Southeastern extent of the North American craton in Texas and northern Chihuahua as revealed by Pb isotopes

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ABSTRACT

The geographic patterns of Pb isotopic compositions of Eocene to Miocene igneous rocks appear to delineate the southeastern edge of the North American Precambrian craton in Trans-Pecos Texas and northern Chihuahua, Mexico. The boundary parallels and lies southeast of the buried fault contact between Ouachita facies thrust sheets and Paleozoic cratonic sedimentary rocks. Lead isotopic data for basalts and granulite xenoliths suggests that the basalts contain a mixture of Pb from mantle and lower-crustal sources. On the northwest side of the boundary, this mixing involves 1.35 to 1.1 Ga cratonic lithosphere and yields linear arrays of $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$. Basaltic magmas on the southeast side of the boundary apparently interacted with more-radiogenic lithosphere accreted during the Ouachita orogeny. Basalts in a 50-km-wide central zone between the northwestern and southeastern provinces have Pb isotopic compositions that are intermediate between those of the northwestern and southeastern sources. In the northwestern province, lead isotopic compositions of intermediate to felsic rocks are less radiogenic than those of associated basalts, whereas in the southeast province they have more radiogenic compositions than the basalts. This isotopic divergence reflects assimilation of contrasting crust of each province.

Most felsic Tertiary rocks of the northwestern province have lower $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ and somewhat elevated $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, suggesting assimilation of relatively high Th/U Precambrian crust. The central province also contains low $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ Precambrian components, but few igneous rocks have elevated $^{208}Pb/^{204}Pb$. Southeastern-province crust appears dominantly Phanerozoic, although Precambrian basement with Pb isotopic compositions near model average crust may be present. The Pb isotopic zonation observed in West Texas is similar to that found in the Appalachians of the northern United States and Canada and in the Caledonides of Europe: that is, a progression from more-radiogenic outboard terranes to less-radiogenic inboard terranes.

Lead isotopic ratios from Tertiary igneous rocks of the northwestern part of Trans-Pecos Texas are similar to those of adjacent New Mexico and southeastern Arizona, although regional basement ages and isotopic characteristics differ. Extending the West Texas isotopic terranes to the southwest holds promise for testing and improving the understanding of the Sonora-Mojave megashear; Precambrian assembly of Gondwana; and correlation of Grenville-Caledonian terranes between the Appalachians, Texas, and eastern to southern Mexico.

INTRODUCTION

The Precambrian and Paleozoic history of the southern edge of the North American craton (Fig. 1) is obscured by a blanket of younger deposits. Therefore, the geologic history and geometry of the craton margin have been derived indirectly. The tectonic history of Precambrian events can be interpreted from the structural and igneous history of the Llano Uplift and scattered exposures of Precambrian rocks in West Texas (King and Flawn, 1953; Flawn, 1956; McGehee, 1979; Soegaard and others, 1991; Mosher, in press; Walker, 1992). The southern edge of the craton changed from a convergent margin to a passive margin following late Precambrian–early Paleozoic rifting and opening of the Iapetus Ocean (Thomas, 1991; Dalziel, 1991). The location of the late Paleozoic margin, and therefore the edge of the craton, can be inferred from the current position of the late Paleozoic Ouachita orogenic system (King, 1937; Flawn and others, 1961; Muehlberger and Tauvers, 1989; Nicholas and Waddell, 1989; Thomas, 1991). The Ouachita system is a sinuous belt of deformed eugeoclinal Paleozoic rocks emplaced against the buttress of the craton edge. It is exposed discontinuously and has been sampled in wells from Mississippi to Chihuahua, Mexico (Fig. 1). The Ouachita rocks may represent late Paleozoic terrane accretion as the South American plate impinged on the North American plate. The lack of a coeval magmatic arc north of the Ouachita belt indicates that the intervening ocean basin was subducted to the south (Wickham and others, 1976).

Understanding the extent and history of the southern craton margin is hampered by the scattered exposure of Precambrian rocks on the craton, the lack of nearby basement outcrops to the south, and the limited exposure of the Ouachita belt. Only 440 km of the fringing Ouachita belt's 2,100-km length is exposed. The Ouachita belt is generally considered to be a continuation of the complex, but better exposed. Appalachian orogen (Hatcher and others, 1989). Mesozoic and Tertiary events along the southern margin, including the opening of the Gulf of Mexico; movement on the Sonora-Mojave megashear (Silver and Anderson, 1974; Anderson and Schmidt, 1983); and Laramide thrusting, have further obscured geologic relationships.

The current position of the craton edge and the Ouachita front have been inferred from geophysical investigations (Keller and others, 1989a, 1989b, and references therein; Culotta and others, 1992). The sinuous gravity highs and lows that follow the edge of the Texas craton (Nicholas and Rozendal, 1975; Viele and Thomas, 1989; Keller and others, 1989b) can be traced on gravity anomaly maps into northern

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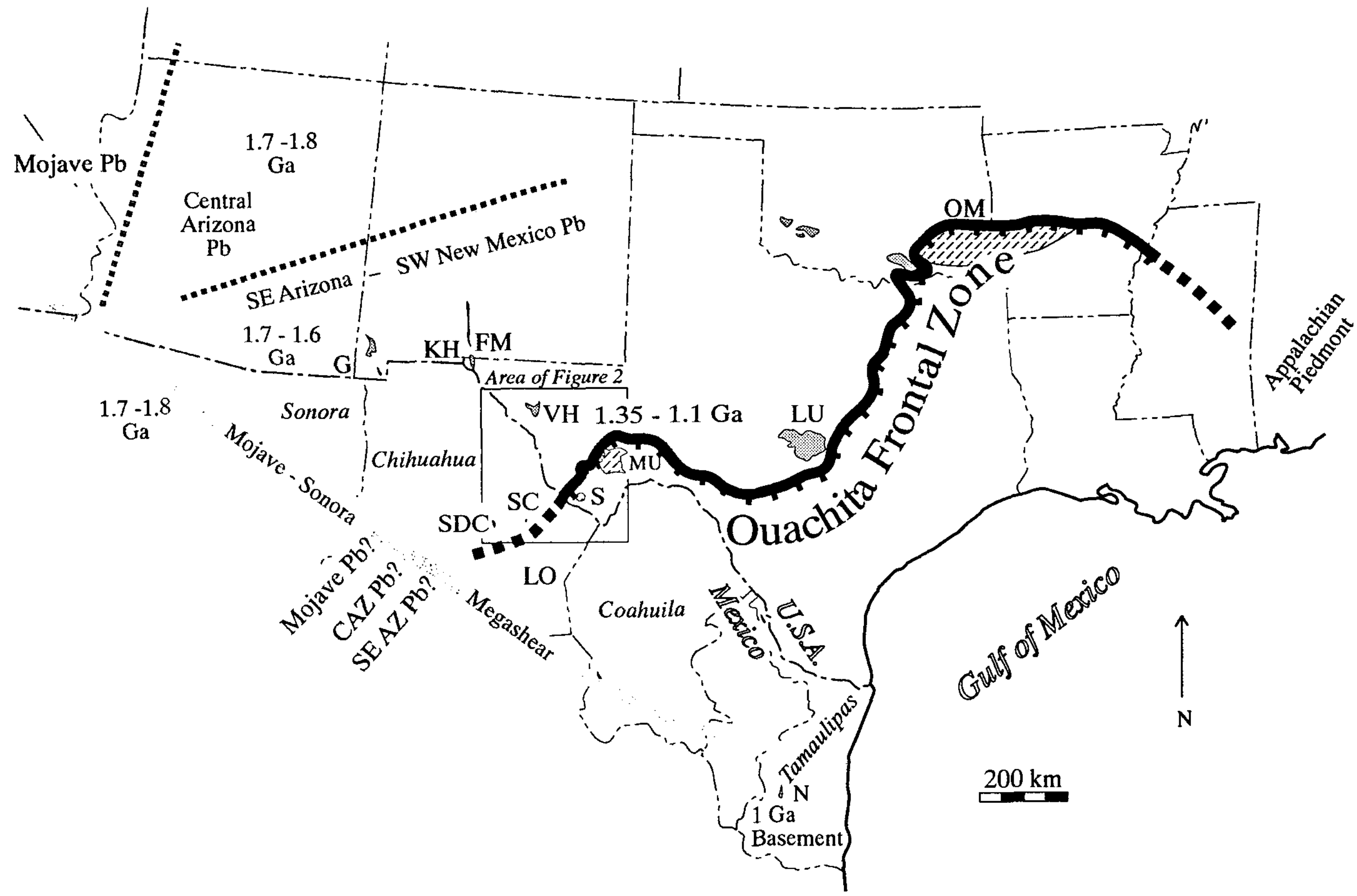

