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Tectonic evolution of the southern Laurentian Grenville orogenic belt

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ABSTRACT

The Grenville orogenic belt along the southern margin of Laurentia records more than 300 m.y. of orogenic activity culminating in arc-continent and continent-continent collision ca. 1150–1120 Ma. Exposures in Texas provide a unique profile across the Grenville orogen from the orogen core to the cratonal margin. In the Llano uplift of central Texas, ca. 1360–1232 Ma upper amphibolite–lower granulite facies, polydeformed supracrustal and plutonic rocks represent the core of the collisional orogen. This exposure contains a suture between a 1326–1275 Ma exotic island-arc terrane and probable Laurentian crust and records A-type subduction. In west Texas, 1380–1327 Ma amphibolite to greenschist facies, polydeformed supracrustal rocks are thrust over ca. 1250 Ma carbonate and volcanic rocks along the cratonal margin. The carbonate and volcanic rocks form a narrow thrust belt with post–1123 Ma synorogenic sedimentary rocks, which grade into undeformed sedimentary rocks northward on the Laurentian craton.

The Texas basement reveals a consistent but evolving tectonic setting for the southern margin of Laurentia during Mesoproterozoic time. This paper summarizes recent advances in our knowledge of the Texas basement and proposes plate models to explain the tectonic evolution of this margin during Mesoproterozoic time. The orogenic history is strikingly similar to that of the Canadian Grenville orogen and requires a colliding continent off the southern Laurentian margin during the assembly of Rodinia.

INTRODUCTION

Grenville-age rocks have become pivotal in constraining plate reconstructions for Rodinia, an early Neoproterozoic supercontinent (Dalziel, 1991; Hoffman, 1991; Moores, 1991). Laurentia, which has a critical position in all models, is bordered on its eastern margin by the north-northeast–trending Grenville orogen, which records both intracratonic and collisional orogenesis (Davidson, 1986; Rivers et al., 1989). In Labrador, crustal shortening telescoped older basement rocks in an intracratonic setting as a result of continent-continent collision farther outboard (Connelly et al., 1995). In Ontario, a long history of island-arc and allochthonous terrane accretion culminated in continent-continent collision (Davidson, 1986; Gower et al., 1990; Culotta et al., 1990). Deep crustal shear zones with northwest-directed transport are observed along the belt (Davidson, 1986) with crustal imbrication resulting in burial to depths in excess of 45 km (Indares, 1993). This orogenic belt continues northward into Greenland and Scandinavia, and scattered inliers in the Appalachians suggest a lateral continuity along the length of the Appalachian orogen (Fig. 1). Recent plate reconstructions interpret South America as the colliding continent (Dalziel, 1991, 1992, 1997, Hoffman, 1991; Moores, 1991; Unrug, 1996) adjacent to this eastern margin of Laurentia,

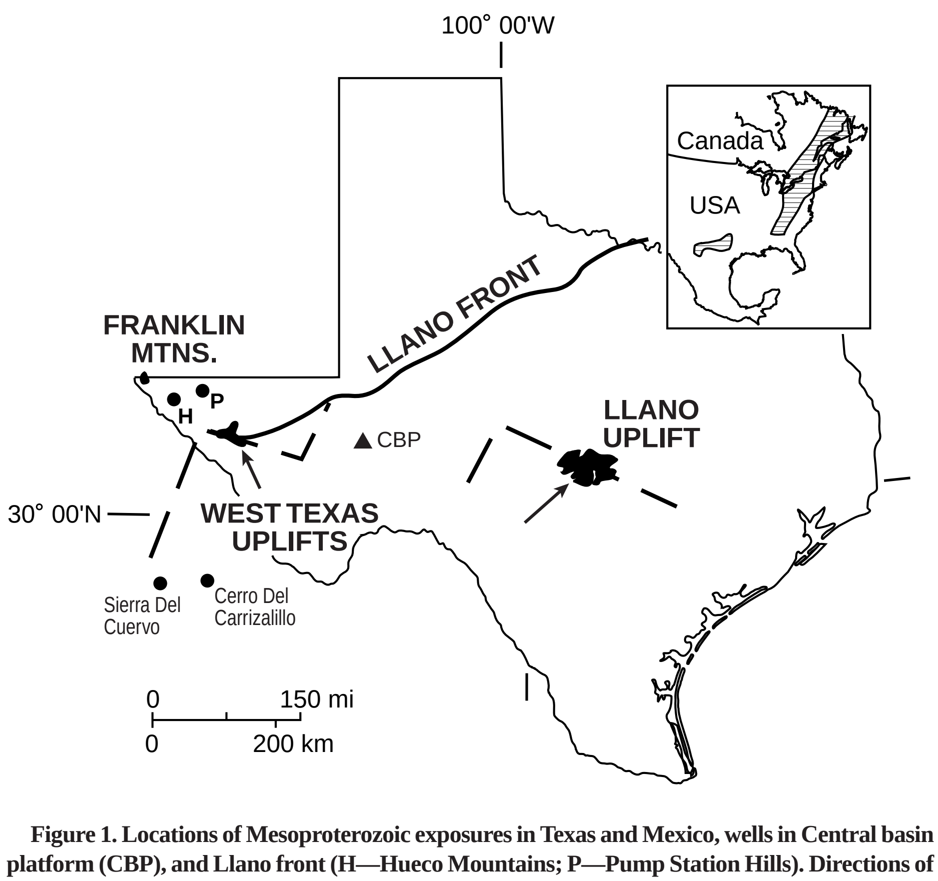

Figure 1. Locations of Mesoproterozoic exposures in Texas and Mexico, wells in Central basin platform (CBP), and Llano front (H—Hueco Mountains; P—Pump Station Hills). Directions of tectonic transport (arrows) are shown for Llano uplift and west Texas exposures. Two possible plate boundaries (dashed) are shown. Boundary in Llano uplift represents a collisional suture, whereas that in west Texas represents closure of a small ocean basin. The equivalent collisional suture in west Texas is to the south near Cerro Del Carrizalillo and Sierra Del Cuervo. Inset shows location of Laurentian Grenville orogenic belts.

