959	NM-279A	9	1.2	32.46	± 0.03	BJ04		
Shingle	63952	NM-279A	14	0.8	34.24	± 0.06	K202		
MD01 Plumbline	63953	NM-279A	8	2.5	35.68	± 0.08	MD01upper		
Lopez Pit	63956	NM-279A	6	1.9	27.45	± 0.07	RG01		
Tampana Road	63957	NM-279A	11	7.2	26.49	± 0.06	RG02		
Dubois #2	63958	NM-260C	21	2.7	35.09	± 0.02	Dubois #2		

¹Supplemental Items. Supplemental Document: Information on irradiation, instrumentation, and analysis. Supplemental Table: U-Pb isotopic data. Please visit <http://doi.org/10.1130/GES01621.S1> or the full-text article on www.gsapubs.org to view the Supplemental Items.

TABLE 2. ARGON ISOTOPE DATA OF DATED SAMPLES

Grain ID	⁴⁰ Ar/ ³⁹ Ar	³⁸ Ar/ ³⁹ Ar	³⁷ Ar/ ³⁹ Ar	³⁶ Ar/ ³⁹ Ar (x 10 ⁻³)	³⁹ Ar _K (x 10 ⁻¹⁵ mol)	K/Ca	⁴⁰ Ar* (%)	Age (Ma)	±1σ (Ma)
Three Rivers: sample Catahoula/Gueydon Fm., sanidine, J = 0.0037867 ± 0.02%, IC = 1.035904 ± 0.001356, NM-271E, Lab# 63231									
02	17.839	0.0446	0.1239	45.13	0.015	4.1	25.3	31.0	3.5
74	4.783	0.0122	0.0646	0.1292	0.549	7.9	99.3	32.581	0.086
89	4.763	0.0115	0.0175	0.0326	0.424	29.1	99.8	32.61	0.11
43	4.873	0.0105	0.0068	0.3903	0.606	74.9	97.6	32.631	0.076
77	4.822	0.0149	-0.0016	0.1828	0.264	-	98.9	32.70	0.18
25	4.879	0.0090	0.0109	0.3769	0.556	46.8	97.7	32.700	0.084
36	4.981	0.0124	0.0235	0.7212	1.557	21.7	95.8	32.712	0.034
24	4.911	0.0030	0.2721	0.5484	0.240	1.9	97.1	32.72	0.19
19	6.112	0.0053	0.0152	4.509	0.744	33.5	78.2	32.784	0.086
75	4.981	0.0075	0.0102	0.6407	0.459	49.8	96.2	32.87	0.10
70	5.321	0.0090	0.4642	1.810	0.602	1.1	90.6	33.086	0.087
85	5.495	0.0122	0.0665	2.264	0.218	7.7	87.9	33.13	0.22
# 05	7.033	0.0045	0.1715	7.483	0.038	3.0	68.7	33.2	1.3
# 97	5.463	0.0434	0.0442	1.408	0.216	11.5	92.5	34.63	0.25
# 13	5.106	0.0104	0.0137	0.1341	0.598	37.1	99.2	34.736	0.077
# 71	5.234	0.0092	0.0134	0.1406	0.960	38.1	99.2	35.595	0.051
# 49	21.70	0.0288	0.0229	53.62	0.182	22.2	27.0	40.13	0.49
# 90	11.75	0.0071	0.4204	2.856	0.318	1.2	93.1	74.26	0.19
Mean age ± 2σ			n = 12	MSWD = 2.60				32.73	0.08
Dubose 3: sample GC#2, sanidine, J = 0.0038331 ± 0.02%, IC = 1.025988 ± 0.001529, NM-279A, Lab# 63951									
27	5.273	0.0127	-0.0111	0.6423	0.205	-	96.4	35.26	0.15
20	5.100	0.0117	0.0010	0.0577	0.479	495.4	99.7	35.269	0.064
15	5.332	0.0204	0.0002	0.8394	0.140	2499.8	95.3	35.27	0.23
07	5.101	0.0117	0.0109	0.0391	0.519	46.9	99.8	35.319	0.061
28	5.113	0.0122	0.0139	0.0787	0.463	36.8	99.6	35.321	0.065
31	5.116	0.0121	0.0062	0.0822	0.459	82.2	99.5	35.328	0.067
30	5.108	0.0120	0.0094	0.0522	0.779	54.5	99.7	35.337	0.040
25	5.116	0.0122	0.0129	0.0773	0.515	39.7	99.6	35.340	0.063
19	5.112	0.0121	0.0176	0.0479	0.300	29.0	99.7	35.377	0.095
01	5.126	0.0117	0.0150	0.0868	0.468	33.9	99.5	35.397	0.068
09	5.118	0.0121	0.0122	0.0490	0.528	41.7	99.7	35.414	0.057
13	5.105	0.0119	0.0171	0.0044	0.680	29.8	100.0	35.421	0.045
33	5.157	0.0118	0.0226	0.1745	0.282	22.6	99.0	35.431	0.092
32	5.135	0.0134	0.0127	0.0853	0.195	40.1	99.5	35.46	0.16
08	5.124	0.0115	0.0073	0.0354	0.389	69.8	99.8	35.478	0.081
23	5.517	0.0127	0.0231	1.367	0.234	22.1	92.7	35.48	0.14
24	5.134	0.0124	0.0125	0.0683	0.366	40.7	99.6	35.486	0.089
18	5.156	0.0117	0.0175	0.0476	0.243	29.2	99.8	35.68	0.12
# 14	5.418	0.0127	0.0087	0.0996	0.616	59.0	99.5	37.374	0.052
Mean age ± 2σ			n = 18	MSWD = 1.14				35.38	0.04
Helms pit: sample GC#3, sanidine, J = 0.0038336 ± 0.02%, IC = 1.028611 ± 0.002036, NM-279A, Lab# 63961									
27	5.156	0.0122	0.0280	0.2779	0.161	18.2	98.4	35.22	0.22
03	5.152	0.0122	-0.0057	0.1148	0.220	-	99.3	35.53	0.15
01	5.154	0.0120	0.0225	0.1244	0.481	22.7	99.3	35.545	0.069
28	5.309	0.0106	-0.0334	0.6049	0.066	-	96.6	35.58	0.54
05	5.149	0.0120	0.0223	0.0830	0.454	22.9	99.6	35.594	0.074
07	5.144	0.0118	0.0337	0.0649	0.548	15.2	99.7	35.604	0.062
06	5.137	0.0125	0.0176	0.0361	0.745	28.9	99.8	35.609	0.045

(continued)

TABLE 2. ARGON ISOTOPE DATA OF DATED SAMPLES (continued)

Grain ID	⁴⁰ Ar/ ³⁹ Ar	³⁸ Ar/ ³⁹ Ar	³⁷ Ar/ ³⁹ Ar	³⁶ Ar/ ³⁹ Ar (x 10 ⁻³)	³⁹ Ar _K (x 10 ⁻¹⁵ mol)	K/Ca	⁴⁰ Ar* (%)	Age (Ma)	±1σ (Ma)
Helms pit: sample GC#3, sanidine, J = 0.0038336 ± 0.02%, IC = 1.028611 ± 0.002036, NM-279A, Lab# 63961 (continued)									
14	5.147	0.0108	-0.0007	0.0639	0.204	-	99.6	35.61	0.16
25	5.413	0.0107	0.0448	0.9513	0.109	11.4	94.9	35.63	0.30
19	5.145	0.0114	0.0232	0.0369	0.210	22.0	99.8	35.66	0.15
16	5.152	0.0120	0.0228	0.0561	0.340	22.4	99.7	35.675	0.097
04	5.168	0.0115	0.0237	0.1072	0.478	21.5	99.4	35.679	0.071
09	5.151	0.0117	0.0174	0.0316	0.585	29.4	99.8	35.715	0.056
10	5.151	0.0118	0.0191	0.0146	0.472	26.7	99.9	35.749	0.068
12	5.167	0.0117	0.0251	0.0695	0.434	20.3	99.6	35.753	0.074
17	5.159	0.0109	0.0154	0.0291	0.258	33.2	99.9	35.77	0.13
15	5.157	0.0118	0.0251	0.0264	0.331	20.4	99.9	35.771	0.100
18	5.155	0.0109	0.0052	-0.0229	0.242	98.7	100.1	35.84	0.13
21	5.205	0.0110	0.0229	0.1440	0.317	22.3	99.2	35.86	0.10
24	5.295	0.0094	0.0099	0.4087	0.099	51.5	97.7	35.90	0.32
11	5.183	0.0111	0.0575	0.0585	0.217	8.9	99.8	35.90	0.14
# 20	6.141	0.0126	0.0102	3.234	0.139	49.8	84.4	36.01	0.24
# 29	5.279	0.0113	0.0549	0.2753	0.102	9.3	98.5	36.09	0.35
# 22	5.228	0.0156	-0.0213	0.0675	0.091	-	99.6	36.12	0.36
# 21	5.288	0.0090	-0.0397	0.2348	0.081	-	98.6	36.18	0.41
# 30	6.218	0.0130	0.0429	3.367	0.118	11.9	84.0	36.26	0.32
# 23	5.321	0.0105	0.0125	0.2240	0.103	40.7	98.8	36.46	0.30
# 26	5.440	0.0130	0.0333	0.6290	0.107	15.3	96.6	36.47	0.32
# 13	5.336	0.0110	0.0908	0.0855	0.158	5.6	99.7	36.92	0.20
Mean age ± 2σ			n = 21	MSWD = 1.29				35.671	0.045
Johnson South: sample GC#4, sanidine, J = 0.003836 ± 0.01%, IC = 1.028611 ± 0.002036, NM-279A, Lab# 63960									
16	5.150	0.0109	0.0153	0.1020	0.246	33.3	99.4	35.56	0.13
14	5.146	0.0125	0.0174	0.0412	0.529	29.4	99.8	35.655	0.061
04	5.147	0.0121	0.0096	0.0176	0.609	52.9	99.9	35.702	0.053
08	5.162	0.0118	0.0188	0.0457	0.388	27.1	99.8	35.752	0.086
13	5.163	0.0122	0.0596	0.0542	0.265	8.6	99.8	35.77	0.12
03	5.159	0.0119	0.0133	0.0257	0.556	38.3	99.9	35.772	0.059
Mean age ± 2σ			n = 6	MSWD = 0.79				35.711	0.059
Smiley: sample GC#5, sanidine, J = 0.0038323 ± 0.02%, IC = 1.028611 ± 0.002036, NM-279A, Lab# 63962									
06	5.008	0.0109	0.0092	0.1866	0.280	55.5	98.9	34.42	0.11
11	4.998	0.0107	0.0166	0.1487	0.231	30.6	99.1	34.43	0.14
# 09	5.176	0.0127	0.0217	0.1417	0.319	23.5	99.2	35.67	0.10
# 12	8.620	0.0183	31.38	12.35	0.084	0.016	87.0	53.0	1.6
# 13	200.2	0.0136	0.0376	2.135	0.462	13.6	99.7	1039.7	5.7
Mean age ± 2σ			n = 2	MSWD = 0.00				34.42	0.17
Lang Creek road: sample JR#2, sanidine, J = 0.0038322 ± 0.02%, IC = 1.028611 ± 0.002036, NM-279A, Lab# 63954									
15	4.675	0.0120	0.0133	0.0385	1.509	38.4	99.8	32.380	0.023
14	4.688	0.0121	0.0215	0.0651	0.717	23.7	99.6	32.418	0.046
07	4.681	0.0120	0.0443	0.0485	0.657	11.5	99.8	32.418	0.048
10	4.685	0.0120	0.0101	0.0383	0.816	50.7	99.8	32.447	0.038
11	4.686	0.0122	0.0290	0.0440	0.665	17.6	99.8	32.451	0.048
05	4.688	0.0124	0.0406	0.0512	0.668	12.6	99.7	32.459	0.047
04	4.686	0.0119	0.0225	0.0299	1.672	22.7	99.8	32.473	0.020
19	4.697	0.0118	0.0054	0.0621	1.600	93.7	99.6	32.473	0.022
09	4.702	0.0121	0.0314	0.0888	0.928	16.2	99.5	32.473	0.035