Figure 1. Selected tectonic features and outcrops of Precambrian rocks in the southern United States and northern Mexico. Lead isotopic provinces; Mojave Pb, central Arizona Pb, and southeast Arizona–southwest New Mexico Pb from Wooden and Miller (1990). Ouachita Frontal Zone after Flawn and others (1961) and Thomas and others (1989). Probable zone of Sonora-Mojave megashear after Anderson and Schmidt (1983) and McKee and others (1990). Basement age estimates from Anderson and Silver (1981) and Ruiz and others (1988). Precambrian outcrops: FM, Franklin Mountains; LU, Llano Uplift; N, Novillo gneiss near Ciudad Victoria; SC, Sierra Carrizolillo; SDC, Sierra del Cuervo; VH, Van Horn Mountains. Other locations: G, Geronimo volcanic field; KH, Kilbourne Hole; LO, La Olivina; MU, Marathon Uplift; OM, Ouachita Mountains; and S, Ouachita facies strata in the Solitario.

Mexico (Aiken and others, 1988). The exact position, however, of the Ouachita front and of the edge of the craton as determined by geophysical data is controversial (Nicholas and Rozendal, 1975; Ewing, 1985; Keller and others, 1989a, 1989b; Culotta and others, 1992). Although the gravity and magnetic data reflect the physical properties of the now-adjacent crustal blocks, they cannot indicate age or geochemical history.

Isotopic studies have proven useful in defining continental crustal provinces, particularly for delineating the extent and age of Precambrian terranes (Kistler and Peterman, 1973; Zartman, 1974; Everson, 1979; DePaolo, 1981; Bennett and DePaolo, 1987; Silver, 1987; Wooden and Miller, 1990). Even where basement rocks are not exposed, magmas commonly carry the isotopic signature of the underlying lithosphere to the surface (Leeman and others, 1992). We present Pb isotopic data for Eocene through Miocene igneous rocks (James and Henry, 1990) that indicate the southeastern extent of 1.35–1.1 Ga lithosphere in Trans-Pecos Texas and northern Chihuahua, Mexico, and define two isotopic provinces (Fig. 2). The boundary between these provinces marks the southeastern extent of cratonal basement rocks in southwest Texas and parallels the buried fault contact between Ouachita system thrust sheets and coeval strata deposited on the craton.

Pb Isotopic Evolution and Sources

Lead isotopic compositions provide a sensitive probe for delineating crustal provinces. Differences in Pb isotopic ratios between crustal terranes reflect the amount of time that parent isotopes (^{238}U, ^{235}U, and ^{232}Th) have contributed daughter products (^{206}Pb, ^{207}Pb, and ^{208}Pb) to the existing Pb in the rocks. The ratios are indicative of time-averaged U/Th/Pb ratios. The initial Pb isotopic composition of an igneous rock is inherited during partial melting in the mantle and crust. Subsequent additions of Pb to the magma by assimilation of country rock and mixing with other magmas may modify the isotopic ratios and concentrations. In continental igneous rocks, these additions can be a large percentage of the total Pb in the rock. Typical

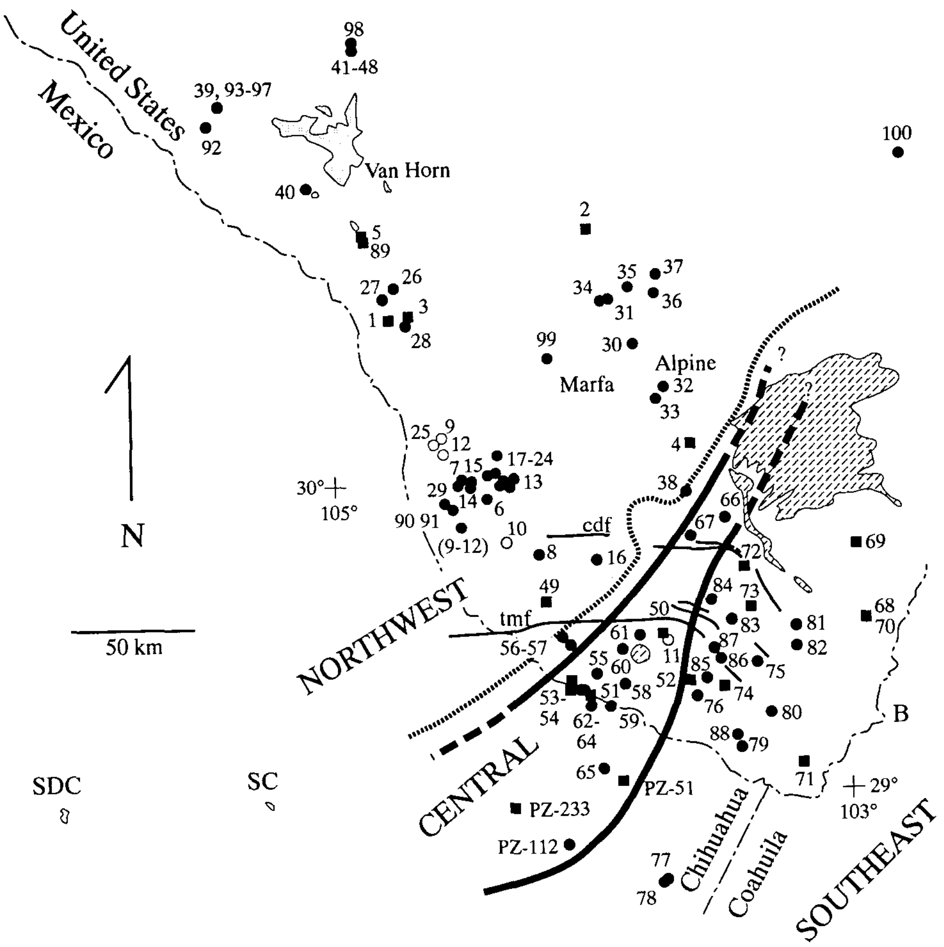

Figure 2. Sampling locations in Trans-Pecos Texas and adjacent Mexico. Outcrops of Precambrian rocks are shown by stippled pattern: SDC, Sierra del Cuervo; SC, Sierra Carrizolillo. Paleozoic Ouachita facies of the Marathon Uplift and Solitario are shown by diagonal dashed pattern. Outcrop of Ouachita inner-zone metamorphic rocks near Boquillas, Coahuila, at B. Sampling localities are keyed by sample number to Table A. Squares are mafic rocks with Mg# > 45; circles have Mg# < 45. Open circles represent collection sites of samples erupted elsewhere; eruption sites for these samples are numbered in parentheses. Samples with PZ prefix are from Cameron and others (1989). Inferred location of buried frontal edge of Ouachita thrust sheets is shown by the dotted bold line (Pearson, 1978; P. Dickerson, 1991, personal commun.). Boundaries of isotopic provinces defined in the text are shown by thick lines; the Chalk Draw (cdf) and Tascotal Mesa (tmf) faults are shown by thin lines.

mantle-derived basaltic rocks have Pb contents of 1 or 2 ppm, whereas potential crustal assimilates have Pb contents of about 10 to 35 ppm. Therefore, the Pb-Th-U system is very sensitive to additions of crustal materials.