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constructions interpret South America as the colliding continent (Dalziel, 1991, 1992, 1997, Hoffman, 1991; Moores, 1991; Unrug, 1996) adjacent to this eastern margin of Laurentia, whereas earlier reconstructions show western Africa instead (e.g., Bird and Dewey, 1970; Hatcher, 1987). Most reconstructions also show Baltica and the Greenland portion of Laurentia forming the northern extension of this belt, although Gower et al. (1990) showed only Baltica interacting with Laurentia.

A Grenvillian orogenic belt also borders the southern margin of Laurentia and is exposed in the central Texas Llano uplift and smaller exposures in west Texas (Fig. 1). In Texas, the east-trending Grenville orogen records both arc-continent and continent-continent collisional orogenesis (Wilkerson et al., 1988; Mosher, 1993; Reese, 1995; Roback, 1996a; Carlson, 1998, and this study). Thus, plate reconstructions that show the assembly of Rodinia along Grenvillian sutures must include a southern continent off the southern margin of Laurentia, an element lacking in most reconstructions (Dalziel, 1991, 1992, 1997; Hoffman, 1991; Borg and DePaolo, 1994; Torsvik et al., 1996; Unrug, 1996). The exception is Moores (1991) who tentatively suggested that Baltica might lie off this southern margin of Laurentia.

In this paper I summarize the results of recent studies along the southern margin of Laurentia and propose the first comprehensive plate model for the Mesoproterozoic tectonic evolution of this margin. New absolute age constraints and careful structural and metamorphic studies allow correlation of tectonic events and settings along the margin. Although further work is needed to test the models proposed herein, a consistent story for the tectonic evolution of the southern margin of Laurentia during Mesoproterozoic time is emerging.

OVERVIEW

Rocks of presumed Grenville affinity lie south of the northeast-trending Llano front, a magnetic and gravity anomaly similar to the Grenville front in the Appalachians (Mosher, 1993) (Fig. 1). Drill cores into basement north of the front contain granitic and rhyolitic rocks of the southern Granite rhyolite terrane (1400–1300 Ma; Van Schmus et al., 1996), whereas south of the front they contain gneisses and metasedimentary rocks. About 300 km south of the front, the core of the southern Grenville orogen is exposed in the Llano uplift of central Texas (Figs. 2 and 3). The uplift contains a collisional suture between a distinct arc terrane and continental crust, medium-temperature eclogitic rocks suggesting burial to depths of ~50 km, and evidence of dynamothermal tectonism ca. 1150–1120 Ma (Wilkerson et al., 1988; Mosher, 1993; Roback, 1996a, 1996b; Carlson, 1998). Smaller exposures in west Texas (near Van Horn, Texas; Fig. 4) contain the northern margin of the orogen, which appears to be a continuation of the Llano front (Fig. 1). There, polydeformed 1400–1300 Ma metasedimentary and metavolcanic rocks were thrust in a transpressional setting over ca. 1250 Ma carbonate and volcanic rocks (Soegaard and Callahan, 1994). Synorogenic conglomerates and sandstones (ca. post-1123 Ma; Roths, 1993) involved in the underlying narrow thrust belt are undeformed 7 km north of the boundary on cratonal Laurentia. Farther west along strike in the Franklin Mountains (near El Paso, Texas), correlative carbonate and volcanic rocks are undeformed (Pittenger et al., 1994). Thus, considered together, the exposures along the southern margin of Laurentia provide a unique profile across the Grenville orogen from the orogen core onto the cratonic margin. No penetrative ductile deformation or metamorphism younger than Mesoproterozoic age has affected the exposed rocks in Texas.

LLANO UPLIFT

The Llano uplift consists of ca. 1360 to 1232 ± 4 Ma metavolcanic, metaplutonic, and metasedimentary rocks (Table 1; Fig. 2) that have been polydeformed synchronous with a moderate- to high-pressure, upper amphibolite to lower granulite facies regional metamorphism (Walker, 1992; Mosher, 1993; Reese, 1995; Roback, 1996a; Carlson, 1998). These rocks were subsequently intruded by 1119 +6/–3 to 1070 ± 2 Ma, syntechtonic to post-tectonic granites (Table 1; Fig. 2) synchronous in part with a generally static, low-pressure, middle amphibolite facies metamorphism (Walker, 1992; Reed, 1995; Reed et al., 1995; Carlson, 1998).