(continued)

TABLE 2. ARGON ISOTOPE DATA OF DATED SAMPLES (continued)

Grain ID	⁴⁰ Ar/ ³⁹ Ar	³⁸ Ar/ ³⁹ Ar	³⁷ Ar/ ³⁹ Ar	³⁶ Ar/ ³⁹ Ar (x 10 ⁻³)	³⁹ Ar _K (x 10 ⁻¹⁵ mol)	K/Ca	⁴⁰ Ar* (%)	Age (Ma)	±1σ (Ma)
Lang Creek road: sample JR#2, sanidine, J = 0.0038322 ± 0.02%, IC = 1.028611 ± 0.002036, NM-279A, Lab# 63954 (continued)									
16	4.691	0.0121	0.0256	0.0339	1.423	19.9	99.8	32.501	0.024
08	4.814	0.0125	0.0149	0.4466	0.596	34.3	97.3	32.503	0.056
18	4.707	0.0120	0.0095	0.0579	0.225	53.6	99.7	32.55	0.15
02	4.704	0.0122	0.0388	0.0565	0.770	13.1	99.7	32.554	0.041
03	4.706	0.0123	0.0370	0.0460	0.417	13.8	99.8	32.587	0.073
Mean age ± 2σ			n = 14		MSWD = 2.13			32.463	0.028
Lang Creek base: sample JR#4, sanidine, J = 0.0038348 ± 0.01%, IC = 1.028611 ± 0.002036, NM-279A, Lab# 63959									
# 03	4.692	0.0150	0.0090	0.5027	0.497	56.4	96.8	31.565	0.072
14	4.734	0.0120	0.0321	0.2221	1.500	15.9	98.7	32.442	0.023
18	4.753	0.0120	0.0136	0.2762	0.597	37.5	98.3	32.450	0.051
08	4.691	0.0119	0.0293	0.0533	0.602	17.4	99.7	32.490	0.057
04	4.700	0.0119	0.0328	0.0775	0.800	15.5	99.6	32.502	0.044
02	5.019	0.0128	0.0443	1.156	1.198	11.5	93.3	32.514	0.038
05	4.791	0.0121	0.0394	0.3685	0.356	13.0	97.8	32.54	0.10
17	4.711	0.0119	0.0259	0.0779	0.295	19.7	99.6	32.572	0.098
07	4.784	0.0114	0.0171	0.3225	0.199	29.8	98.0	32.57	0.17
12	4.714	0.0114	0.0196	0.0705	0.474	26.1	99.6	32.605	0.067
# 16	4.748	0.0119	0.0219	0.1483	0.952	23.3	99.1	32.682	0.035
# 11	4.739	0.0120	0.0264	0.1191	0.234	19.3	99.3	32.69	0.14
# 15	4.738	0.0121	0.0164	0.0959	0.426	31.2	99.4	32.722	0.074
# 10	4.849	0.0117	0.0031	0.2638	0.800	165.5	98.4	33.131	0.044
# 01	4.896	0.0122	0.0189	0.2512	0.067	27.0	98.5	33.49	0.53
# 09	5.537	0.0104	0.0521	0.3613	0.187	9.8	98.1	37.70	0.18
# 13	5.808	0.0119	0.0118	0.2795	1.482	43.2	98.6	39.706	0.025
# 06	6.606	0.0117	0.0092	0.0623	0.568	55.6	99.7	45.615	0.067
Mean age ± 2σ			n = 9		MSWD = 1.15			32.481	0.034
Stoeltje: sample K#2, sanidine, J = 0.0038325 ± 0.02%, IC = 1.028611 ± 0.002036, NM-279A, Lab# 63952									
02	4.987	0.0126	0.0195	0.3114	0.162	26.2	98.2	33.98	0.20
03	4.964	0.0115	0.0065	0.1729	0.302	79.0	99.0	34.09	0.11
05	5.242	0.0116	0.0171	1.118	0.252	29.8	93.7	34.09	0.14
24	5.249	0.0128	-0.0253	1.120	0.074	—	93.6	34.11	0.42
17	4.980	0.0109	-0.0031	0.2141	0.259	—	98.7	34.12	0.12
22	4.998	0.0117	0.0029	0.2590	0.161	175.5	98.5	34.15	0.20
01	5.249	0.0116	0.0226	1.106	0.219	22.6	93.8	34.17	0.16
09	4.980	0.0126	-0.0240	0.1692	0.267	—	99.0	34.19	0.11
07	4.946	0.0118	0.0172	0.0461	0.389	29.6	99.8	34.234	0.081
16	4.963	0.0126	0.0255	0.1045	0.212	20.0	99.4	34.24	0.15
10	4.992	0.0115	-0.0033	0.1895	0.193	—	98.9	34.25	0.16
11	5.040	0.0119	0.0144	0.3208	0.537	35.6	98.1	34.321	0.060
13	5.111	0.0110	0.0030	0.5537	0.138	169.6	96.8	34.33	0.22
06	4.973	0.0115	0.0066	0.0749	0.435	77.6	99.6	34.351	0.072
# 14	5.178	0.0118	-0.0016	0.6008	0.371	—	96.6	34.695	0.086
# 20	5.396	0.0109	0.0042	1.245	0.125	122.3	93.2	34.88	0.26
# 21	5.271	0.0119	0.2072	0.6128	0.080	2.5	96.9	35.43	0.40
# 08	6.626	0.0114	0.0016	0.1023	0.304	312.4	99.5	45.64	0.11
# 25	14.52	0.0265	0.0310	7.679	0.093	16.5	84.4	84.0	2.8
# 12	110.4	0.0137	0.0339	0.5214	0.394	15.0	99.9	645.2	3.7
Mean age ± 2σ			n = 14		MSWD = 0.83			34.240	0.061

(continued)

TABLE 2. ARGON ISOTOPE DATA OF DATED SAMPLES (continued)

Grain ID	⁴⁰ Ar/ ³⁹ Ar	³⁸ Ar/ ³⁹ Ar	³⁷ Ar/ ³⁹ Ar	³⁶ Ar/ ³⁹ Ar (x 10 ⁻³)	³⁹ Ar _K (x 10 ⁻¹⁵ mol)	K/Ca	⁴⁰ Ar* (%)	Age (Ma)	±1σ (Ma)
Plum: sample MD#1, sanidine, J = 0.0038342 ± 0.02%, IC = 1.028611 ± 0.002036, NM-279A, Lab# 63953									
# 11	5.208	0.0110	-0.0453	0.4280	0.087	—	97.5	35.22	0.36
24*	5.144	0.0117	0.0038	0.0619	0.817	134.1	99.6	35.575	0.042
05	5.160	0.0118	0.0056	0.0681	0.399	91.8	99.6	35.652	0.076
10	5.164	0.0117	0.0140	0.0670	0.464	36.3	99.6	35.687	0.070
14	5.151	0.0117	0.0106	0.0203	0.577	48.3	99.9	35.690	0.057
09	5.197	0.0125	0.0211	0.1100	0.350	24.2	99.4	35.830	0.091
16	5.188	0.0119	0.0398	0.0831	0.182	12.8	99.6	35.83	0.17
13	5.197	0.0110	0.0494	0.0967	0.278	10.3	99.5	35.87	0.12
19	5.239	0.0122	0.0103	0.2096	0.294	49.5	98.8	35.91	0.10
# 01	5.197	0.0112	0.0189	0.0370	0.464	27.0	99.8	35.975	0.069
# 15	5.205	0.0121	0.0340	0.0699	0.661	15.0	99.7	35.976	0.049
# 12	5.214	0.0122	0.0143	0.0707	0.652	35.7	99.6	36.024	0.052
# 26*	5.216	0.0125	0.0282	0.0826	0.352	18.1	99.6	36.041	0.097
# 27*	5.230	0.0115	0.0516	0.1026	0.197	9.9	99.5	36.11	0.18
# 04	5.244	0.0120	0.0243	0.1125	0.591	21.0	99.4	36.151	0.055
# 36*	5.232	0.0118	0.0142	0.0664	0.307	35.8	99.6	36.18	0.12
# 18	5.232	0.0122	0.0313	0.0164	0.299	16.3	100.0	36.27	0.10
# 08	5.325	0.0100	0.0254	0.3242	0.144	20.1	98.2	36.28	0.22
# 33*	5.247	0.0123	0.0051	0.0403	0.166	99.5	99.8	36.32	0.22
# 03	5.351	0.0121	0.0057	0.0501	0.570	89.9	99.7	37.001	0.056
# 31*	5.393	0.0114	0.0239	0.0226	0.405	21.3	99.9	37.377	0.092
# 28*	5.472	0.0114	0.0243	0.2207	0.357	21.0	98.8	37.52	0.10
# 25*	5.449	0.0116	0.0302	0.1304	0.148	16.9	99.3	37.55	0.24
# 32*	5.493	0.0117	0.0318	0.2611	0.287	16.0	98.6	37.59	0.13
# 17	5.457	0.0119	-0.0013	0.0757	0.458	—	99.6	37.673	0.069
# 22*	5.447	0.0131	-0.0041	0.0160	0.265	—	99.9	37.75	0.12
# 23*	5.463	0.0120	0.0412	0.0338	0.209	12.4	99.9	37.84	0.16
# 30*	5.485	0.0147	0.0415	0.0560	0.086	12.3	99.8	37.95	0.42
# 20	5.574	0.0140	0.0246	0.2754	0.120	20.7	98.6	38.09	0.26
# 21*	5.620	0.0110	0.0202	0.3647	0.177	25.3	98.1	38.24	0.18
# 34*	5.552	0.0127	0.0271	0.1113	0.169	18.8	99.4	38.29	0.22
# 29*	5.954	0.0124	0.0312	-0.0065	0.274	16.4	100.1	41.30	0.14
# 06	6.679	0.0117	-0.0034	0.1777	0.326	—	99.2	45.84	0.10
# 35*	265.8	0.0123	0.0435	0.0228	0.354	11.7	100.0	1286.3	5.4
Mean age ± 2σ			n = 8		MSWD = 2.53			35.679	0.081
Lopez pit: sample RG#1, sanidine, J = 0.0038328 ± 0.02%, IC = 1.0259881 ± 0.001529, NM-279A, Lab# 63956									
10	3.958	0.0116	0.0099	0.0515	0.749	51.7	99.6	27.402	0.042
06	3.969	0.0122	0.0013	0.0810	0.592	402.3	99.4	27.413	0.049
23	4.079	0.0118	0.0055	0.4470	0.466	92.0	96.8	27.428	0.067
22	4.235	0.0192	0.0247	0.9201	0.185	20.7	93.6	27.55	0.16
15	4.015	0.0125	0.0151	0.1411	0.446	33.7	99.0	27.617	0.066
11	4.044	0.0126	0.0406	0.2357	0.122	12.6	98.4	27.64	0.24
# 13	4.131	0.0125	0.0326	0.4810	0.304	15.7	96.6	27.740	0.097
# 14	4.035	0.0126	0.0108	0.1349	0.416	47.2	99.0	27.767	0.068
# 20	4.120	0.0118	0.0069	0.2646	0.320	73.5	98.1	28.086	0.087
# 21	4.212	0.0124	0.0331	0.4848	0.153	15.4	96.7	28.29	0.19
# 02	5.432	0.0128	0.0334	4.475	0.142	15.3	75.7	28.57	0.25
# 08	4.216	0.0120	0.0102	0.3179	0.639	50.1	97.8	28.647	0.046