Geologic Setting

Precambrian igneous and metamorphic rocks that constitute the southern part of the North American craton crop out in small, scattered areas in Trans-Pecos Texas and northern Chihuahua (Fig. 1). The rocks range from granite and rhyolite to amphibolite, layered mafic intrusions, and diverse metasedimentary rocks. Sparse U-Pb zircon ages range between ~1.35 and ~1.1 Ga (Wasserburg and others, 1962; Blount and others, 1988; Copeland and Bowring, 1988; Walker, 1988, 1992; Soegaard and others, 1991). Complex multi-phase deformation appears contemporaneous with ~1.1–1.2 Ga northward-vergent folding and thrusting along an east-trending belt from Trans-Pecos Texas to the Llano district in central Texas (Bristol and Mosher, 1989; Nelis and others, 1989; Carter, 1989; Mosher, in press). Metamorphism was concurrent with deformation and metamorphic grade appears to decrease from the southeast to the northwest. Overall, the late Middle Proterozoic history of Texas is similar to that of the Grenville province in the eastern United States and Canada (Mosher, in press; Walker, 1992).

Two sequences of Paleozoic sedimentary rocks overlie or were thrust over these Precambrian rocks (King, 1937; Flawn and others, 1961; Viele, 1989; Thomas, 1991). A sequence of dominantly shallow-marine (shelf?) carbonates was deposited directly upon the Precambrian rocks. The other sequence consists of dominantly clastic rocks that were deposited in the ocean basin that then separated North and South America. During the late Paleozoic Ouachita orogeny, these later rocks were thrust over the Precambrian and cratonic sedimentary rocks along the southern margin of North America. In West Texas (Fig. 2), the leading edge of the thrust sheets of Ouachita facies is exposed in the Marathon region and in the Solitario, a 14-km-diameter laccolithic uplift to the southwest, and is penetrated or inferred from well data in adjacent areas (Pearson, 1978). The metamorphic inner zone of the Ouachita orogenic belt is exposed in one small outcrop south of the Rio Grande near the village of Boquillas, Coahuila (Flawn and others, 1961).

The Eocene through Miocene volcanic rocks of the Trans-Pecos magmatic province (Barker, 1977, 1987; Henry and McDowell, 1986; Price and others, 1987) compose part of the cover that obscures the Precambrian rocks and the Ouachita belt in West Texas and Chihuahua, Mexico. Although the volcanic rocks hide structural and lithologic relationships, they are also sensitive geochemical probes that show the influence of the lithosphere through which they have passed (Cameron and Cameron, 1986; Gunderson, 1986; Nelson and others, 1987; Cameron and others, 1989; James and Henry, 1991a). Rocks of the Trans-Pecos magmatic province are divided into three age groups that formed during two major tectonic episodes (Henry and McDowell, 1986; Henry and others, 1991). The largest volumes of igneous

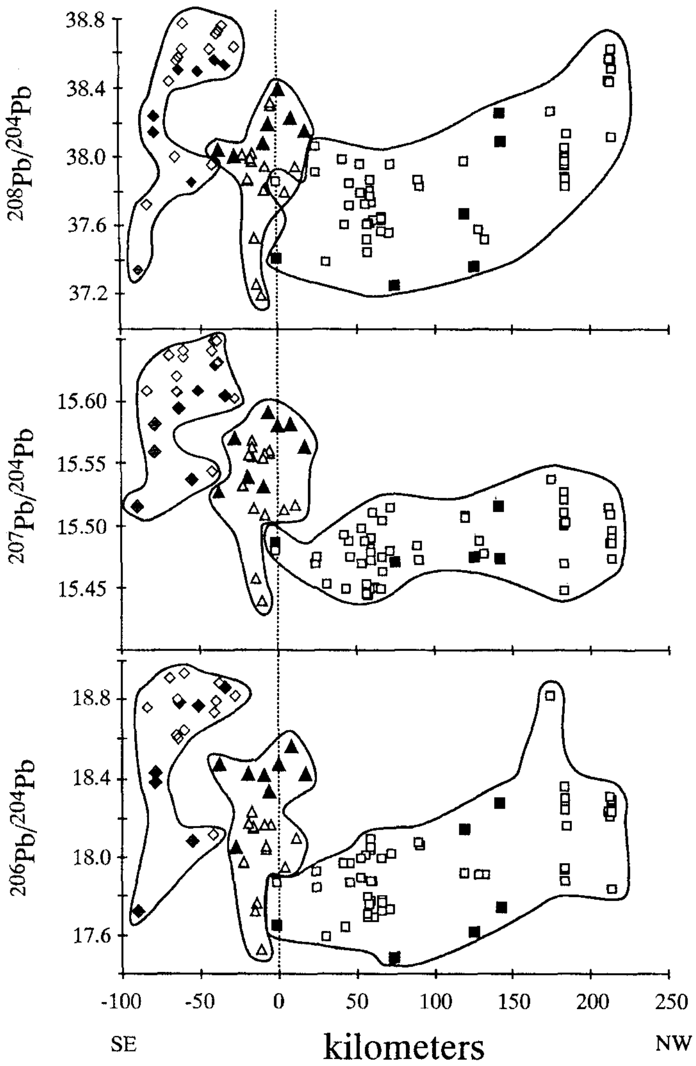

Figure 3. Lead isotopic ratios of Tertiary whole rocks and feldspars versus distance in kilometers from the Ouachita front (see Figure 2 for location). Squares represent northwestern province samples; triangles, central province; and diamonds, southeastern province. Solid symbols represent rocks with Mg# > 45.

rock were emplaced between 48 and 31 Ma in a continental arc related to subduction off the west coast of North America. These rocks include a western belt of hypersthene-normative, alkali-calcic differentiation suites that range from relatively minor primitive basalts to voluminous rhyolites. Concurrently, similar but more alkalic rocks were emplaced in an eastern belt. At about 30 Ma, the stress regime changed from the maximum principal stress (σ_1) east-northeast to the minimum principal stress (σ_3) east-northeast (that is, east-northeast extension) (Price and Henry, 1984). Subsequent magmatism has a substantial intraplate component (Gunderson and others, 1986; James and Henry, 1991a). In the early part of this extensional regime (30–27 Ma), bimodal suites of nepheline-normative hawaiite and metaluminous to peralkaline rhyolite were erupted. Differentiation suites are limited to silica-undersaturated series, some of which evolved as far as nepheline syenite (Carman and others, 1975). The youngest igneous activity in Texas, between 24 and 17 Ma, consists of small volumes of alkali basalt and hawaiite associated with Basin and Range faulting. All three of these igneous suites have been extensively sampled and analyzed for their Pb isotopic compositions. These isotopic data yield contrasting, yet complementary, information on the composition, age, history, and distribution of tectonostratigraphic terranes along the southern edge of the North American craton.

ANALYTICAL METHODS

Lead isotopic analyses were performed on feldspar separates and whole-rock samples of Tertiary igneous rocks. Many of the samples were originally collected and processed for K-Ar age analyses (Henry and others, 1986). Radiogenic and other loosely held lead was removed by partial dissolution using warm, high-purity 16% HF (Ludwig and Silver, 1977). Powdered whole-rock samples were leached 1 hr with hot 6 N HCl to remove secondary carbonate and Pb introduced during processing. Samples were dissolved in screw-top Teflon containers on a hotplate using HF and HNO_3. Lead and U were separated using HBr and HNO_3 chemistry on AG 1 × 8 exchange resin. The Pb blank contribution, between 100 and 50 picograms, is inconsequential. Whole-rock data are corrected for decay of U and Th. Mass spectrometry was performed on a Finnigan MAT 261 multi-collector mass spectrometer at the University of Texas at Austin.