Recent U/Pb geochronology (Walker, 1992; Reese, 1995; Roback, 1996a) has shown that the previously described stratigraphy (see Barnes, 1981) is unusable in its present form. Rocks mapped as a single unit vary significantly (>100 m.y.) in age and in many cases cannot be genetically related. In the eastern uplift, where most of the recent detailed work has been conducted, three individual lithotectonic domains and intrusive rocks that crosscut one or more domains have been defined (Mosher, 1996; Roback, 1996a)(Figs. 2 and 3). The southernmost domain, the Coal Creek domain, is a tonalitic to dioritic arc terrane (Garrison, 1981b, 1985; Roback, 1996a). The Coal Creek domain structurally overlies the Packsaddle domain to the north along the southwest-dipping Sandy Creek ductile thrust zone (Carter, 1989; Roback, 1996a; Whitefield, 1997). The Packsaddle domain consists of metavolcanic and metasedimentary supracrustal rocks intruded by metaplutonic rocks, all of which are polydeformed, and near the Coal Creek domain boundary, highly transposed (Carter, 1989; Nelis et al., 1989; Reese, 1995). The Packsaddle domain structurally overlies the Valley Spring domain to the north along a southwest-dipping ductile thrust zone (Reese, 1995). The Valley Spring domain is a polydeformed granitic gneiss terrane that consists of supracrustal and plutonic rocks and contains an older crustal component (ca. 1360 Ma) that may represent the southern margin of Laurentia (Reese et al., 1992; Reese, 1995; Roback, 1996a). The Valley Spring domain is the least-studied domain, and additional work (in progress) will probably subdivide it further. Each of these domains, summarized in the following, consists of rocks with a wide range in ages (Figs. 2 and 3; Table 1). I have extrapolated these domains to the central and western uplift, using previous stratigraphic correlations (e.g., Barnes, 1981), but further geochronological work is needed to test these relationships. Previous stratigraphic names are referenced below where helpful in relating recent work to previous literature.

Coal Creek Domain

The Coal Creek domain consists of a long-lived, 1326 ± 2 to 1275 +2/–1 Ma plutonic complex (Figs. 2 and 3), interpreted as an ensimatic arc (Roback, 1996a), that shows an early intrusive, deformational, and metamorphic history unique to that of the rest of the uplift. A large (6 × 2.3 km) tabular body of serpentinized harzburgite (Coal Creek Serpentinite) has been tectonically emplaced within the plutonic complex and shows a complicated history of serpentinization, metamorphism, and deformation (Gillis, 1989; Mosher and Gillis, unpublished data). The oldest parts of the complex are 1326 ± 2 to 1301 +2/–1 Ma, folded, well-foliated, gray, mafic to tonalitic gneisses (previously mapped as Big Branch Gneiss), found primarily south of the serpentinite, that underwent dynamothermal metamorphism ca. 1292 Ma (Roback, 1996a). North of the serpentinite, these gray tonalitic gneisses are cut by a younger, dioritic to tonalitic suite (previously mapped as part of the Packsaddle Schist Click Formation; older Packsaddle Schist of Mosher, 1993). These younger (1286 +6/–4 to 1275 +2/–1 Ma) cogenetic plutonic rocks show well preserved cross-cutting intrusive relationships and truncate the fabric in the older tonalitic gneisses, but are themselves foliated (Roback, 1996a). The Coal Creek domain also contains gabbros, amphibolites, mafic schists, and minor talc-rich and serpentinite bodies, all of which increase in abundance southward approaching the Coal Creek Serpentinite. Mafic rocks are Fe-rich, low- to medium-K_2O tholeiites composi-