(continued)

TABLE 2. ARGON ISOTOPE DATA OF DATED SAMPLES (continued)

Grain ID	⁴⁰ Ar/ ³⁹ Ar	³⁸ Ar/ ³⁹ Ar	³⁷ Ar/ ³⁹ Ar	³⁶ Ar/ ³⁹ Ar (x 10 ⁻³)	³⁹ Ar _K (x 10 ⁻¹⁵ mol)	K/Ca	⁴⁰ Ar* (%)	Age (Ma)	±1σ (Ma)
Lopez pit: sample RG#1, sanidine, J = 0.0038328 ± 0.02%, IC = 1.0259881 ± 0.001529, NM-279A, Lab# 63956 (continued)									
# 24	4.301	0.0120	-0.0051	0.5134	0.197	—	96.5	28.82	0.16
# 18	4.399	0.0155	0.0073	0.4441	0.068	70.2	97.0	29.65	0.46
# 04	4.597	0.0125	0.0250	0.4138	0.527	20.4	97.4	31.087	0.060
# 19	4.872	0.0132	0.0079	0.2680	0.522	64.6	98.4	33.27	0.16
# 07	5.121	0.0122	-0.0024	0.1381	0.596	—	99.2	35.243	0.050
# 09	46.26	0.0119	0.0171	0.8486	0.636	29.8	99.5	297.25	0.74
Mean age ± 2σ			n = 6	MSWD = 1.90				27.449	0.072
Tampico Road: sample RG#2, sanidine, J = 0.0038332 ± 0.02%, IC = 1.0259881 ± 0.001529, NM-279A, Lab# 63957									
11	3.904	0.0128	0.0413	0.4649	0.375	12.4	96.6	26.211	0.081
07	3.798	0.0116	-0.0012	0.0554	0.837	—	99.6	26.287	0.035
19	3.892	0.0119	0.0171	0.3674	0.485	29.9	97.2	26.311	0.063
05	3.910	0.0130	0.0132	0.4224	0.221	38.6	96.8	26.32	0.14
14	4.593	0.0667	0.0112	2.722	0.105	45.4	82.5	26.36	0.29
02	3.844	0.0123	0.0907	0.1724	0.746	5.6	98.9	26.419	0.040
16	4.124	0.0126	0.0242	1.079	0.290	21.1	92.3	26.46	0.11
10	3.833	0.0117	0.0134	0.0757	0.430	38.0	99.4	26.494	0.067
06	3.849	0.0120	0.0069	0.1244	1.443	73.7	99.1	26.500	0.021
01	3.833	0.0121	0.0125	0.0538	2.086	40.8	99.6	26.542	0.015
22	4.041	0.0120	-0.0005	0.7467	0.233	—	94.5	26.56	0.14
# 04	3.958	0.0122	0.0094	0.2361	1.422	54.5	98.3	27.034	0.024
# 13	3.992	0.0111	0.0002	0.2050	0.323	3112.9	98.5	27.32	0.10
# 21	3.974	0.0115	0.0174	0.1198	0.605	29.3	99.1	27.386	0.051
# 09	4.503	0.0121	0.0778	1.848	0.328	6.6	88.0	27.55	0.10
# 18	4.995	0.0129	0.0279	3.481	0.212	18.3	79.4	27.58	0.16
# 17	26.34	0.0222	0.2391	75.48	0.074	2.1	15.4	28.22	0.82
# 08	4.236	0.0120	0.0136	0.5856	0.380	37.5	95.9	28.242	0.083
# 03	6.150	0.0140	0.1533	7.055	0.203	3.3	66.3	28.34	0.20
# 15	4.773	0.0118	0.0500	0.1404	0.256	10.2	99.2	32.88	0.12
# 12	5.031	0.0192	0.0124	0.5041	0.643	41.0	97.1	33.893	0.056
Mean age ± 2σ			n = 11	MSWD = 7.15				26.49	0.06
Dubose 2 sample: J = 0.0078727 ± 0.01%, IC = 1.030347 ± 0.0011211, NM-265C, Lab# 62698									
02	2.503	0.0146	-0.0011	0.1239	0.369	—	98.5	35.10	0.13
24	2.492	0.0108	0.0175	0.0851	1.874	29.2	99.0	35.121	0.030
05	2.498	0.0119	0.0179	0.1043	1.724	28.5	98.8	35.124	0.033
20	2.492	0.0124	0.0112	0.0830	2.654	45.7	99.0	35.130	0.023
08	2.491	0.0116	0.0061	0.0772	2.243	84.3	99.1	35.134	0.026
18	2.504	0.0104	0.0055	0.1198	2.204	92.8	98.6	35.140	0.029
15	2.493	0.0119	0.0066	0.0779	3.965	77.6	99.1	35.162	0.017
01	2.502	0.0109	0.0041	0.1054	1.070	123.1	98.8	35.168	0.051
12	2.519	0.0124	0.0079	0.1609	6.039	64.2	98.1	35.177	0.015
25	2.503	0.0111	0.0047	0.1074	1.137	107.8	98.7	35.177	0.046
11	2.506	0.0116	0.0087	0.1147	1.604	58.5	98.7	35.185	0.036
10	2.491	0.0114	0.0072	0.0612	3.040	70.7	99.3	35.203	0.021
23	2.492	0.0120	0.0099	0.0619	3.737	51.6	99.3	35.206	0.018
28	2.521	0.0121	0.0084	0.1552	2.948	60.5	98.2	35.224	0.023
03	2.497	0.0107	0.0079	0.0750	3.136	64.6	99.1	35.228	0.019
27	2.508	0.0098	0.0162	0.1104	1.247	31.6	98.7	35.234	0.043
19	2.522	0.0101	0.0069	0.1550	0.951	73.7	98.2	35.237	0.057

(continued)

TABLE 2. ARGON ISOTOPE DATA OF DATED SAMPLES (*continued*)

Grain ID	$^{40}\text{Ar}/^{39}\text{Ar}$	$^{38}\text{Ar}/^{39}\text{Ar}$	$^{37}\text{Ar}/^{39}\text{Ar}$	$^{36}\text{Ar}/^{39}\text{Ar}$ ($\times 10^{-3}$)	$^{39}\text{Ar}_K$ ($\times 10^{-15}$ mol)	K/Ca	$^{40}\text{Ar}^*$ (%)	Age (Ma)	$\pm 1\sigma$ (Ma)
Dubose 2 sample: $J = 0.0078727 \pm 0.01\%$, $IC = 1.030347 \pm 0.0011211$, NM-265C, Lab# 62698 (<i>continued</i>)									
16	2.496	0.0116	0.0093	0.0684	3.629	54.7	99.2	35.237	0.018
17	2.513	0.0127	0.0070	0.1246	2.085	72.5	98.6	35.246	0.029
06	2.526	0.0114	0.0055	0.1641	0.792	92.5	98.1	35.257	0.066
13	2.524	0.0098	0.0114	0.1541	1.321	44.7	98.2	35.281	0.044
# 29	2.503	0.0120	0.0081	0.0812	2.427	63.3	99.1	35.288	0.024
# 26	2.497	0.0109	0.0066	0.0566	1.932	77.8	99.3	35.293	0.028
# 04	2.564	0.0127	0.0083	0.2847	1.017	61.2	96.7	35.296	0.058
# 22	2.527	0.0119	0.0072	0.1543	1.761	71.0	98.2	35.310	0.034
# 09	2.535	0.0123	0.0440	0.1742	1.026	11.6	98.1	35.390	0.054
# 07	2.606	0.0108	0.0082	0.3936	1.710	62.0	95.5	35.438	0.042
# 21	2.572	0.0070	0.0046	0.2733	0.415	111.3	96.9	35.45	0.12
# 14	2.892	0.0114	0.0044	0.9394	0.891	116.6	90.4	37.189	0.083
Mean age $\pm 2\sigma$			$n = 21$	MSWD = 2.66				35.190	0.020

Notes: Single-grain dates are shown at 1σ (68%) confidence, whereas sample dates ("mean age") are reported at 2σ (95%) confidence. Isotopic ratios are corrected for blank, radioactive decay, and mass discrimination, and not corrected for interfering reactions. Errors quoted for individual analyses include analytical error only, without interfering reaction or J uncertainties (measure of uncertainty). Mean age is the weighted mean age. Mean age error is the weighted error of the mean, multiplied by the root of the mean squared weighted deviates (MSWD) where $MSWD > 1$, and also incorporates uncertainty in J factors and irradiation correction uncertainties. Isotopic abundances are after Steiger and Jäger (1977). Dash—no data. # symbol preceding sample ID denotes analyses excluded from mean age calculations. $^{39}\text{Ar}_K$ — ^{39}Ar produced from irradiation of ^{39}K . $^{40}\text{Ar}^*$ —radiogenic ^{40}Ar . Negative $^{37}\text{Ar}/^{39}\text{Ar}$ ratio—no detectable ^{37}Ar above background values. IC—detector calibration, which is measured $^{40}\text{Ar}/^{39}\text{Ar}$ divided by 295.5. NM—irradiation identifier; Lab#—laboratory identifier. Ages are calculated relative to FC-2 Fish Canyon Tuff sanidine interlaboratory standard at 28.201 Ma. Decay constant [λ_K (total)] = $5.463 \times 10^{-10}/\text{a}$.