RESULTS

Lead isotopic ratios and concentrations are listed in Table A.[1] Sampling locations are shown in Figure 2. The data set represents the entire known range of ages and compositions of magmatism in West Texas. With only a few exceptions, ages of the samples (Table A) are well constrained from either K-Ar dating (Henry and others, 1986) or detailed stratigraphy. Both alkalic and alkali-calcic suites are well represented, and compositions range from basalt to high-silica rhyolite. Silicic compositions make up a large part of the sample set because extensive ash-flow tuffs were targeted for K-Ar dating.

The first-order variations in $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ are abrupt changes in ratios near the Ouachita front (Fig. 3). Southeastward of the front, rocks have relatively high and diverse isotopic ratios. Immediately northwest of the Ouachita front, all ratios are lower. The average $^{207}Pb/^{204}Pb$ of northwestern province rocks is distinctly lower than the average $^{207}Pb/^{204}Pb$ of the other provinces. The $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ in the northwestern province are lowest near the Ouachita front and increase to the northwest. The character of the changes from northwest to southeast and its provinciality is also obvious in the variation of $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ (Fig. 4). Three isotopically distinct groups of analyses represent what we believe to be two isotopic provinces and a central overlap zone. Rocks to the northwest on the craton have relatively low $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ compared to crustal evolution curves (Stacey and Kramers, 1975). To the southeast, on crust apparently accreted during the Ouachita orogeny, rocks have higher $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ (that is, more radiogenic) and proportionally higher $^{208}Pb/^{204}Pb$. These ratios fall near the zero-age end of the crustal evolution curves. A 50-km-wide zone with rocks having intermediate isotopic ratios lies between the northwestern and southeastern isotopic provinces. There is no obvious correlation of isotopic ratios with age (Table A).

[1]GSA Data Repository item 9310, Table A, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

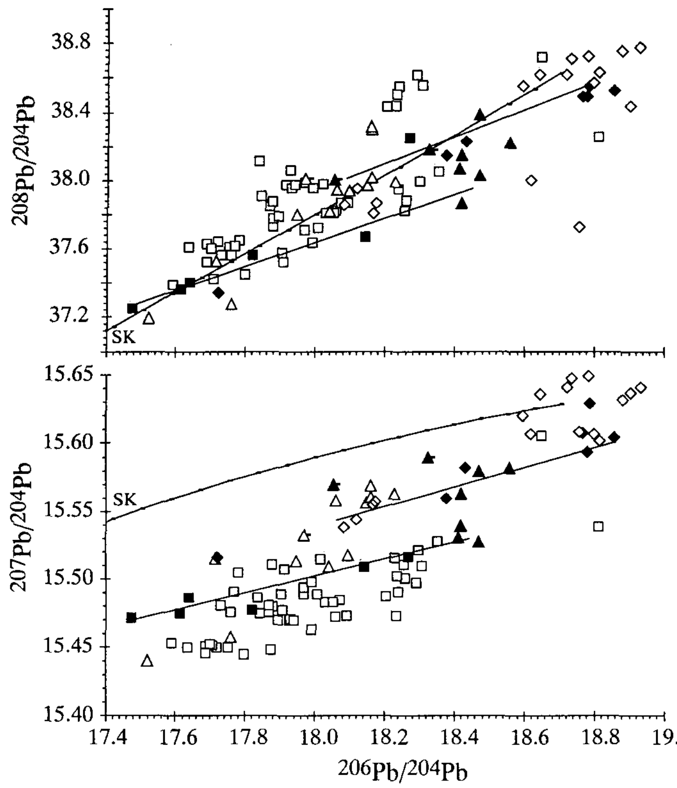

Figure 4. $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ for Tertiary igneous rocks of Trans-Pecos Texas and adjacent Mexico. Symbols as in Figure 3. Symbols with horizontal tick marks indicate samples from Cameron and others (1989). Curve SK represents average crust (Stacey and Kramers, 1975), with tick marks at 50 Ma intervals. Lines are fit through mafic samples (Mg# > 45) by eye.

In general, rocks of the northwestern and southeastern provinces have distinct Pb isotopic characteristics, regardless of composition. Mafic and silicic rocks in each province have broadly similar isotopic ratios that differ from those of the other province. In the central province, isotopic compositions of mafic samples overlap with those of the adjacent provinces, and many felsic samples have isotopic compositions similar to those of the northwest province. In detail, the variation within each province is correlated with rock composition. Basalts plot along distinct linear trends, and intermediate and felsic rocks diverge systematically from these trends (Fig. 4). This divergence accentuates provincial Pb characteristics. Felsic rocks are more radiogenic than mafic rocks in the southeastern province and less radiogenic than the primitive rocks in the northwestern province.

Our primary goal is to show the regional differences in Pb isotopic compositions in Trans-Pecos Texas and to elucidate the geometry and tectonic evolution of terranes in this region. Although the details of petrogenesis will be discussed more fully elsewhere, it is important to outline the probable sources of Pb in these rocks. The wide range of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ and the different trends seen in the covariation of these ratios suggest that multiple sources were involved in Tertiary magma genesis.

Sources of the Basalts

The most compositionally primitive basalts in Trans-Pecos Texas are dikes and scattered flows of 24 to 17 Ma Basin and Range alkali basalt and hawaiite in the Sierra Vieja (Dasch, 1969; Irving and Frey, 1984; Henry and Price, 1986a), near Terlingua (Nelson and Schieffer, 1990), in the Bofecillos Mountains (Henry and Price, 1986a), east of Big Bend National Park (Dahl and Lambert, 1986), and in the Davis Mountains. Other analyzed basalts include 27 Ma alkalic basalts from the Bofecillos Mountains, a 36 Ma alkalic basalt in the Davis Mountains (Irving and Frey, 1984), several basalts in the Van Horn Mountains caldera (Henry and Price, 1986b), and some basaltic intrusions and flows in and north of Big Bend National Park.

Lead analyses of these basalts, all with Mg# greater than 45, scatter along two linear trends on a $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagram (Fig. 4). Northwestern and related central-province basalts form an array with relatively low $^{207}Pb/^{204}Pb$ values. Analyses of mafic rocks from the southeastern province and some analyses of central-province rocks form a more scattered trend parallel to the northwestern array, but at higher $^{207}Pb/^{204}Pb$. Below, we first consider evidence that the arrays reflect variable isotopic ratios within the mantle beneath each province. This would imply that the basalts are uncontaminated reflections of the local mantle. We then discuss a more likely explanation, that contributions of mantle and crust have yielded mixing lines reflecting isotopic differences in the lithosphere of each province.

Many of the basalts have petrographic and chemical hallmarks of mantle-derived magmas. They are nepheline-normative, have Mg# as high as 66 and Ni contents up to 260 ppm, and many contain ultramafic xenoliths (Nelson and Schieffer, 1990). The presence of mantle xenoliths generally implies rapid transit through the crust with little or no interaction (for example, Glazner and Farmer, 1992). More fractionated basalts and hawaiites, down to about Mg# 45, also show no obvious trace- or major-element evidence for interaction with crust. Simple mantle partial melting followed by fractional crystallization without crustal assimilation can account for the trace-element concentrations of these basalts (Gunderson and others, 1986; Nelson and others, 1987; Kuentz and others, 1991; James and Henry, 1991a). Additionally, Sr and Nd isotopic data from Trans-Pecos Texas (Cameron and Cameron, 1986; Cameron and others, 1989; Schucker, 1989) suggest mantle sources with little involvement of crustal materials.