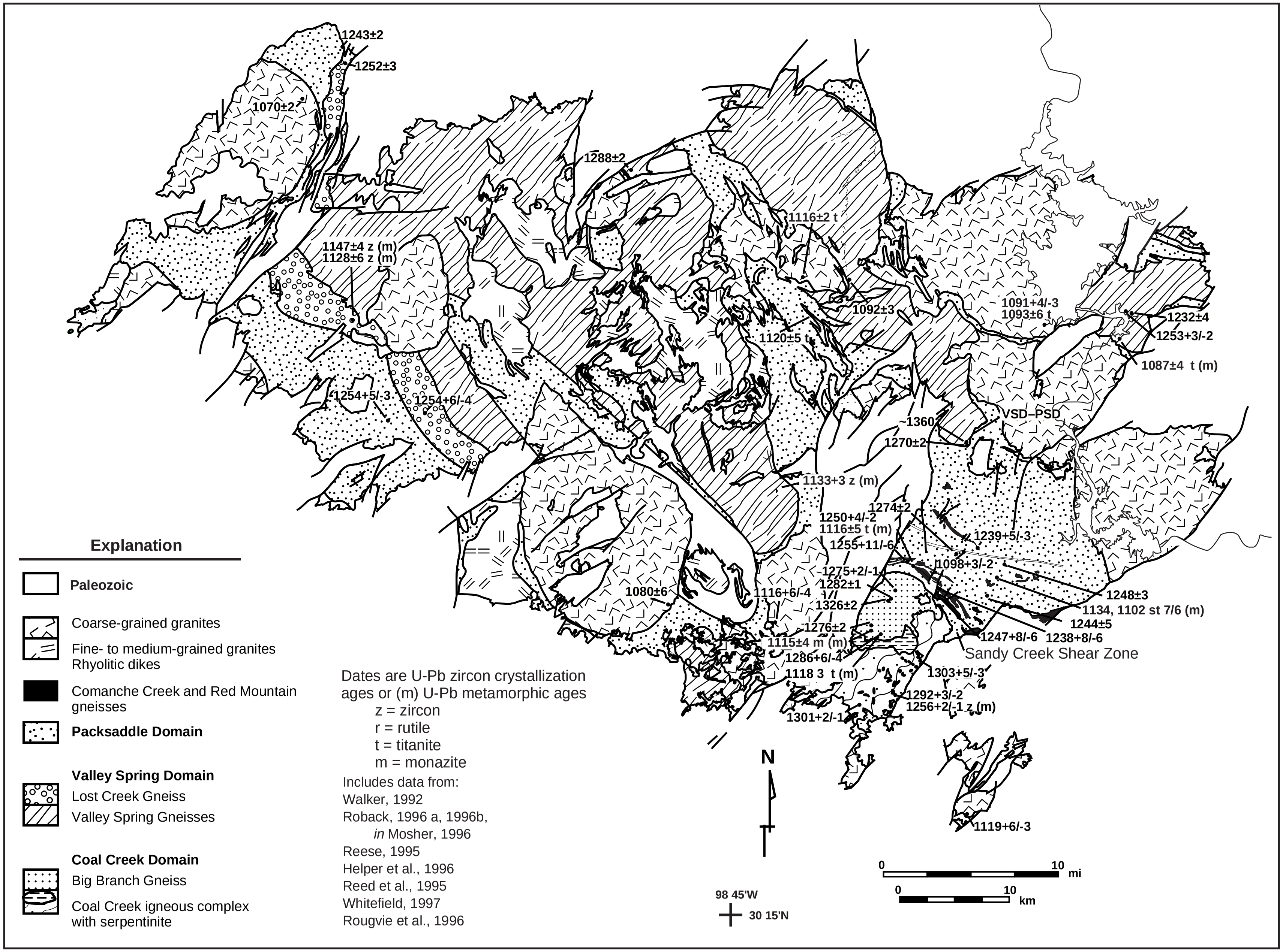

Figure 2. Geologic map of the Llano uplift, central Texas, showing lithotectonic domains and U/Pb dates (see Table 1). The uplift is an erosional window through Phanerozoic sedimentary cover. The rocks are locally cut by normal and oblique-slip faults related to the Ouachita orogeny. Modified after Barnes (1981) and Reed (1996a). (VSD–PSD—Valley Spring–Packsaddle domain boundary for southeastern uplift.)

tionally similar to present-day island arc tholeiites and ocean floor basalts (Garrison, 1981a, 1981b). An enigmatic younger metamorphism has been dated as 1256 +2/–1 Ma (Roback, 1996a). The structural stacking within the Coal Creek domain (older tonalitic gneisses overlying serpentinite that overlies younger plutonic rocks that become less mafic away from the serpentinite) suggests that the serpentinite represents arc basement or associated oceanic crust that has been tectonically imbricated with the roots of an ensimatic arc (Roback, 1996a).

The Coal Creek domain rocks have distinctly different geochemical and Nd and Pb isotopic signatures than those of the Packsaddle and Valley Spring domains to the north, indicating that the arc evolved separately from the rest of the uplift (Roback et al., 1995; Roback, 1996a; Whitefield, 1997). Initial Pb isotopic data from tectonized granitic rocks within the Packsaddle domain and Valley Spring domain and from post-tectonic granites plot along a 1.1 Ga $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ isochron (James and Walker, 1992; Smith et al., 1997), whereas Pb isotopic data for Coal Creek domain rocks plot above this isochron (higher $^{207}Pb/^{204}Pb$ for a specific $^{206}Pb/^{204}Pb$) (Roback et al., 1995; Roback, 1996a; Smith et al., 1997, Fig. 13). Sm-Nd isotopic data yield older model ages (1679 to 1403 Ma; e_{Nd} +1.2 and +3.9) for the Coal Creek domain than for most of the Packsaddle domain (1478 to 1276 Ma; e_{Nd} +2.4 to +4.8), the Valley Spring domain (1370 to 1231 Ma; e_{Nd} +3.6 to +5.4), and post-tectonic granites (1344 to 970 Ma; e_{Nd} +2.6 to +5.2) (Patchett and Ruiz, 1989; Roback et al., 1995; Whitefield, 1997; Smith et al., 1997, Fig. 14). The petrologic character is also different with plagioclase being the dominant feldspar in Coal Creek domain rocks and K feldspar in Packsaddle domain and Valley Spring domain rocks. The boundary between the Coal Creek and the Packsaddle domains is abrupt, and is marked by the change in the petrologic, geochemical, and Pb and Nd isotopic character of the rocks (Whitefield, 1997; Roback, 1996a). Rocks of questionable origin in the Packsaddle domain (cf. white gneiss of Roback, 1996a), yield distinct isotopic signatures tying them to the Packsaddle and Valley Spring domains (Whitefield, 1997; R. Roback, 1996, personal commun.).

Packsaddle Domain

Polydeformed rocks of the Packsaddle domain (Fig. 2) consist of hornblende, graphite, biotite, muscovite and actinolite schists, marbles, calc-silicate rocks, quartzites, and quartzofeldspathic rocks. These generally supracrustal rocks are interpreted to have been shallow shelf and slope

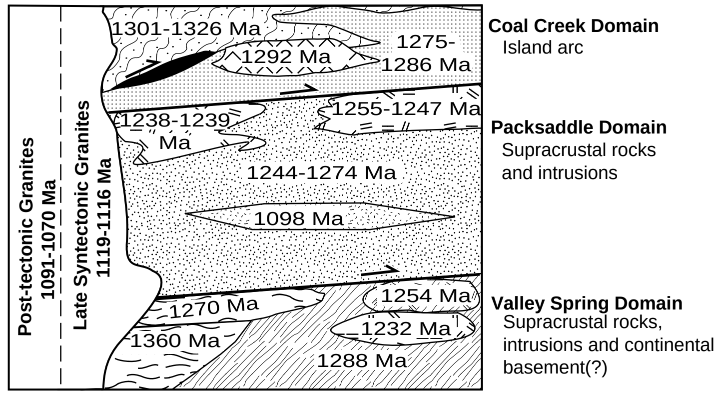

Figure 3. Structural column showing the spatial relationships among dated rocks and domains for the Llano uplift. Coal Creek Serpentinite is represented by solid black in Coal Creek domain. Intrusive rocks in Packsaddle domain and Valley Spring domain shown by random parallel line dashes are considered part of the same period of igneous activity and are stitching plutons for these two domains. Only the 1098 +3/–2 Ma rhyolite dike (Packsaddle domain) and post-tectonic granites are undeformed. Sources for data are given in Table 1. Modified from Mosher (1996).