Correction factors (all irradiations): ($^{39}\text{Ar}/^{37}\text{Ar}$)_{Ca} = 0.000653 ± 0.0000038 ; ($^{36}\text{Ar}/^{37}\text{Ar}$)_{Ca} = 0.0002633 ± 0.00000049 ; ($^{40}\text{Ar}/^{39}\text{Ar}$)_K = 0.007529 ± 0.000237 . _{Ca}—isotopes produced from irradiation of calcium; _K—isotopes produced from irradiation of potassium.

Zircon phenocrysts were acquired from the heavy mineral fraction during heavy liquid separation done to concentrate sanidine for $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Zircons of the South Somerville and Upper Alabama Ferry (Little Brazos) samples obtained from the same aliquot that yielded sanidine phenocrysts sent to New Mexico Tech for $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Zircons of the Helms and Johnson South samples were obtained from splits of the samples used for $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Zircon U-Pb analyses were conducted by ID-TIMS in the R. Ken Williams '45 Radiogenic Isotope Geosciences Laboratory at Texas A&M University. Detailed analytical methods are provided in the Supplemental Document (footnote 1). Most analyses were conducted on relatively large single grains, but, in an attempt to minimize the potential for age biasing by populations of differing grain sizes, aliquots of two to four very small grains were also analyzed.

RESULTS

New $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb dates are presented (Figs. 2–4; Tables 2–3) for groups of volcanic ash beds exposed in Gonzales, Karnes, Live Oak, and Starr Counties. All new Eocene samples come from quarry exposures, and all Oligocene Catahoula Group samples come from outcrop exposures. Samples from Gonzales County were acquired from active bentonite quarries, and samples

from Karnes County are from inactive uranium mining pits, whereas Live Oak and Starr County samples are from outcrop exposures. The volcanic ash samples collected in Karnes County can be related to the late Eocene stratigraphy of Eargle et al. (1975), and the Gueydan Formation (Catahoula Group) volcanic ashes are placed in the stratigraphy reported by McBride et al. (1968). Dating of bentonite samples in Gonzales County revealed some conflict with geologic mapping (Proctor et al., 1974), and sample locations are placed on a modified map base (Fig. 5) showing a revised boundary between the Yegua Formation and Jackson Group map units.

A composite stratigraphic section is used for south Texas (Fig. 2), showing formations that can be reasonably identified in that area. The commonly used Caddell and Wellborn Formation names are excluded from this stratigraphic diagram because those two formations are not lithologically distinct from other upper Eocene formations in the area and cannot be reliably identified. Radiometric dating reveals conflict with previous geologic mapping in Gonzales County. Conflicting use of formation names commonly used in reports on upper Eocene strata in Texas show that most of the formation and member names proposed for parts of the upper Eocene section have utility only in a restricted geographic area close to their type sections. When used for geologic mapping, these units are mapped by attempting to laterally trace erosion-resistant sandstone beds that are lithologically similar to beds lower or higher in the

TABLE 3. U-Pb ISOTOPIC DATA

Sample†	Spike	n	Compositional parameters								Radiogenic isotope ratios								Isotopic ages					
			U	Th	Pb	²⁰⁶ Pb*	²⁰⁶ Pb*	Pb*	Pb _c	²⁰⁶ Pb	²⁰⁸ Pb	²⁰⁷ Pb	Error	²⁰⁷ Pb	Error	²⁰⁶ Pb	Error	Corr.	²⁰⁷ Pb	²⁰⁷ Pb	²⁰⁶ Pb	²⁰⁶ Pb	²⁰⁶ Pb	
			(ng)§	U†	(pg)§	(× 10 ⁻¹³ mol)††	(mol%)††	Pb _c ††	(pg)††	²⁰⁴ Pb§§	²⁰⁶ Pb††	²⁰⁶ Pb††	(%)†††	²³⁵ U††	(%)†††	²³⁸ U††	(%)†††	coef.††	²⁰⁶ Pb†††	±§§§	²³⁵ U†††	±§§§	²³⁸ U†††	±§§§
South Somerville																								
(Z10) SSomerville zirc10	TAMU-1	1	2.85	0.697	17.8	0.6281	97.57	12.8	1.29	745	0.224	0.046613	1.533	0.034068	1.888	0.005301	0.886	0.597	29.42	36.72	34.02	0.63	34.08	0.30
(Z11) SSomerville zirc11	TAMU-1	1	2.13	0.576	12.6	0.4711	98.30	17.9	0.67	1067	0.185	0.046757	1.376	0.034292	1.677	0.005319	0.765	0.586	36.85	32.90	34.24	0.56	34.20	0.26
(Z12) SSomerville zirc12	TAMU-1	1	3.66	0.765	24.2	0.8074	96.19	8.2	2.63	475	0.246	0.046733	1.346	0.034197	1.511	0.005307	0.285	0.643	35.61	32.18	34.14	0.51	34.12	0.10
(Z14) SSomerville zirc14	TAMU-1	1	3.79	0.671	25.3	0.8307	94.77	5.7	3.77	346	0.211	0.045800	2.110	0.033250	3.411	0.005265	2.556	0.787	-12.87	50.93	33.21	1.11	33.85	0.86
(Z50) SSomerville zirc1	TAMU-1	1	3.23	0.716	22.0	0.7136	94.35	5.3	3.52	320	0.212	0.042994	4.120	0.031465	4.392	0.005308	0.570	0.528	-167.97	102.45	31.46	1.36	34.13	0.19
(Z51) SSomerville zirc2	TAMU-1	1	2.00	0.586	13.5	0.4425	94.45	5.3	2.14	326	0.192	0.047651	3.090	0.034998	3.264	0.005327	0.480	0.427	82.00	73.26	34.93	1.12	34.25	0.16
(Z52) SSomerville zirc3	TAMU-1	1	3.41	0.694	21.5	0.7581	97.53	12.6	1.58	732	0.225	0.047191	0.813	0.034765	1.391	0.005343	1.030	0.815	58.91	19.36	34.70	0.47	34.35	0.35
(Z53) SSomerville zirc4	TAMU-1	1	2.37	0.621	16.0	0.5210	94.37	5.3	2.56	322	0.204	0.047723	1.765	0.034784	2.093	0.005286	0.863	0.556	85.57	41.82	34.72	0.71	33.99	0.29
(Z56) SSomerville zirc7	TAMU-1	1	3.53	0.567	27.0	0.7803	89.99	2.8	7.19	180	0.183	0.046875	4.329	0.034339	4.696	0.005313	1.120	0.434	42.87	103.38	34.28	1.58	34.16	0.38
(Z58) SSomerville zirc9	TAMU-1	1	0.97	0.640	9.6	0.2127	81.52	1.4	3.97	98	0.233	0.052887	14.105	0.038528	14.839	0.005284	1.550	0.514	323.96	320.00	38.39	5.59	33.97	0.52
(Z59) SSomerville zirc6	TAMU-1	1	4.33	1.381	37.1	0.9573	91.29	3.9	7.57	207	0.447	0.047034	3.659	0.034397	3.942	0.005304	0.750	0.459	50.93	87.27	34.34	1.33	34.10	0.25
Upper Alabama Ferry (at Little Brazos)																								
(Z2) Little Brazos	TAMU-1	1	1.14	0.860	9.2	0.3108	97.08	11.0	0.77	620	0.274	0.046447	1.946	0.041794	2.090	0.006526	0.375	0.462	20.89	46.67	41.57	0.85	41.93	0.16
(Z3) Little Brazos	TAMU-1	1	1.87	0.870	14.4	0.5061	98.55	22.6	0.61	1249	0.277	0.046506	0.815	0.041718	0.947	0.006506	0.295	0.571	23.94	19.53	41.50	0.38	41.80	0.12
(Z4) Little Brazos	TAMU-1	1	1.60	0.964	12.7	0.4323	98.25	19.0	0.63	1034	0.306	0.046313	0.782	0.041533	0.932	0.006504	0.221	0.745	13.96	18.77	41.32	0.38	41.79	0.09
(Z5) Little Brazos	TAMU-1	1	1.47	0.807	18.2	0.3990	81.65	1.5	7.39	99	0.270	0.048860	5.690	0.043820	5.991	0.006505	0.430	0.719	141.12	133.45	43.55	2.55	41.80	0.18
(Z52) Little Brazos	TAMU-1	2	1.67	0.965	13.9	0.4527	96.70	9.9	1.27	548	0.308	0.046548	1.325	0.041830	1.500	0.006518	0.381	0.559	26.08	31.76	41.61	0.61	41.88	0.16
(Z53) Little Brazos	TAMU-1	3	9.15	0.649	64.7	2.4718	99.66	92.7	0.69	5351	0.208	0.046803	0.382	0.041887	0.881	0.006491	0.746	0.903	39.18	9.14	41.67	0.36	41.71	0.31
(Z55) Little Brazos	TAMU-1	3	7.49	0.862	56.8	2.0293	99.25	43.8	1.27	2404	0.278	0.046994	0.379	0.042168	1.508	0.006508	1.424	0.968	48.90	9.04	41.94	0.62	41.82	0.59
(Z6) Little Brazos	TAMU-1	1	1.07	0.946	13.0	0.2895	83.05	1.7	4.87	107	0.312	0.048139	5.684	0.043169	6.011	0.006504	0.712	0.506	106.09	134.20	42.91	2.53	41.79	0.30
(Z7) Little Brazos	TAMU-1	4	2.29	0.861	17.9	0.6205	98.18	17.9	0.95	992	0.279	0.047341	1.351	0.042437	1.508	0.006501	0.559	0.451	66.49	32.13	42.20	0.62	41.77	0.23
(Z8) Little Brazos	TAMU-1	2	4.01	0.713	29.6	1.0900	98.90	28.7	1.00	1650	0.226	0.046154	0.616	0.041508	1.054	0.006523	0.779	0.815	5.68	14.83	41.30	0.43	41.91	0.32
(Z9) Little Brazos	TAMU-1	4	2.87	1.143	23.2	0.7769	99.03	36.1	0.63	1868	0.362	0.046174	0.510	0.041354	0.765	0.006496	0.463	0.762	6.71	12.27	41.14	0.31	41.74	0.19
Helms																								
(Z31) Basal Helms zirc6	ET535	1	0.25	0.992	3.5	0.0578	71.00	0.9	1.91	64	0.319	0.044191	11.080	0.033596	11.581	0.005514	0.970	0.546	-100.02	271.94	33.55	3.82	35.45	0.34
(Z34) Basal Helms zirc8	ET535	3	0.75	1.037	7.0	0.1729	86.88	2.3	2.11	142	0.333	0.046787	3.858	0.035659	4.096	0.005528	0.301	0.807	38.37	92.22	35.58	1.43	35.54	0.11
(Z35) Basal Helms zirc9	ET535	1	0.50	0.986	5.0	0.1153	84.44	1.9	1.72	120	0.317	0.046338	5.201	0.035248	5.482	0.005517	0.459	0.639	15.25	124.86	35.17	1.90	35.47	0.16
(Z65) Basal Helms zirc1	TAMU-1	1	0.48	0.729	5.0	0.1103	81.10	1.4	2.08	99	0.234	0.047369	6.543	0.035985	6.883	0.005510	0.480	0.725	67.86	155.55	35.90	2.43	35.42	0.17
(Z67) Basal Helms zirc2	TAMU-1	1	0.42	1.038	5.0	0.0963	77.53	1.2	2.26	83	0.334	0.044523	9.066	0.033826	9.498	0.005510	0.554	0.789	-81.69	221.72	33.78	3.16	35.42	0.20
(Z68) Basal Helms zirc3	TAMU-1	1	0.44	0.915	4.2	0.1005	85.32	2.0	1.40	127	0.294	0.047064	5.073	0.035855	5.354	0.005525	0.431	0.676	52.46	120.94	35.77	1.88	35.52	0.15
(Z69) Basal Helms zirc4	TAMU-1	1	0.86	0.900	7.1	0.1987	90.95	3.4	1.60	206	0.289	0.046680	2.626	0.035678	2.800	0.005543	0.276	0.664	32.87	62.83	35.60	0.98	35.64	0.10
(Z70) Basal Helms zirc5	TAMU-1	1	0.55	0.912	5.0	0.1270	87.19	2.3	1.51	146	0.293	0.046899	3.886	0.035672	4.119	0.005517	0.403	0.611	44.09	92.79	35.59	1.44	35.46	0.14
(Z71) Basal Helms zirc6	TAMU-1	1	0.42	0.941	4.4	0.0958	82.10	1.6	1.69	104	0.302	0.046316	7.128	0.035286	7.493	0.005526	0.599	0.633	14.09	171.18	35.21	2.59	35.52	0.21
(Z82) Basal Helms zirc2	ET535	1	0.37	0.990	3.1	0.0860	91.36	3.7	0.66	216	0.318	0.046330	3.060	0.035219	3.245	0.005513	0.236	0.803	14.85	73.48	35.15	1.12	35.44	0.08
(Z83) Basal Helms zirc3	ET535	1	0.42	1.007	5.2	0.0968	75.88	1.1	2.49	77	0.324	0.047322	9.209	0.036063	9.639	0.005527	0.450	0.955	65.49	219.02	35.97	3.41	35.53	0.16
(Z84) Basal Helms zirc4	ET535	1	1.36	0.799	10.1	0.3132	93.64	4.9	1.72	294	0.257	0.041876	2.830	0.031843	2.963	0.005515	0.334	0.448	-234.01	71.29	31.83	0.93	35.45	0.12
(Z89) Basal Helms zirc9	ET535	1	0.66	0.979	5.0	0.1517	94.27	5.7	0.75	326	0.315	0.046522	2.058	0.035361	2.243	0.005513	0.196	0.959	24.76	49.32	35.28	0.78	35.44	0.07