Certainly, a major source of these mafic magmas was the mantle, and one explanation for the large range of $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ is mixing of less-radiogenic Pb from old mantle lithosphere with more-radiogenic Pb from the asthenosphere or young lithospheric mantle. At the radiogenic end of the northwestern array a reasonable end member is a Pb isotopic composition similar to that of many Basin and Range basalts, and to mantle xenoliths with apparent asthenospheric Pb (Ben Othman and others, 1990; Kempton and others, 1991) (Fig. 5, field M). This field falls on the Northern Hemisphere Reference Line for MORB (Hart, 1984). Analyses of clinopyroxenes that may represent lithospheric mantle have similar, but more scattered, values (Ben Othman and others, 1990). The Pb data for West Texas are insufficient to establish lithospheric versus asthenospheric mantle sources for the most-radiogenic Pb. The less-radiogenic component in these basalts might also be mantle-derived. Several authors have argued that continental basalts may derive low $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ from old lithospheric mantle with low time-integrated U/Pb (Everson, 1979; Kempton and others, 1991). If the Trans-Pecos basalts are free of crustal contamination, then this is a logical explanation of nonradiogenic Pb isotopic ratios.

Several of the basalts that contain lherzolite xenoliths, however, also contain xenoliths from the lower to middle crust (Nelson and Schieffer, 1990; Rudnick and Cameron, 1991; Cameron and others,

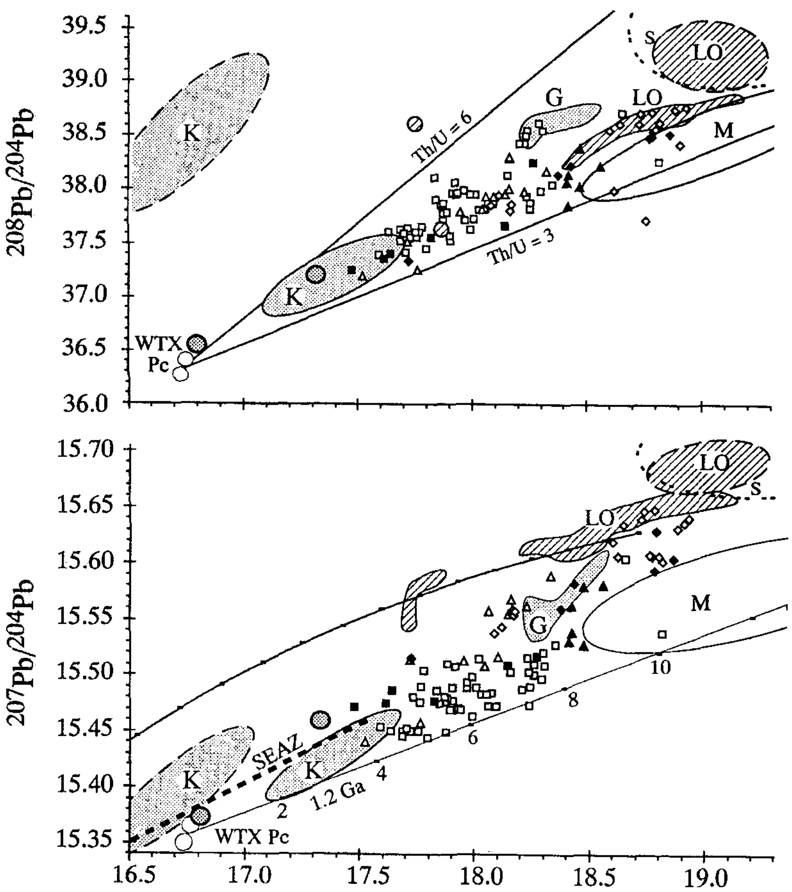

Figure 5. $^{206}Pb/^{204}Pb$ **versus** $^{207}Pb/^{204}Pb$ **and** $^{208}Pb/^{204}Pb$ **in Trans-Pecos samples and isotopic compositions of possible sources. See text for discussion. Symbols for Tertiary samples as in Figure 3. Possible northwestern lower-crust compositions are shaded fields. K, Kilbourne Hole xenoliths (Reid and others, 1989); G, Geronimo granulite xenoliths (Kempton and others, 1990); and dark shaded circles for Davis Mountains xenoliths (Kuentz and others, 1991; Ward and Walker, 1991). Southeastern lower crust in diagonal ruled pattern, generalized from analyses of lower-crustal xenoliths from La Olivina, LO (Cameron and others, 1992). Fields enclosed by dashed lines, S, represent data from metasedimentary xenoliths. Mantle field, M, generalized from Ben Othman and others (1990) and Kempton and others (1991). Short-dashed field includes analyses of Phanerozoic sedimentary upper crust from the southeast and northwest (Cameron and others, 1991, 1992; James and Henry, 1991b). Initial ratios for West Texas Precambrian feldspars, WTX Pc, are from Table A. Isochron shows 1.2 Ga growth from WTX Pc for the** $^{238}U/^{204}Pb$ **values labeled at ticks. Short-dashed line, SEAZ, shows a small section of trend of Precambrian whole-rock leads from southeastern Arizona (Wooden and Miller, 1990) for comparison with West Texas Precambrian initial Pb ratios.**

1992; Ward and Walker, 1992). These xenoliths include two-pyroxene granulites with basaltic compositions, intermediate to silicic orthogneisses, and paragneisses. Lead isotopic data for mafic granulitic inclusions from the Davis Mountains (location 2, Fig. 2) (Ward and Walker, 1992) and for many xenoliths from Kilbourne Hole, New Mexico (Reid, 1989; Reid and others, 1989), lie at the nonradiogenic end of the northwestern-province $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ array. Granulite xenoliths from La Olivina, Chihuahua, at the edge of the southeastern province (Fig. 1) (Rudnick and Cameron, 1991; Cameron and others, 1992) represent reasonable end members that can explain the spread of southeastern-province isotopic data.

The Pb compositions of the Davis Mountains and Kilbourne Hole mafic granulite inclusions lie at the low $^{206}Pb/^{204}Pb$–$^{207}Pb/^{204}Pb$ ends of the Pb arrays of northwest-province mafic rocks (Fig. 5). This is strong evidence for a lower-crustal source of Pb in these basalts. Upper-crustal contamination appears unlikely given that most of these basalts have $^{87}Sr/^{86}Sr$ less than 0.704 (Dasch, 1969; Kuentz and others, 1990), whereas exposed Precambrian crust in West Texas typically has $^{87}Sr/^{86}Sr$ greater than about 0.8 (Denison and Heatherington, 1969; Barker and others, 1977; Norman and others, 1987). Also, as shown in the section on Pb in the felsic rocks, the upper crust probably has $^{207}Pb/^{204}Pb$ too low to serve as end members for the basalts (Fig. 5).

Interaction of the southeastern mafic magmas with lower crust also seems likely. Lead isotopic ratios of granulite xenoliths from La Olivina have a wide range that parallels that of the southeastern-province mafic rocks, but with higher $^{207}Pb/^{204}Pb$ (Fig. 5) (Cameron and others, in press). The range of isotopic ratios in the La Olivina granulitic xenoliths and the small contrast in ratios between the basalts and these xenoliths, however, does not present as clear a case for mixing as is suggested by the northwestern granulite and basalt data. As in the northwestern province, upper-crustal rocks cannot account for the spread of the data toward lower ratios. Exposed upper-crustal rocks in the southeast and central provinces have Pb isotopic ratios somewhat more radiogenic than average modern crust (Fig. 5) (Cameron and others, 1991; James and Henry, 1991a), whereas the basalts have lower $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$.

The presence of lower-crustal xenoliths in some of the northwestern basalts with the lowest $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ (Kuentz and others, 1991; Ward and Walker, 1991) makes the lower crust a logical source of nonradiogenic Pb, although we cannot rule out old lithospheric mantle sources. The more radiogenic end of the array trends toward typical mantle compositions. The crude 1.2 Ga "age" that can be calculated from the slope of the northwestern-province data may be coincidental or may represent mixing between ~1.2 Ga crust and mantle with similar initial ratios. In the southeastern province, the isotopic ratios of the mafic rocks lie between similar, but possibly higher $^{207}Pb/^{204}Pb$, mantle compositions and data points for deep crustal xenoliths from La Olivina (Fig. 5) (Cameron and others, 1992). Like basalts in the northwestern province, the local lower to middle crust is a logical source of Pb that contrasts with Pb from the mantle.