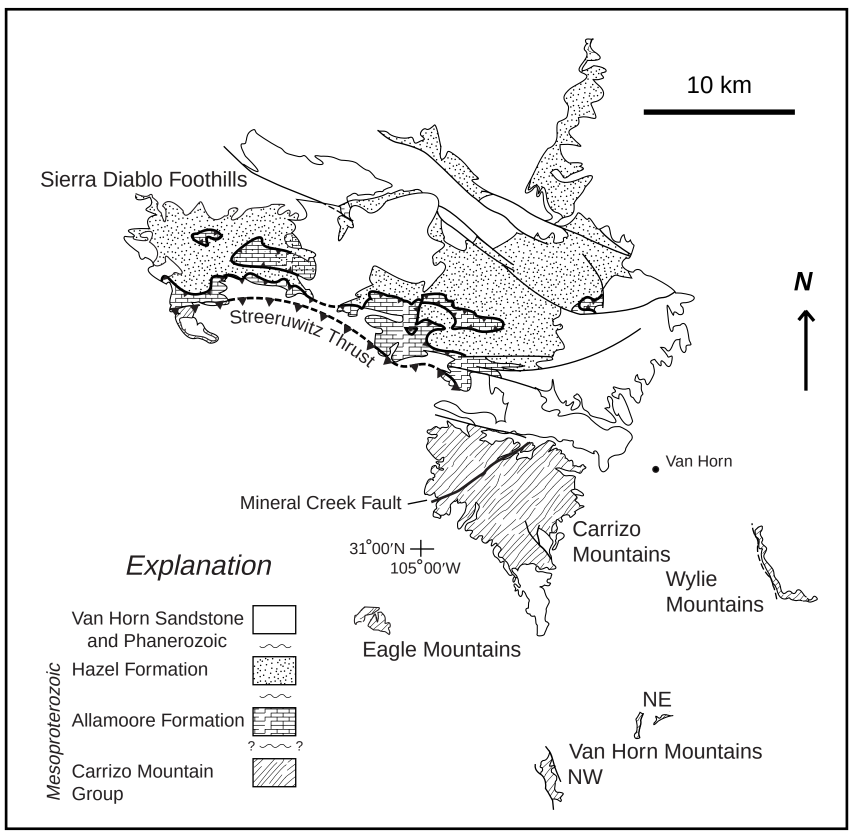

Figure 4. Geologic map of Mesoproterozoic exposures in west Texas, near Van Horn. The rocks have been uplifted and locally cut by Basin and Range faults (thin lines). Mesoproterozoic faults are shown by thick lines. Modified from Grimes (unpublished data).