(continued)

section. Consequently, geologic mapping cannot extend the Caddell and Well-born Formations far along the outcrop belt without using closely spaced drilling work (e.g., Eargle et al., 1975) to determine position of beds buried beneath alluvium fill of large river valleys. This type of control is not available in most areas. Dating of volcanic ash beds can provide the age control needed to correlate strata that otherwise cannot be traced with confidence along the outcrop belt.

■ SIZE OF SANIDINE PHENOCRYSTS IN DISTAL VOLCANIC ASH BEDS

Data on maximum grain size and cross-section area of sanidine phenocrysts in the volcanic ash beds are presented in Table 4. Recent work on dating detrital sanidine in sedimentary rocks (e.g., Hereford et al., 2016; Karlstrom et al., 2016;

TABLE 3. U-Pb ISOTOPIC DATA (*continued*)

Sample†	Spike	n	Compositional parameters							Radiogenic isotope ratios							Isotopic ages							
			U (ng)§	Th U¶	Pb (pg)§	²⁰⁶ Pb* (× 10 ⁻¹³ mol)††	²⁰⁶ Pb* (mol%)††	Pb* Pb _c ††	Pb _c (pg)††	²⁰⁶ Pb ²⁰⁴ Pb§§	²⁰⁸ Pb ²⁰⁶ Pb##	²⁰⁷ Pb ²⁰⁶ Pb##	Error (%)†††	²⁰⁷ Pb ²³⁵ U##	Error (%)†††	²⁰⁶ Pb ²³⁸ U##	Error (%)†††	Corr. coef.##	²⁰⁷ Pb ²⁰⁶ Pb†††	±§§§	²⁰⁷ Pb ²³⁵ U†††	±§§§	²⁰⁶ Pb ²³⁸ U†††	±§§§
Johnson South																								
(Z44) Basal HW Johnson zirc2	TAMU-1	1	0.29	1.067	6.2	0.0673	56.43	0.5	4.23	43	0.343	0.050519	17.024	0.038326	17.644	0.005502	1.004	0.633	218.96	393.57	38.19	6.61	35.37	0.35
(Z45) Basal HW Johnson zirc3	TAMU-1	2	0.55	0.995	6.4	0.1270	78.35	1.3	2.85	86	0.320	0.048528	6.524	0.036979	6.887	0.005527	0.639	0.599	125.06	153.45	36.87	2.49	35.53	0.23
(Z48) Basal HW Johnson zirc5	TAMU-1	1	0.56	0.974	5.3	0.1287	85.80	2.1	1.72	131	0.313	0.046672	4.738	0.035458	5.010	0.005510	0.405	0.694	32.47	113.38	35.38	1.74	35.42	0.14
(Z49) Basal HW Johnson zirc2	ET535	1	0.51	0.756	4.8	0.1177	85.26	1.9	1.65	127	0.243	0.045194	5.445	0.034240	5.706	0.005495	0.328	0.809	-45.21	132.24	34.19	1.92	35.33	0.12
(Z50) Basal HW Johnson zirc3	ET535	1	0.34	1.032	6.3	0.0773	60.69	0.5	4.08	47	0.332	0.048930	11.900	0.037119	12.369	0.005502	0.877	0.559	144.46	278.89	37.01	4.50	35.37	0.31
(Z52) Basal HW Johnson zirc4	ET535	1	0.42	1.025	3.7	0.0971	89.34	2.9	0.94	175	0.329	0.045228	4.146	0.034363	4.361	0.005510	0.436	0.533	-43.37	100.64	34.31	1.47	35.42	0.15
(Z53) Basal HW Johnson zirc5	ET535	1	0.70	0.921	6.2	0.1615	88.20	2.6	1.75	158	0.296	0.045848	3.413	0.034834	3.626	0.005510	0.261	0.834	-10.38	82.33	34.77	1.24	35.42	0.09
(Z56) Basal HW Johnson zirc7	ET535	1	0.26	0.959	2.9	0.0598	79.30	1.3	1.26	90	0.308	0.045582	8.458	0.034544	8.847	0.005496	0.875	0.483	-24.43	204.59	34.48	3.00	35.33	0.31
(Z57) Basal HW Johnson zirc8	ET535	1	0.23	1.077	3.2	0.0530	72.01	0.9	1.67	67	0.346	0.046560	20.228	0.035251	20.609	0.005491	0.917	0.433	26.74	484.58	35.18	7.13	35.30	0.32
(Z58) Basal HW Johnson zirc9	ET535	1	0.54	0.914	5.4	0.1231	83.36	1.7	1.99	112	0.294	0.045263	5.994	0.034247	6.302	0.005488	0.454	0.698	-41.48	145.45	34.19	2.12	35.28	0.16
(Z78) Basal HW Johnson zirc7	ET535	2	0.72	0.937	6.7	0.1638	86.26	2.2	2.11	136	0.301	0.046047	3.908	0.034916	4.140	0.005499	0.262	0.898	0.09	94.09	34.85	1.42	35.35	0.09
(Z79) Basal HW Johnson zirc8	ET535	1	0.41	0.870	3.2	0.0930	92.11	3.9	0.64	237	0.280	0.045612	3.069	0.034538	3.237	0.005492	0.271	0.649	-22.84	74.21	34.48	1.10	35.31	0.10

[†]Z1, Z2, etc. are internal laboratory labels for fractions composed of single-zircon-grain aliquots; all fractions were annealed and chemically abraded, after Mattinson (2005).

[§]U and total Pb content of zircon remnants after chemical abrasion.

[¶]Model Th/U ratio calculated from radiogenic ²⁰⁸Pb/²⁰⁶Pb ratio and ²⁰⁷Pb/²³⁵U age.

^{††}Pb* and Pb_c represent radiogenic and common Pb, respectively; ²⁰⁶Pb* (mol%) is with respect to radiogenic, blank, and initial common Pb.

^{§§}Measured ratio corrected for spike and fractionation only. Daly Pb analyses are corrected for 0.22%/AMU mass bias based on repeat analysis of reference material NBS-981. Faraday U analyses are corrected for mass bias based on measured ²³³U/²³⁵U ratio.

^{##}Corrected for fractionation, spike, and common Pb; up to 1 pg of common Pb was assumed to be procedural blank: ²⁰⁶Pb/²⁰⁴Pb = 18.66 ± 0.60%; ²⁰⁷Pb/²⁰⁴Pb = 15.54 ± 0.25%; ²⁰⁸Pb/²⁰⁴Pb = 37.62 ± 0.55% (all uncertainties 1σ). Excess over blank was assigned to initial common Pb.