Sources of Intermediate to Felsic Rocks

In contrast to the mafic rocks, the evolved rocks in Trans-Pecos Texas have clearly interacted with crust, and some may be direct crustal melts. Trace-element studies are compatible with assimilation of lower and upper crust (James and Henry, 1991a). These interactions have accentuated the isotopic differences between provinces seen in the basalts. The differences in the felsic and intermediate rocks between provinces can be attributed to interaction with different crustal sections. The overall differences between the mafic and felsic rocks for each province are apparent in Figure 4. Examples of related rocks from each province show the relationships between compositions and isotopic ratios clearly (Fig. 6). The zoned Marble Canyon stock (Price and others, 1986) represents an example of a genetically related suite from the northwestern province. The most mafic compositions plot near the northwestern mafic array, but samples with higher SiO_2 have increasingly lower $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$, but higher $^{208}Pb/^{204}Pb$. In the southeastern province, four ~42 Ma samples from the Christmas Mountains show a large increase in $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$, with increase in SiO_2. The mafic hawaiite samples lie on the array defined by southeastern mafic samples, and the quartz syenites lie near modern crustal lead values. An example from the central province is a suite from the Bofecillos Mountains. The most-mafic 27 Ma samples are close to the most-mafic samples from the southeastern province. More-silicic rocks of the same age have lower $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$, and two nearby high-silica peralkaline rhyolite samples with 35.5 Ma ages are even less radiogenic.

In the northwestern and central provinces, the changes in isotopic ratios that are correlated with differentiation may be attributed to assimilation of Precambrian upper and lower crust. Unfortunately, few whole-rock samples of local Precambrian crust have been analyzed. Probable Pb compositions of Precambrian upper crust, however, can be modeled from initial Pb ratios and ages (Table A). Pb isotopic compositions of these Precambrian rocks should lie near a 1,200 Ma isochron originating from the initial Pb ratios. Such an isochron (Fig. 5) is a close lower limit to the Tertiary data on $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagrams. This implies that similar rocks may dominate the Pb budget of the felsic rocks.

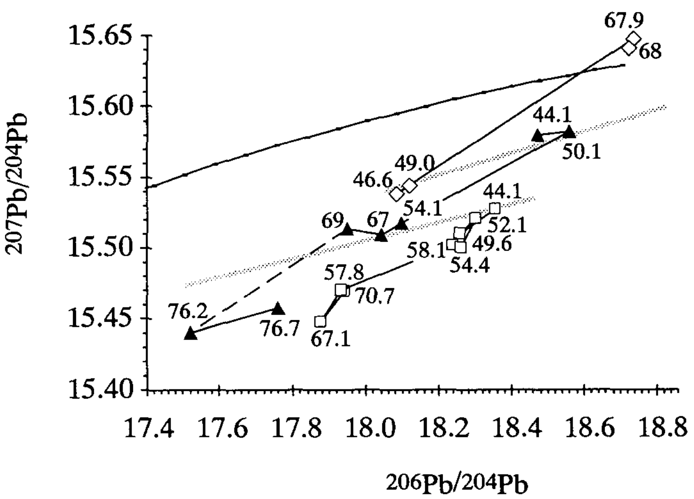

Figure 6. $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ of samples showing correlation of isotopic ratios with SiO_2 content. More-felsic rocks in the northwestern and central province are less radiogenic than related basalts; more-felsic rocks in the southeastern province are more radiogenic than related basalts. Numbers next to symbols are SiO_2 content of sample. Squares, Marble Canyon Stock (northwestern province); triangles, Bofecillos Mountains (central); diamonds, Christmas Mountains (southeastern).

In contrast, most of the felsic samples from the northwest province plot toward higher $^{208}Pb/^{204}Pb$ than the mafic samples (Figs. 4 and 5), which suggests a different or additional source. The higher $^{208}Pb/^{204}Pb$ of these rocks indicates involvement of a source with higher long-term Th/U. Again using the initial Pb of West Texas Precambrian samples as a starting point (Fig. 5), assimilants with long-term Th/U of at least 6 would be required. Most Pb analyses of Precambrian rocks from southwestern New Mexico indicate time-integrated Th/U of less than 6 and have $^{208}Pb/^{204}Pb$ too low to represent sources (Stacey and Hedlund, 1979; J. Wooden, 1992, personal commun.). Nonetheless, Th/U ratios of 6 are not unusual, and West Texas upper crust could contain units with sufficiently high $^{208}Pb/^{204}Pb$ to be the source of Pb seen in the felsic to intermediate rocks.

Lower crust is an alternative assimilant. The composition of some felsic rocks in northwestern Trans-Pecos Texas suggests major lower-crustal inputs (Shannon and Goodell, 1986; J. A. Wolff, 1990, personal commun.). Although the lower crust is commonly cited as having high $^{208}Pb/^{204}Pb$ with respect to $^{206}Pb/^{204}Pb$, many metaigneous lower-crustal xenoliths have relatively high $^{206}Pb/^{204}Pb$ and only slightly elevated $^{208}Pb/^{204}Pb$ (Esperança and others, 1988; Rudnick and Goldstein, 1990; Cameron and others, 1992). Two granulitic xenoliths from the Davis Mountains (Kuentz and others, 1991; Ward and Walker, 1992), the only data for Texas, have sufficiently low $^{206}Pb/^{204}Pb$, but their $^{208}Pb/^{204}Pb$ ratios seem too low to represent a source (Fig. 5). The samples, however, may not be representative of the range of local lower crust. Granulite-grade metasedimentary and silicic charnockitic gneiss xenoliths from Kilbourne Hole, New Mexico (Fig. 1), have exceptionally high $^{208}Pb/^{204}Pb$ and low $^{206}Pb/^{204}Pb$ (Fig. 5) (Reid, 1989; Reid and others, 1989), and "meta-diorite" xenoliths from the Geronimo volcanic field of southern Arizona (Fig. 1) (Kempton and others, 1990) have $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ similar to high $^{208}Pb/^{204}Pb$ northwestern rhyolites, although the xenoliths have higher $^{207}Pb/^{204}Pb$.

Lower crust similar to xenoliths from the Davis Mountains, Kilbourne Hole, and the Geronimo volcanic field is a possible source of Pb in the northwestern felsic rocks, as is local upper crust. The apparent heterogeneity of crustal sources is not surprising. Structural complexities and low-angle faulting in the Precambrian basement (King and Flawn, 1953; Wilkerson and others, 1988; Bristol and Mosher, 1989; Soegaard and others, 1991; Walker, 1992; Mosher, in press) indicate that vertical lithologic and isotopic differences in the crust should be the rule in the Grenville terranes of Texas. Alternatively, part of the diversity of Pb isotopic signatures might derive from differing degrees of partial melting of a Precambrian source containing high Th or U phases (Hogan and Sinha, 1991). The range of possible sources for Pb in the northwestern province reflects the small number of modern isotopic analyses from Precambrian rocks and crustal xenoliths.

In the southeastern province, the tendency of felsic rocks to plot away from the southeastern basalt array and toward higher $^{207}Pb/^{204}Pb$ may also be attributed to several crustal sources (Fig. 5). Deep crust that has been suggested as the source of Pb in the southeastern mafic rocks is one possibility, and Ouachita sedimentary rocks that have Pb somewhat more radiogenic than modern crust (Fig. 5) (Cameron and others, 1991) are another. In the central area, the decrease in $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ with increasing SiO_2 (Figs. 4 and 6), generally without an increase in $^{208}Pb/^{204}Pb$ above that seen in nearby mafic rocks, suggests assimilation of Precambrian upper crust like that seen in the northwest without addition of a high $^{208}Pb/^{204}Pb$ (lower crust?) component.