TABLE 1. GEOCHRONOLOGY FOR THE MESOPROTEROZOIC EXPOSURES

	Dates (Ma)	Rock type	Reference
LLANO UPLIFT			
Coal Creek domain (CCD)			
Big Branch Gneiss	1326 ± 2* z	Tonalitic gneiss	Roback, 1996a
	1303 +5/–3* z	Tonalitic gneiss	Walker, 1992
	1301 +2/–1* z	Tonalitic gneiss	Roback, 1996a
Coal Creek plutonic complex	1292 +3/–2* z	Leucotonalite	Roback, 1996a
	1286 +6/–4* z	Hornblende gabbro	Roback, 1996a
	1282 ± 1* z	Leucogranodiorite	Roback, 1996a
	1276 ± 2* z	Tonalite	Roback, 1996a
	1275 +2/–1* z	Tonalite	Roback, 1996a
	1256 +2/–1*(m) z	Amphibolte	Roback, 1996a
	1118 ± 3* (m) t	Hornblende gabbro	Roback, 1996a
Dike	1115 ± 4* (m) m	Granitic dike	Roback, unpub. data, *in* Mosher, 1996
Packsaddle domain (PSD)			
Packsaddle "Schist"	1274 ± 2* z	White gneiss	Roback, 1996a
	1256 +6/–4 z	Quartz/feldspar gneiss	Roback, 1996b
	1248 ± 3 z	Volcanic rock†	Reese, 1995
	1247 +8/–6 z	Quartz/feldspar mylonite	Walker, 1992
	1244 ± 5 z	Volcanic rock†	Reese, 1995
	1243 ± 2 z	Quartz/feldspar gneiss	Walker, 1992
Sill	1255 +11/–6* z	Granite sill	Whitefield, 1997
	1250 +4/–2* z	Granite sill	Roback, 1996a
Red Mountain Gneiss	1239 +5/–3 z	Granite sill	Walker, 1992
Comanche Creek Gneiss	1238 +8/–6 z	Quartzmonzonite sill	Walker, 1992
Dike	1098 +3/–2 z	Rhyolite dike, undeformed	Walker, 1992
Packsaddle "Schist"	1134–1102 (m)st	Al-, Fe-rich pelites	Roback, 1996b, preliminary Pb^{207}/Pb^{206} age
Valley Spring domain (VSD)			
Valley Spring Gneiss	~1360 z	Gneiss	Reese, 1995
	1288 ± 2 z	Gneiss (type locality)	Roback, unpub. data, *in* Mosher,1996
	1270 ± 2 z	Augen gneiss	Reese, 1995
	1253 +3/–2 z	Foliated granitic rock	Roback, 1996b
Lost Creek Gneiss	1254 +6/–4 z	Quartz/feldspar gneiss	Roback, 1996b
	1252 ± 3 z	Quartz/feldspar gneiss	Walker, 1992
Inks Lake Gneiss ('Valley Spring')	1232 ± 4 z	Foliated granitic rock	Walker, 1992
Mason County eclogitic rocks	1147 ± 4* (m) z	Eclogite	Roback, 1996b
Oxford County eclogitic rocks	1133 ± 2* (m) z	Retrogressed eclogite	Roback, 1996b
Mason County eclogitic rocks	1128 ± 6* (m) z	Eclogite	Roback, 1996b
VSD/PSD/CCD	1115 ± 6* (m)m,t,r	Metamorphic rocks	Roback, 1996b
Town Mountain Granites			
Grape Creek pluton	1119 +6/–3 z	Syntectonic	Reed et al., 1995
Legion Creek pluton	1116 +6/–4 z	Syntectonic	Walker, 1992
Wolf Mountain pluton	1116 ± 2* t	Syntectonic	Roback, unpub. data, *in* Mosher, 1996
Oatman granite	1120 ± 5* t	Syntectonic	Rougvie et al., 1996
Llanite dike	1092 ± 2 z	Post-tectonic	Helper et al., 1996
Lone Grove pluton	1091 +4/–3 z	Post-tectonic	Walker, 1992
	1093 ± 6* t	Post-tectonic	Rougvie et al., 1996
Enchanted Rock pluton	1080 ± 6 z	Post-tectonic	Rougvie et al., 1996
Katemcy pluton	1070 ± 2 z	Post-tectonic	Rougvie et al., 1996
VAN HORN AREA			
Carrizo Mountain Group	1380 ± 20 z	Rhyolite	Soegaard et al., 1996
	1370 z	Rhyolite	Copeland and Bowring, unpub. data
	1327 ± 28 z	Rhyolite	Roths, 1993
Allamoore Formation	1256 ± 5 z	Felsic tuff	Glahn et al., 1996
	1247 ± 4 z	Felsic tuff	Glahn et al., 1996
Hazel Formation	1123 ± 29 z	Granite boulder	Roths, 1993
	1121 ± 23 z	Rhyolite boulder	Roths, 1993
FRANKLIN MOUNTAINS			
Castner Marble	1260 ± 20 z	Felsic tuffs	Pittenger et al., 1994
Thunderbird rhyolite	1111 ± 43 z	Rhyolite	Roths, 1993
Red Bluff Granite	1120 ± 35 z	Granite	Shannon et al., 1997
	1086 ± 5 z	Granite	Shannon et al., 1997
SIERRA DEL CUERVO, MEXICO	1333 +10/–8 z	Metagabbro	Blount, 1993
	1274 +6/–5 z	Metagranite	Blount, 1993
	1080 ± 5 z	Trondhemite	Blount, 1993
CENTRAL BASIN PLATFORM	1163 ± 4 z	Mafic intrusion	Keller et al., 1989

Note: All data, unless otherwise designated, are U/Pb zircon crystallization ages obtained using large multiple grain fractions. (m) metamorphic age; z—zircon; t—titanite, m—monazite; r—rutile; st—staurolite. Metamorphic zircons generally are rounded and lack internal, concentric igneous zoning. See references for more details.

*U/Pb ages determined using small size fractions (0.001–0.166 mg).

†Euhedral, multifaceted, zircons with internal, concentric zoning.

sediments with intermittent mafic and felsic volcanic flows, tuffs, and volcaniclastic deposits (i.e., arc and flank environment; Garrison, 1981a, 1981b; Mosher, 1993). Some intrusive rocks, generally sills, have been identified (Carter, 1989; Nelis et al., 1989; Roback, 1996a). One unit shows evidence of extensive weathering prior to metamorphism, producing probable laterites (Carlson and Reese, 1994). Near the Coal Creek domain boundary in the southeastern uplift, complete transposition of units precludes determination of many protoliths and original contact relationships. Farther north in the Packsaddle domain, deformation is less intense, and primary sedimentary structures and rare basaltic pillow lavas are preserved (Farmer, 1977; Reed et al., 1996). Metasedimentary units are abundant near the Valley Spring domain boundary in the southeastern uplift.

The supracrustal rocks record >30 m.y. of deposition (Figs. 2 and 3, Table 1). Felsic metavolcanic rocks interlayered with metasedimentary rocks have been dated as 1244 ± 5 and 1248 ± 3 Ma (Reese, 1995). Fine-grained quartzofeldspathic mylonitic rocks of the Packsaddle domain from within the Sandy Creek shear zone yield similar ages (1255 +11/–6 to 1247 +8/–6 Ma, Walker, 1992; Roback, 1996a; Whitefield, 1997), although some are considered sills, based on primary textures in less sheared zones (Roback, 1996a; Whitefield, 1997). Other younger granite (Red Mountain Gneiss) and quartz monzonite (Comanche Creek gneiss; marginal Big Branch Gneiss facies of Garrison, 1985) sills dated as 1238 +8/–6 Ma and 1239 +5/–3 Ma (Walker, 1992), respectively, intrude the Packsaddle domain supracrustal rocks. The oldest dated Packsaddle unit is a white gneiss ~4 km north of the Coal Creek domain boundary that yields an igneous crystallization age of 1274 ± 2 Ma (Roback, 1996a), indicating that some of the Packsaddle domain is older.