^{†††}Calculated ages are based on the decay constants of Jaffey et al. (1971).

^{§§§}Errors are 2σ, propagated using the algorithms of Schmitz and Schoene (2007) and Crowley et al. (2007).

Note: Analyses excluded from age calculations due to a xenocrystic component, Pb loss, or imprecision are given in Supplemental Table S1 (see text footnote 1). Spike column indicates analyses conducted with either the EarthTime U-Pb tracer solution (ET535) or the in-house U-Pb tracer solution (TAMU-1). *n*—number of zircon grains in analysis. Negative ²⁰⁷Pb/²⁰⁶Pb dates indicate analyses that are adversely affected by inaccurate assumptions in either the common Pb isotope values or in the mass bias correction.

Repasch et al., 2017) is proving to be a valuable tool for determining high-precision maximum depositional ages. Furthermore, these precise detrital crystal ages can often allow individual grains to be linked to caldera sources. Using detrital grain ages for provenance in paleogeographic reconstructions, including river drainage patterns, requires consideration of long-distance airborne travel of tephra, as reported by Sarna-Wojcicki et al. (1981), Walker (1981), and Bonadonna and Houghton (2005). Data presented by Sarna-Wojcicki et al. (1981) show that tephra particle size decreases exponentially with distance, with rapid decrease in particle size in proximal areas and much lower rate of decrease in distal areas. Grain geometry and size also have a significant control on dispersal. It is generally thought that most coarse (i.e., 200–500 μm) sanidine and zircon crystals fall out of the eruptive column within several tens of kilometers (Rose et al., 2003), whereas finer crystals (<100 μm) may travel a couple of hundred kilometers (Matthews et al., 2012). However, some studies have invoked long airborne transport distances of volcanically sourced detrital zircons and sanidine (Fan et al., 2015; Aslan et al., 2018). As shown by our work here, large (~500 μm) sanidines can be transported in the ash column for hundreds of kilometers from their source calderas. All volcanic ash samples dated here are from distal portions of ash beds, and most contain a similar range of tephra particle size.

The coastal plains tephra deposits can be utilized to determine the extent to which coarse material can be transported in the ash plume, as these deposits are ash fall units. Phenocrysts can be reliably separated from other ash components in bentonites, where the glass is altered to clay. In these occurrences, the basal layer contains the coarsest phenocrysts and provides data on the maximum size of phenocrysts carried by the ash plume. Samples of 3–5 kg weight yield sanidine grains up to 150–200 μm in size in deposits of the Eocene–Oligocene volcanic ash beds from east Texas, at sites a minimum of 650 (Brazos County) to 800 km (Houston County) distant from the nearest eruptive center in west Texas. None of the dated ash beds match dates of calderas in the Trans-Pecos area of Texas or the San Juan (Colorado) or Mogollon-Datil (New Mexico) volcanic fields. The major eruptive center of explosive volcanic activity is in northern Mexico, located 300 km west of Texas (McDowell and McIntosh, 2012; Ferrari et al., 2017). More distal deposits of volcanic ash in northern Louisiana (McGuire et al., 2010) contain zircon phenocrysts up to 100 μm in size.

The largest glass shards and phenocrysts occur in the South Somerville ash exposed in Washington County of the Brazos River Valley (Heintz et al., 2015). This ash contains bubble-wall glass shards to 800 μm maximum diam-

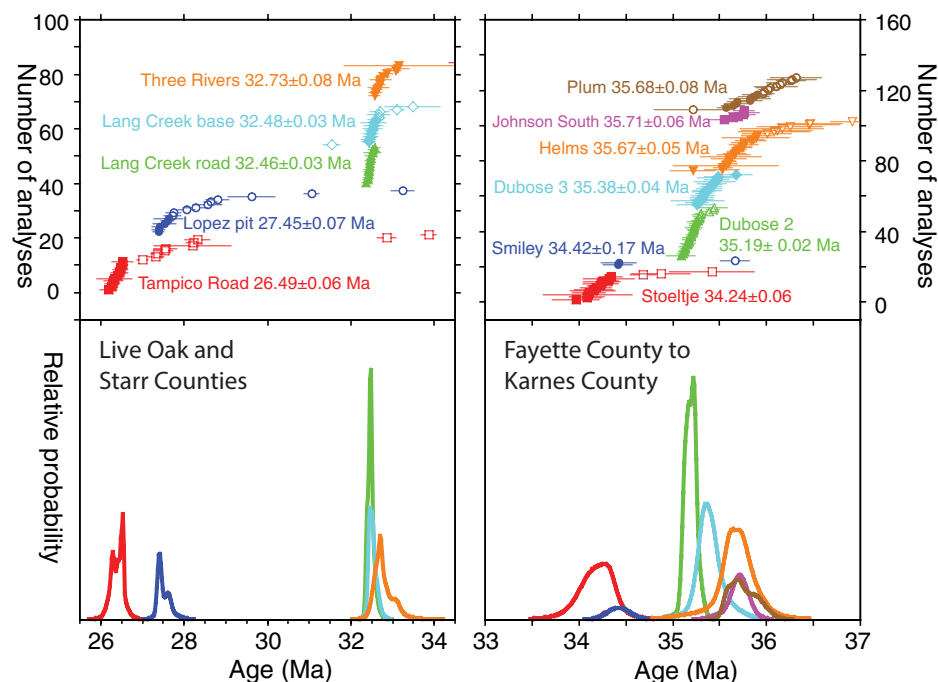


Figure 3. Summary of new $^{40}\text{Ar}/^{39}\text{Ar}$ dates showing grain populations in dated volcanic ashes. Grains shown as filled dots are used to calculate the dates; open dots are excluded from calculations. All dates shown are reported at 95% uncertainty level.

eter and sanidine grains to $>528\ \mu\text{m}$ maximum axis dimension in a sample of 96 sanidine measured grains (Fig. 6; Table 4). Back-scattered electron element mapping in phenocrysts by microprobe analysis reveals that sanidine is the dominant feldspar mineral and occurs with accessory quartz and plagioclase (Fig. 6A). Minute glass inclusions are present in many grains (Fig. 7), an indication of early, rapid crystallization from the source magma.

These crystal sizes are unexpectedly coarse for distal deposits when compared with compilations of volcanic ash dispersal (Sarna-Wojcicki et al., 1981; Walker, 1981; Bonadonna and Houghton, 2005). The South Somerville ash in east Texas is 650 km distant from the closest silicic eruptive center in the Trans-Pecos area, but the Trans-Pecos does not have a known caldera of the same age ($34.10 \pm 0.02\ \text{Ma}$) as the South Somerville ash deposit (Heintz et al., 2015). However, the date is coeval with a major episode of silicic magmatic activity in the northern Sierra Madre Occidental (McDowell and McIntosh, 2012; Ferrari et al., 2017). The South Somerville ash also has correspondingly larger pumice clasts, the largest with length of 1–2 mm. Pumice clasts in distal volcanic ash beds usually have larger dimensions than the bubble-wall glass shards. Phenocrysts from the base of the bentonite beds in the Gonzales County bentonite district include some sanidine grains of 150–200 μm diameter, deposited 550 km distant from the closest eruptive center in the Trans-Pecos area.

$^{40}\text{Ar}/^{39}\text{Ar}$ –U–Pb PAIRED DATES

Samples of four volcanic ash samples were dated by single-crystal methods on co-occurring sanidine and zircon phenocrysts (Fig. 4). The goal of this dating was to evaluate the accuracy of dating with these minerals from the same ash bed and to explore the potential for systematic interlaboratory bias of the type described by Schoene et al. (2006). The expectation was that sanidine dating would provide slightly younger dates than zircon dating, because zircon in these eruptive systems demonstrate nonzero magma residence time and zircon U–Pb dates are commonly slightly older than known eruptive ages or sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ ages (e. g., Schoene et al., 2006; Deering et al., 2016). This difference highlights the potential for small biases due to sample selection, possibly coupled with differing intermethod dating procedures.

This study shows that $^{40}\text{Ar}/^{39}\text{Ar}$ sanidine and U–Pb zircon dating of phenocrysts both provide high-resolution dating of Paleogene volcanic ash. The U–Pb dates are slightly less precise than the $^{40}\text{Ar}/^{39}\text{Ar}$ dates, with uncertainties in the range of ± 0.05 – $0.06\ \text{Ma}$ or 0.1%–0.2%. At this level of resolution, the accuracy of some zircon ages may depend on factors not yet resolved. However, for the purposes of correlation and stratigraphic control described here, the equivalence is close enough to justify use of either dating method to produce high-resolution geochronology for volcanic ash, even in samples containing altered feldspars.