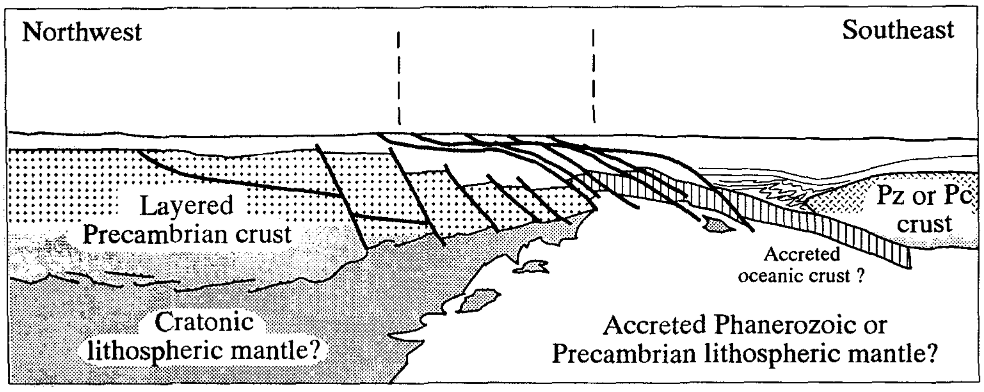

Figure 7. Diagrammatic northwest-southeast cross section from West Texas into Coahuila, Mexico. Pluses represent Precambrian upper crust of the North American craton; vertical ruling represents possible Paleozoic oceanic crust; jackstraws represent possible accreted Precambrian crust.

TERRANE COMPOSITION AND HISTORY

The Pb isotopic ratios of Tertiary Trans-Pecos igneous rocks show the location of two distinct terranes and a transition zone between them (Figs. 2 and 7). We propose that these isotopic terranes derive from the interactions of mantle sources; several lower-crustal sources, as typified by granulite xenoliths in basalts; and two upper-crustal sections. These are shown in diagrammatic cross section in Figure 7. Mantle sources contribute small amounts of moderately radiogenic Pb, but contrasting crustal sources dominate the Pb budget of almost all of the volcanic rocks.

The northwestern-province crust is relatively nonradiogenic Precambrian craton, much of it affected by the Grenville orogeny. Basement ages range from 1.4 to 1.1 Ga (Soegaard and others, 1991; Walker, 1992; Blount and others, 1988). Depleted-mantle Nd model ages of Precambrian rocks in Texas are between 1.6 and 1.2 Ga (Nelson and DePaolo, 1985; Norman and others, 1987; Patchett and Ruiz, 1989).

The southeastern crust has Pb isotopic characteristics similar to modern average crust, but the basement age is obscure. As far as is known, the southeastern block is composed of allochthonous Ouachita sedimentary and low-grade metamorphic rocks but may also contain oceanic and heterogeneous continental crust from the North and South American plates. Lead analyses of Ouachita rocks are somewhat more radiogenic than modern crustal averages (Cameron and others, 1991), as are lower-crustal granulite inclusions in basalts (Fig. 7) (Cameron and others, 1992). Alternatively, accreted continental fragments may be Precambrian in age and have a geochemical history yielding an "average" signature. Permian and Triassic igneous rocks in central Coahuila have initial Sr ratios between about 0.706 and 0.708 (Jones and others, 1984; McKee and others, 1990), also suggesting the presence of older crust. A Precambrian basement age is supported by Proterozoic zircon dates on xenoliths from La Olivina, Chihuahua, some with minimum ages as old as 1.6 Ga (Rudnick and Cameron, 1991).

The central zone rocks are not distinct in Pb isotopic ratios and appear to reflect overlap of the northwestern and southeastern provinces. The most mafic rocks have isotopic ratios that spread between analyses of northwestern and southeastern basalts. Many of the evolved rocks, however, trend toward low $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$, as in the northwestern province. It appears that the central province contains the same Precambrian upper crust as is seen in the northwestern province, although it may have been thinned or otherwise modified by late Precambrian–Cambrian rifting.

The width of the central province is about 50 km. This implies a steep contact between southeastern and northwestern province lithosphere. Furthermore, it is in line with the thin-skinned style of the Ouachita orogeny and implies only minor involvement of cratonic basement in deformation. It appears that the geometry of the southeastern craton margin in West Texas is more a reflection of late Precambrian–Cambrian rifting than of Late Paleozoic collision. Although similar conclusions have been reached based on geophysical data from the Ouachita Mountains (Keller and others, 1989a), recent deep seismic studies across south-central Texas (Culotta and others, 1992) have been interpreted as suggesting involvement of Grenville-age basement in Ouachita thrusting.

The isotopically defined province boundaries lie near two geologic boundaries. The boundary between the northwestern province and central area closely parallels the northern limit of Ouachita facies thrust sheets (Fig. 2). This is surprising because these sheets are only a thin veneer resting tectonically on North American craton. We suspect that the proximity of these boundaries is fortuitous. In contrast, the central-southeastern province boundary, which we believe marks the southeastern edge of the North American craton, coincides with abrupt changes in late Cenozoic fault trends. The Tascotal Mesa and Chalk Draw fault systems swing from east-west to northwest-southeast at this boundary (Fig. 2). Surface displacement on these faults is mostly Basin and Range in age, but they have long, pre-Tertiary histories (Dickerson, 1980). This change in fault trends apparently represents a discontinuity in basement types.

The isotopic provinces in Trans-Pecos Texas and Chihuahua are part of broader continental-scale isotopic and age provinces that continue into, out from, and along the craton margin (Fig. 1). The extent of the southeastern province and the nature of the crust farther to the southeast is not well known. Exposures of Paleozoic rocks to the southeast are few and little studied. The Pb isotopic compositions of galena from Coahuila and Nuevo Leon (Cumming and others, 1979), however, are like those of the southeastern province of West Texas and Chihuahua. A collage of rocks of diverse ages may compose the basement if the southern margin of the craton is as complex as the Appalachian orogen (Hatcher and others, 1989), and the basement farther southeast may be greatly different from what we have sampled.

Pb isotopic characteristics of Tertiary rocks of New Mexico and southern Arizona are broadly like those of the northwestern province of Trans-Pecos Texas, although the Precambrian basement terranes differ substantially. Most analyses of Tertiary igneous rocks from southwestern New Mexico (Stacey and Hedlund, 1983) fall within the range of the northwestern samples on $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ diagrams. The initial leads of 1.35 to 1.1 Ga Precambrian rocks in Trans-Pecos Texas and the Llano uplift (James and

Walker, 1992) fall just below the linear array of analyses of 1.7 to 1.4 Ga whole rocks from southern New Mexico and southeastern Arizona (Fig. 5) (Stacey and Hedlund, 1983; Wooden and others, 1988; Wooden and Miller, 1990; Wooden and Aleinikoff, 1991; Wooden, 1992, personal commun.). At 1.35 to 1.1 Ga, the isotopic ratios of rocks from Arizona and New Mexico would have been even higher in comparison to the Trans-Pecos initial ratios. It appears that 1.7 to 1.4 Ga crust similar to that seen in New Mexico and Arizona played a minor role, if any, in 1.35 to 1.1 Ga magma genesis in Trans-Pecos Texas. In contrast, the initial Pb isotopic ratios for the 1.5 to 1.3 Ga granite-rhyolite province of the mid-continent (Shuster and others, 1991) are similar to the Texas initial ratios. This suggests that the basement of northwestern Trans-Pecos Texas has affinities with crustal provinces of the mid-continent (James and Walker, 1992). If material was accreted during the Grenville orogeny, it must have had Th/U/Pb characteristics very similar to the craton to the north.