Valley Spring Domain

The Valley Spring domain dominantly consists of microcline-quartz (biotite/hornblende) gneisses and lesser amounts of schist, amphibolite, metagabbro, and marble (McGehee, 1979). In the northeastern uplift, the rocks are primarily granitic in composition, whereas in the western uplift, the rock types are more varied. Barnes (1988) suggested that probable protoliths are ignimbrites and rhyolitic volcanic rocks interbedded with local mafic igneous rocks, calcareous tuffs, limestones, and volcaniclastic deposits. Some gneisses are considered to have arkose and quartzofeldspathic sandstone protoliths on the basis of their mineralogy and field relationships (Garrison et al., 1979). In one location, textures indicative of peritidal carbonates have been preserved (Reed et al., 1996), and manganese deposits (Hess and Gobel, 1987) and a barite gneiss (Droddy, 1978) also suggest sedimentary origins. In some areas, protoliths for the gneisses are difficult to determine due to deformation and migmatization, although a wide range in $\delta^{18}O$ isotopic values (11.7‰–17‰) suggests multiple protoliths (Rougvie, 1993). Some gneisses show evidence of extreme chemical weathering prior to metamorphism (Droddy, 1978). The Valley Spring domain differs from the Packsaddle domain in that the rocks are predominately granitic in composition and represent terrigenous clastic rocks as well as volcanic and plutonic granitic rocks.

Dated igneous rocks range in crystallization age from 1288 ± 2 to 1232 ± 4 Ma (to perhaps ca. 1360 Ma) (Walker, 1992; Reese, 1995; Mosher, 1996; Roback, unpublished data)(Figs. 2 and 3, Table 1) and vary in degree of deformation from moderately foliated to polydeformed (Denny and Gobel, 1986; Helper, 1996). A thin (5 m) laterally extensive (>32 km) rhyolitic pyroclastic sheet at the tectonized Valley Spring domain–Packsaddle domain boundary has been dated as 1270 ± 2 Ma (Reese, 1995). The "Valley Spring Gneiss" (Inks Lake Gneiss; Reese, 1995) dated by Walker (1992) as 1232 ± 4 Ma is only moderately foliated, in contrast to adjacent polydeformed Valley Spring domain gneisses (Helper, 1996), indicating that it is probably an intrusion (Reese, 1995). Several gneisses contain zircons as old as ca. 1360 Ma (Reese, 1995), suggesting that part of the gneiss may represent older crust correlative with the southern Granite rhyolite terrane or that Laurentia was proximal and acted as a sediment source (Reese et al., 1992; Reese, 1995; Roback, 1996a).

Igneous Activity

In addition to the Coal Creek domain plutonic complex, two other major periods of igneous activity have affected the uplift. The first period, defined by an almost continuous span of ages from 1255 +11/–6 to 1232 ± 4 Ma (Walker, 1992; Roback, 1996b; unpublished data; Whitefield, 1997) (Table 1), appears to affect all of the uplift except the Coal Creek domain. Both the Packsaddle and Valley Spring domains contain abundant foliated granitic rocks of this age, and the granitic Lost Creek Gneiss in the western uplift, which has been arbitrarily grouped with the Valley Spring domain, also yields ages in this range (Walker, 1992; Roback, unpublished data). Although some of these rocks are clearly intrusive and others are volcanic rocks, all provide evidence of igneous activity during this time and suggest that the Packsaddle and Valley Spring domains were in close proximity. The older igneous rocks (1288 ± 2 to 1270 ± 2 Ma) within the Packsaddle and Valley Spring domains may be part of this period of igneous activity, but the ~15 m.y. hiatus from 1270 to 1255 Ma makes this less certain. The older igneous rocks in the Valley Spring domain are also granitic in composition, but the one from the Packsaddle domain (white gneiss, Roback, 1996a) is not.

Coarse-grained Town Mountain Granite and associated medium- to fine-grained granite plutons intruded the metamorphic rocks across the entire uplift during the second period of igneous activity between 1119 +6/–3 to 1070 ± 2 Ma (Walker, 1992; Reed, et al., 1995; Roback, 1996b), indicating that all domains were juxtaposed at this time. The youngest Town Mountain Granite intrusions (1091 +4/–3 to 1070 ± 2 Ma; Walker, 1992) are generally circular, undeformed, coarse-grained, pink K_2O-rich granite plutons. Associated medium- to fine-grained granites locally appear to be cogenetic with the coarse-grained Town Mountain Granite and are not distinctly different chemically (Cook et al., 1976). The oldest Town Mountain Granite intrusions (1119 +6/–3 to 1116 +6/–4 Ma) are late syntectonic (Reed and Helper, 1994; Reed, 1995, 1996b; 1119 +6/–3 Ma replaces previously reported preliminary age). Locally, ductile shear zones with protomylontic to ultramylonitic fabrics cut several of these otherwise undeformed granites and the surrounding country rocks (Reed and Helper, 1994; Reed, 1996a; Davidow, 1996). One large sheet-like intrusion, the Wolf Mountain intrusion, was folded by a broad, open regional fold (F_5?; see following) during solidification, as evidenced by a complex internal fabric, multiple dikes, and localized healed shear zones in the hinge region and a simpler internal structure on the limbs (Reed, 1995). Although these granites are deformed, they do not contain the penetrative fabrics of the country rock and only record the waning stages of orogenesis (Reed and Helper, 1994). Low-pressure contact metamorphic aureoles are observed around both late synorogenic and postorogenic granites (Reed, 1995; see following).