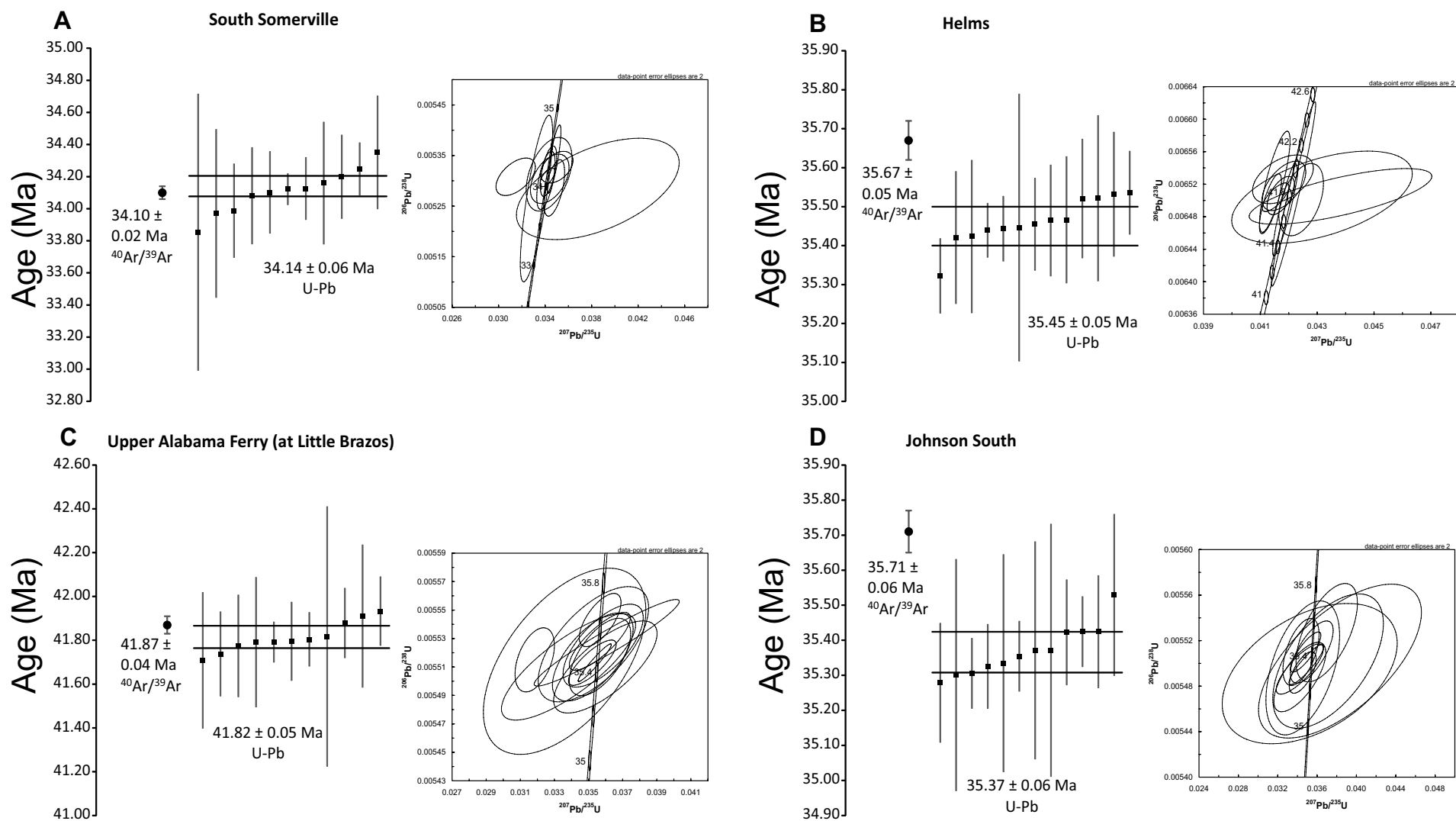


Figure 4. Paired $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb dates for selected Eocene volcanic ash samples in Texas. Paired $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb dates for selected Eocene volcanic ash samples in Texas. Black dots are $^{40}\text{Ar}/^{39}\text{Ar}$ dates and squares are $^{206}\text{Pb}/^{238}\text{U}$ dates (2σ error bars) for individual analyses deemed to be unaffected by Pb-loss or xenocrystic inheritance (Table 2). Black lines are 2σ error limits for the weighted mean of $^{206}\text{Pb}/^{238}\text{U}$ dates. Insets are U-Pb concordia diagrams.

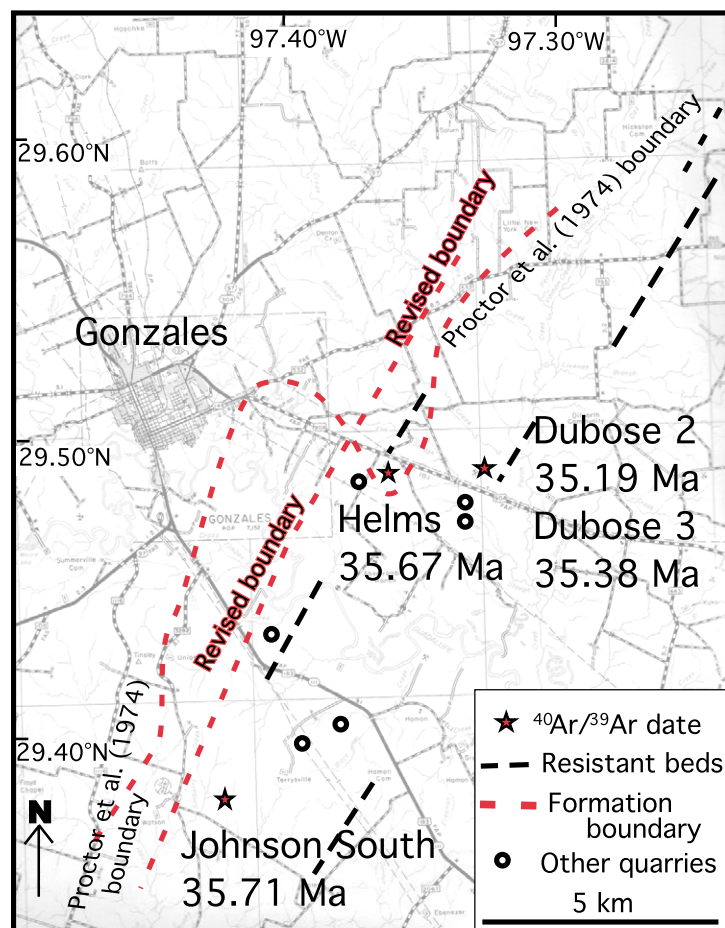


Figure 5. Radiometric dating placement of the Yegua Formation–Jackson Group boundary compared to the boundary shown on the Geologic Atlas of Texas, Seguin sheet (Proctor et al., 1974) in the bentonite district of Gonzales County, Texas.

DISCUSSION

The radiometric dates on 18 volcanic ash or bentonite beds from the Texas coastal plains range from 41.84 ± 0.016 Ma to 26.49 ± 0.06 Ma (compiled from dating in south Texas [Fig. 2] and dating in east Texas [Heintz et al., 2015]). Two additional analyses are excluded as they did not yield a reliable young subpopulation of ages, likely related to extensive reworking. Heintz et al. (2015) used bulk ash, glass, and apatite compositions to infer an arc-type volcanic source region within the Sierra Madre Occidental volcanic field of western Mexico

for volcanic ash in the Texas coastal plains and adjacent states. The main part of that source area is 1000 km distant from the east Texas part of the Gulf of Mexico coastal plains. Coastal plains Texas volcanic ash and bentonites have composition and geochemical data similar to those of rocks of the ignimbrite flareup (McDowell and Clabaugh, 1979) of the Sierra Madre Occidental, which show pulses of silicic magmatism activity (Ferrari et al., 1999, 2017; Nieto-Samaniego et al., 1999; McDowell and McIntosh, 2012).

The south Texas dated samples correspond to expected stratigraphic order except for dates in the Gonzales bentonite district. Radiometric dating shows that the Johnson South and Helms samples, which are of similar age, are included in strata mapped (Proctor et al., 1974) as being within the top of the Manning Formation in the south part of the map area and within the top of the Yegua Formation to the north of the Guadalupe River (Fig. 4). This is a large difference in stratigraphic level if published mapping is accepted. Quarry exposures also reveal an unreported structural complication: strata in the Helms bentonite quarry have a reversed dip angle compared to strata from surrounding areas. The Gonzales bentonite district lies within the limits of the Balcones–Luling fault trend, with major faulting present at depth in Gonzales County (Tucker, 1967). Movement on Balcones–Luling faults remained active from 70 to 20 Ma (Jackson et al., 2011), but the effects of faulting have not previously been recognized in outcrop mapping. The combination of unreliable formation identification and unrecognized geologic structure is enough to account for the discrepancy found between geologic maps and radiometric dating control.

The new radiometric dates in south-central and south Texas confirm the expectation that volcanic ash beds extend across the state of Texas in the coastal plain outcrop belt and that volcanic eruptive events were episodic. The Plum, Helms, and Johnson South bentonite samples in Gonzales and Fayette Counties have the same date, within error, consistent with being part of the same volcanic ash bed. This date is very close to that of the Graham Road ash of Brazos County (Heintz et al., 2015), clustering together at ca. 35.7–35.8 Ma. Another group of volcanic ash beds, which includes the Conquista, Stoeltje, and Smiley ash beds of Karnes and Gonzales Counties (dates presented here) and the South Somerville, Tarball Quarry, and Gibbons Creek ash beds of Washington and Grimes Counties (Heintz et al., 2015), clusters together at ca. 34.1–34.5 Ma. Each cluster is likely to be from the same source cluster of vents, indicating distinct episodes of volcanic eruption during the Priabonian. The uppermost Eocene cluster of volcanic ash beds extends as far east as Mississippi, where seven bentonites occur in the upper part of the Yazoo Formation (Obradovich et al., 1993). Recognition of pulsing volcanism on a scale of several million years is reported by Ferrari et al. (1999, 2017), and McDowell and McIntosh (2012) reports 1–2 m.y. pulses of ignimbrite emplacement separated by lulls in activity of 1–5 m.y. Grouping of volcanic ash beds reported here occurs at intervals of ~1 m.y., and the groups were deposited during a time of major ignimbrite emplacement in the northern Sierra Madre Occidental volcanic field (McDowell and McIntosh, 2012; Ferrari et al., 2017). Regardless of whether pulses of ignimbrite emplacement coincide exactly with times of

TABLE 4. DIMENSIONS OF 96 SANIDINE GRAINS IN A SOUTH SOMERVILLE ASH GRAIN MOUNT

Area (μm^2)	Major axis length (μm)	Minor axis length (μm)	Area (μm^2)	Major axis length (μm)	Minor axis length (μm)	Area (μm^2)	Major axis length (μm)	Minor axis length (μm)
153,546	556	352	59,208	606	124	36,709	256	183
150,783	483	397	58,813	335	224	35,919	347	132
150,783	596	322	58,418	401	186	35,130	253	177
141,310	492	366	56,050	283	252	32,762	326	128
108,153	445	309	54,077	357	193	32,367	244	169
106,969	528	258	52,103	289	230	32,367	292	141
103,417	413	319	52,103	324	205	30,393	212	182
102,232	496	262	51,314	294	222	28,815	213	172
97,101	418	296	50,524	296	217	27,630	228	154
96,312	452	271	50,524	365	176	27,630	285	123
96,312	458	268	50,129	272	234	27,236	220	157
94,733	363	332	49,340	406	155	26,841	242	141
88,022	488	229	47,366	299	202	25,657	284	115
86,838	452	245	47,366	290	208	24,078	267	115
82,102	533	196	46,972	270	222	24,078	208	148
80,523	451	227	46,182	296	199	23,288	188	158
78,154	437	228	45,787	382	153	23,288	189	157
78,154	395	252	44,209	291	193	22,499	241	119
77,365	369	267	43,024	283	194	21,710	292	95
75,786	389	248	42,235	271	199	21,710	177	157
73,418	345	271	41,446	311	170	21,710	191	145
71,050	346	261	40,656	302	171	21,315	190	143
67,497	400	215	40,261	244	210	20,525	200	130
67,102	400	213	39,867	258	197	19,341	244	101
65,523	333	251	39,472	255	197	18,157	169	137
65,129	313	265	38,683	239	206	17,762	218	104
65,129	516	161	37,893	283	170	17,368	171	130
64,339	360	228	37,893	287	168	16,973	164	132
63,550	353	229	37,498	258	185	16,973	183	118
63,155	363	222	37,104	356	133	16,578	204	103
63,155	373	216	37,104	251	188	14,999	185	103
59,997	333	229	36,709	443	106	9868	134	93

Note: These numbers represent minimum sizes for all grains because they are measured on cross-sectioned grains embedded in epoxy, where the cross section may not be through the center of each grain.

major explosive eruption, variation in rates of eruptive action is observable in the coastal plains deposits and is a useful feature for characterizing eruption frequency in areas with many volcanic ash beds.