The Pb isotopic pattern of the southern margin of the craton in Texas is similar to that across the northeastern craton margin (that is, the northern Appalachian orogen) (Ayuso and Bevier, 1991). Compared to Texas, Devonian and Silurian plutons in the Appalachians of the northeastern United States and southeastern Canada (Ayuso and Bevier, 1991) have similar, but slightly higher, $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ on the craton and somewhat higher $^{207}Pb/^{204}Pb$ in the outboard areas (Fig. 8). The basement in both regions has a similar Grenville-age history (Mosher, in press) and similar Pb isotopic characteristics. More-radiogenic crust lies outboard of less-radiogenic Grenville crust in both areas. In the northern Appalachians, crosscutting plutonic rocks show that the outboard terranes were adjacent to the craton in the early Paleozoic. In Trans-Pecos Texas and Mexico, lower Paleozoic crust is present but was not accreted until the late Paleozoic Ouachita orogeny. This progression in Pb isotopic characteristics from inboard-nonradiogenic to outboard-radiogenic is also seen in the Caledonian orogen in Britain (Blaxland and others, 1979; Hampton and Taylor, 1983) and Ireland (Dixon and others, 1990).

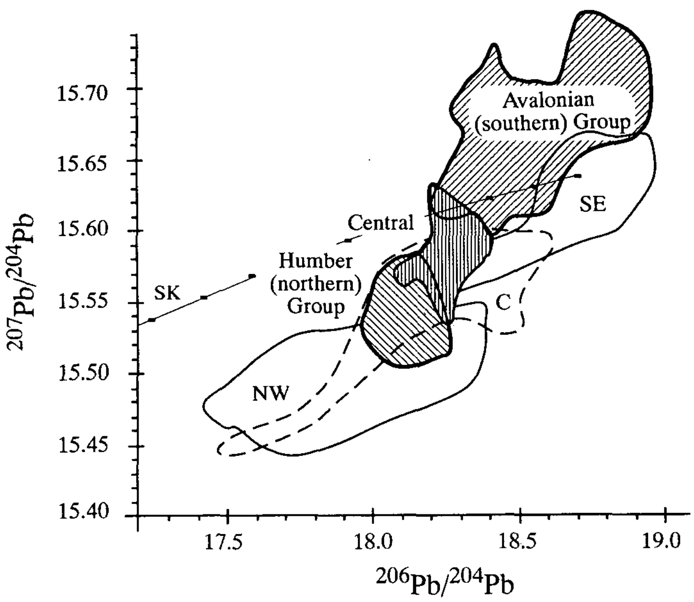

Figure 8. Pb isotopic compositions of the Trans-Pecos isotopic terranes (open fields) compared to initial Pb from Devonian and Silurian plutons in the northern Appalachians (in ruled patterns) (Ayuso and Bevier, 1991). Model average crust of Stacey and Kramers (1975) is labeled SK. Both areas, as well as the British Caledonian, show a similar progression from less radiogenic inboard to more radiogenic outboard.

Tectonic Implications

Mapping the southwestern continuations of the two lithospheric terranes defined by Pb isotopes may help in the understanding of several paleogeographic problems, such as the location of the Sonora-Mojave megashear, the continuation of the Grenville-Appalachian belt into southern Mexico, and the early history of Gondwana. The postulated Sonora-Mojave megashear (Silver and Anderson, 1974; Anderson and Schmidt, 1983) is a major Late Jurassic left-lateral transform fault system that cut the North American plate between California and the Gulf of Mexico (Fig. 1). Precambrian age terranes are offset about 800 km across this fault system. Subsequent deformation, magmatism, and sedimentation has obscured the fault along much of its length. The megashear should cut the Pb isotopic discontinuity documented here if it continues to trend southwest from Trans-Pecos Texas through Chihuahua (Figs. 1 and 2). The isotopic boundary associated with the Ouachita front may terminate against a terrane with Pb characteristics similar to those of southern Arizona and New Mexico (Fig. 1) (Wooden and others, 1988; Wooden and Miller, 1990). As shown earlier, there may be little isotopic difference between the northwestern Texas terrane and the southeast Arizona–southwest New Mexico terrane, although both contrast with the southeastern province of Texas. An even more-distinctive high $^{207}Pb/^{204}Pb$ and high $^{208}Pb/^{204}Pb$ terrane, a sliver of the Mojave crustal province of Wooden and others (1988) and Wooden and Miller (1990), could lie to the northwest along the south side of the megashear (Fig. 1, Mojave Pb?). The isotopic contrast between Mojave crustal province and the northwestern terrane of West Texas and Chihuahua should be large and might allow better location of the megashear.

The Sonora-Mojave megashear may also link Grenville-age rocks in Texas and Chihuahua with a band of Grenville-age rocks stretching from Ciudad Victoria in eastern Mexico to Oaxaca in southern Mexico. Lead isotopic data from ore deposits, which commonly sample an average of local crustal Pb, indicate broad isotopic similarities between these regions (Cummings and others, 1979; Ruiz and others, 1988). Galena from ore deposits in Chihuahua immediately west of Trans-Pecos Texas have some of the lowest $^{206}Pb/^{204}Pb$ ratios in Mexico (Cummings and others, 1979). The ratios overlap with those in the Trans-Pecos northwestern province and indicate continuation of the province westward toward the megashear. Ore deposits in southern Mexico in the states of Guerrero and Puebla, in areas of probable Grenville-age basement, have comparable low $^{206}Pb/^{204}Pb$ (Cummings and others, 1979). Ruiz and others (1988), however, noted that in southern and eastern Mexico, Paleozoic Appalachian-Caledonian rocks lie west of Grenville-age metamorphic rocks, opposite of the rest of North America. This suggests that the Pb isotopic gradient may be opposite of that in Trans-Pecos Texas.

Correlation of Grenville rocks in Texas and Mexico has become important in light of recent reconstructions of the positions of North America, Antarctica, and Australia in the late Precambrian. Moores (1991) and Dalziel (1991) hypothesized that, prior to late Precambrian rifting, the Grenville front extended westward from its position in Trans-Pecos Texas into adjacent Antarctica. This proposed orientation of plates suggests that an extension of the isotopic boundary discussed here may be found in Antarctica rather than in southern Mexico.

CONCLUSIONS

Initial Pb isotopic ratios of Tertiary igneous rocks delineate two markedly different crustal provinces in Trans-Pecos Texas and northeastern Chihuahua. The boundary between these provinces trends approximately N35°E and parallels the trace of the buried Ouachita front. We interpret this boundary to be the contact between the North American craton and allochthonous rocks of the Ouachita orogeny. This contact is steep and cuts the entire crust and possibly the upper mantle. The geometry of the margin was established by late Precambrian–Cambrian rifting and was not greatly modified by the Ouachita orogeny.

Basalts from the northwestern cratonic province have Pb isotopic analyses that lie on probable mixing lines between mantle Pb compositions and relatively less-radiogenic Pb compositions of lower-crustal granulite xenoliths. Mixing between mantle and more-radiogenic deep-crustal Pb is also likely in the southeastern basalts. Intermediate to felsic rocks in the northwest appear to have assimilated Precambrian lower and upper crust with low $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ and diverse $^{208}Pb/^{204}Pb$. Felsic southeastern rocks appear to have assimilated upper or lower crust with high $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$.

The Pb isotopic characteristics of northwestern Trans-Pecos rocks are similar to those of the granite-rhyolite province to the north, in the mid-continent. Further mapping of crustal provinces and discontinuities defined by Pb isotopes may help in our understanding of paleotectonic problems presented by the Sonora-Mojave Megashear, correlation of Grenville-age terranes in Texas and southern Mexico, and the correlation of pieces of Gondwana. A similar Pb isotopic zonation, from more-radiogenic compositions outboard to less-radiogenic compositions inboard, occurs elsewhere along the Ouachita-Alleghanian-Caledonian orogen, including the northern Appalachians and the British Isles, and may be characteristic of the orogen.

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