Another component of the dating work to pursue is the documentation of the chemistry of glass shards (e.g., Heintz et al., 2015), making tephrochronology a viable tool for correlating Texas Eocene and Oligocene tephra deposits with strata across the Gulf of Mexico region. The new radiometric dates provide numerical age control for the palynology biozones of the late Eocene in Texas (Elsik and Yancey, 2000), and make it possible to integrate the palynology biozones with the paleomagnetic time scale and with the cyclostratigraphy of the Brazos River Valley. There are no published paleomagnetic data for Texas strata of this age, but with a new chronostratigraphic framework, paleomagnetism becomes a valuable tool for dating Eocene–Oligocene episodes of climate change and sea-level change of this region.

■ OLIGOCENE GEOLOGIC HISTORY IN SOUTH TEXAS

The new dates reveal the presence of a thick interval of lower Oligocene strata in the outcrop belt of south Texas. Strata of the lower Gueydan Formation below the Soledad Member provide dates ranging from 32.73 ± 0.08 Ma to 32.46 ± 0.03 Ma, placing them within the lower Rupelian Stage. Brown and Loucks (2009) limited the Catahoula Group in Texas to the late Rupelian and Chattian Stages and concluded that lower Rupelian strata are absent from the outcrop belt across Texas, in line with previous interpretation of a major unconformity being present between the outcropping Jackson and Catahoula Groups (Galloway and Kaiser, 1980; Galloway et al., 1982). The unconformity concept is based on the lack of early Rupelian dates in typical Catahoula strata of the shallow subsurface and outcrop belt, a gap now filled by dates revealing lower Rupelian deposits within the Gueydan Formation.

Figure 6. Calibrated backscattered electron (BSE) images and elemental X-ray maps of grain mounts for South Somerville volcanic ash taken with a Cameca SX50 electron microprobe at Texas A&M University Geosciences Microprobe Laboratory. Intensity of gray in grains shown in panels B–D corresponds with relative composition percent of indicated element. (A) Composition map. (B) Potassium element map of grains. (C) Aluminum element map of grains. (D) Silicon element map of grains.

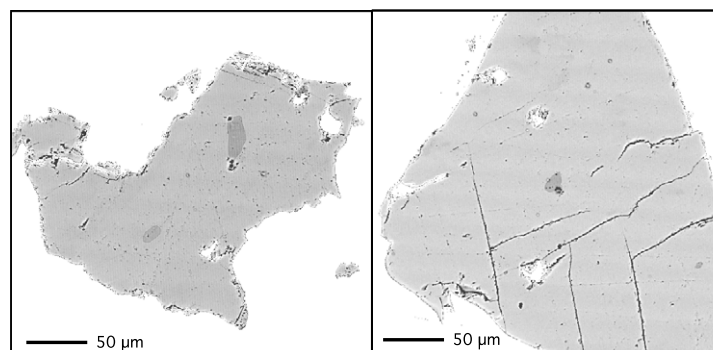
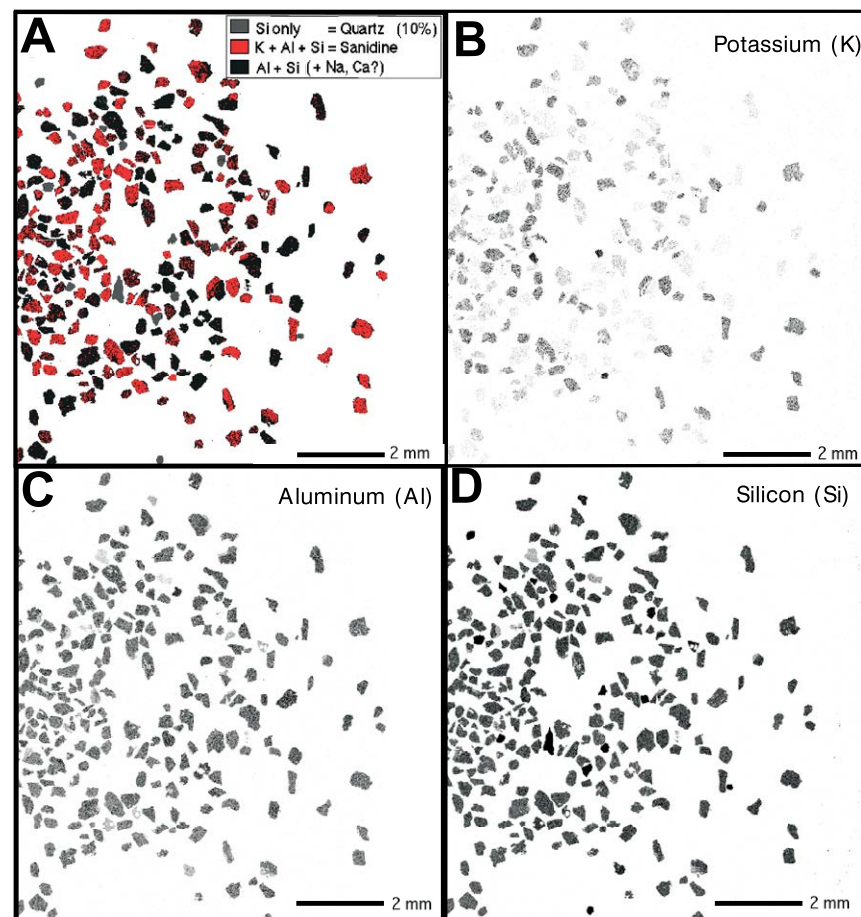


Figure 7. Backscattered electron images of sanidine grain mounts, with tiny inclusions of glass (dark gray blebs within light gray sanidine).

Field relations also fail to show evidence of a long-duration unconformity in south Texas. The lower Rupelian Gueydan Formation overlies the Frio Clay Formation (of Bailey [1926] and earlier work cited therein), a transitional unit between the upper Eocene Jackson Group and the Oligocene Gueydan Formation. In most places, the Frio Clay Formation has conformable upper and lower contacts or minor disconformable contact with the Gueydan Formation (Bailey, 1926). The Frio Clay Formation pinches out to the north and strata mapped as Catahoula overlie Jackson Group strata with disconformity, but a comparable disconformity is not present in east-central Texas where the uppermost Eocene volcanic ash (34.10 ± 0.02 Ma; Heintz et al., 2015) is conformable with strata mapped as Catahoula Formation (Deussen, 1924). A broad basal Oligocene disconformity is probably limited to the San Marcos uplift of central Texas and thus does not represent a regional event. At the end of the Eocene, there is a Texas-wide change from dominantly marine deposition to dominantly non-marine deposition. While a local disconformity is an expected feature of this type of environmental change, where radiometric dating is available there is no support for the concept of a statewide regional unconformity.

Instead of a time of erosion, the great thickness of Catahoula Group sediments (Gueyden and Frio Formations) in south Texas (Bailey, 1926) suggests that the high-standing Trans-Pecos volcanic field (Parker et al., 1988) and other highgrounds in the southern Rocky Mountains region built up a nonmarine depositional fan. The Oligocene was a time of resurgent uplift in the southern Rocky Mountains (Galloway et al., 2011; Mackey et al., 2012) and Colorado Plateau (Schulze et al., 2015), forming a western highland source area (Cather et al., 2008; Xu et al., 2017) and drainage system capable of delivering large amounts of sediment to the Gueydan Formation and feeding delta complexes of the subsurface Frio trend in south Texas (Bebout et al., 1978). This suggests that the conglomeratic sediment of the Soledad Member in the Gueydan Formation is a coarse layer that accumulated at the time of maximum buildup. This is a substantially different interpretation of early Oligocene geologic history than that based on presence of a regional basal Oligocene unconformity. Nonetheless, it is based on high-accuracy dating of volcanic ash beds that reveals the presence of a thick interval of strata deposited during the early Rupelian.

CONCLUSIONS

New radiometric dating of upper Eocene and Oligocene strata in south Texas provides many numerical dates for strata of the Gulf of Mexico coastal plains and places volcanic ash-bearing intervals into a numerical time scale tied to magnetostratigraphy. Volcanic ash occurs in Eocene–Oligocene strata as far east as Mississippi where they can be tied to marine microfossil biozonation. In Texas, the dating of units with established palynology biozonation and cyclostratigraphy provides a means of integrating lithostratigraphy with the numerical and magnetostratigraphy time scales. Clusters of radiometric dates at ca. 34.1–34.5 Ma and at ca. 35.7–35.8 Ma across the Texas coastal plains

indicate times of greater explosive volcanic eruptions and reveal increasing frequency of volcanic ash deposition during the late Eocene. The younger cluster of volcanic ash beds (ca. 34.1–34.5 Ma) extends eastward to Mississippi (Obradovich et al., 1993). Paired $^{40}\text{Ar}/^{39}\text{Ar}$ dating of sanidine and U–Pb dating of zircon shows that both methods produce comparable high-accuracy dates for Paleogene volcanic ash beds. Sanidine phenocryst grains as large as 528 μm in longest dimension occur in distal volcanic ash deposits as far as 650 km from the eruptive source, and grains as large as 150 μm diameter occur as far as 800 km from eruptive source. Dates of coastal plains volcanic ash beds do not match with dates of known calderas in the Trans-Pecos (west Texas), Mogollon-Datil (New Mexico), or San Juan (Colorado) volcanic fields of the United States, pointing to a source in the northern Sierra Madre Occidental in western Mexico.

Application of new dating improves correlation of strata, reveals unrecognized geologic structures, and makes possible testing of interpretations of geologic history. The presence of lower Rupelian strata in the outcrop belt of south Texas fills in a geologic history for a time interval previously unknown and considered to be missing across the state. Instead of a period of early Oligocene non-deposition, volcanic ash dating provides evidence for the buildup of a nonmarine depositional fan in south Texas. This knowledge greatly improves the accuracy of paleogeography, paleoclimatic reconstruction, and paleodrainage reconstructions for a time interval when Gulf Coast climates changed from warm and wet to seasonal dry (Yancey et al., 2003; Miller et al., 2009).

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