The Town Mountain Granite and associated granitic plutons, which compose nearly half of the Llano exposure, have homogeneous major element compositions with both I-type and A-type characteristics (Barker et al., 1996). Nd and Pb isotopic data (given in foregoing) and initial $^{87}Sr/^{86}Sr$ ratios (0.7048–0.7061; Garrison et al., 1979) indicate either depleted mantle or juvenile lower crustal sources for the magmas (Patchett and Ruiz, 1989; Barker et al., 1996; Smith et al., 1997). Although granitic gneisses of the Valley Spring domain have Pb and Nd isotopic values similar to those of the granites, the initial $^{87}Sr/^{86}Sr$ ratios (~0.7105 at 1.1 Ga, Smith et al., 1997) are different, indicating that the Valley Spring domain gneisses were not a major magma source for the granites (Barker et al., 1996; Smith et al., 1997). Anatexis of slightly older, juvenile tonalitic crust is favored by trace element models for one elliptical pluton (Smith et al., 1997).

Deformation

Metamorphic rocks of all three domains record a polyphase deformational history that occurred synchronous with a high-pressure, amphibolite to granulite facies metamorphism. Both the Packsaddle and Valley Spring domains are generally pervasively deformed, whereas parts of the Coal Creek domain (1286 +6/–4 to 1275 +2/–1 Ma plutonic suite) are much less deformed. A wide (2–3 km), high-strain mylonitic zone (Sandy Creek shear zone; Fig. 2) forms the boundary between the Coal Creek and Packsaddle domains (Carter, 1989; Roback, 1996a), and the rocks immediately north of the boundary within the Packsaddle domain are the most intensely deformed and transposed rocks within the Llano uplift. The boundary between the Packsaddle and Valley Spring domains in the southeastern uplift is a narrow (~100 m wide), low-strain ductile shear zone, and mylonites are found throughout the Packsaddle domain (Reese, 1995). Tectonic transport for all of these ductile shear zones, as indicated by asymmetry of porphyroclasts in mylonites, is toward the northeast (Reese, 1995; Whitefield, 1997).

In the southeastern uplift, the Packsaddle domain rocks record five phases of outcrop- to regional-scale, noncoaxial, noncoplanar folding (F_1–F_5), and formation of five associated penetrative metamorphic foliations (S_1–S_5) (Mosher, 1993). Detailed studies (Carter, 1989; Nelis et al., 1989; Reese, 1995) of these rocks have shown a complex history as summarized in the following. F_2 are isoclinal folds of S_1 and S_0 that locally fold F_1, producing type II (mushroom; Ramsey, 1967) interference patterns. F_3 folds are northeast-verging, tight to isoclinal, nearly chevron-shaped folds of S_2 and locally F_2, whereas F_4 are north-verging, closed to tight, asymmetric chevron folds. F_5 are northeast-verging, overturned, open to tight folds of all previous generation structures. Each fold generation is characterized by a penetrative axial-planar foliation. These foliations are typically crenulation cleavages of previous generation foliations with metamorphic differentiation along the limbs. The regionally pervasive foliation is a composite of S_1 and S_2 foliations, although locally near the Coal Creek domain boundary, S_3 is dominant. S_2 is also a mylonitic foliation in places and is folded by subsequent fold generations. F_2, F_3, and F_5 fold hingelines are southeast- to south-southeast trending, although F_5 folds show less spread, and have primarily southeast-trending hingelines. S_2,

S_3, and S_5 foliations are northwest striking and southwest dipping, except where reoriented by younger folds. F_4 fold hingelines, in contrast, are generally east trending with east-striking foliations, although they are folded by F_5 folds. Locally, minor, late-stage to postcontractional, north-south extension is observed (Carter et al., 1993; Reese, 1995). Although the intensities of deformation and transposition increase toward the Coal Creek domain boundary, the complexity, orientations, and geometry of the structures do not change.

All three domains are affected by the dominant S_2 foliation of the Packsaddle domain. S_2 foliation in the Packsaddle domain can be traced southward into the Sandy Creek shear zone, where it becomes mylonitic (Carter, 1989), and into the Coal Creek domain (Roback, 1996a; Whitefield, 1997). In the Coal Creek domain, locally developed, post-S_2 structures are similar in orientation and superposed geometry to those in the Packsaddle domain, but because they affect plutonic rather than supracrustal rocks, the structures are difficult to directly correlate (Gillis, 1989). S_2 foliation also can be traced northward from the Packsaddle domain into the Valley Spring domain, and it becomes mylonitic in the ductile shear zone at the domain boundary (Reese, 1995). This ductile shear zone is folded by subsequent fold generations. Farther north within the Valley Spring domain of the eastern uplift, rocks are polydeformed with styles, orientations, and superposed geometries (Helper, 1996; Denny and Gobel, 1986) similar to those of the Packsaddle domain in the southeastern uplift, but further work is necessary to demonstrate the temporal relationships.

The timing of polyphase folding and mylonitization in the southeastern uplift is constrained between 1238 +8/–6 to 1098 +3/–2 Ma by pretectonic to post-tectonic sills and dikes in the Packsaddle domain (Walker, 1992) (Figs. 2 and 3). Within the Sandy Creek shear zone, sills ranging in age from 1255 +11/–6 Ma (Whitefield, 1997) to 1238 +8/–6 Ma (Walker, 1992) are mylonitized along with the enclosing Packsaddle domain rocks, providing a lower limit on the timing of mylonitization. North of the shear zone in the Packsaddle domain, granitic sills (Red Mountain Gneiss) dated as 1239 +5/–3 Ma (Walker, 1992) are folded by F_2–F_5 and contain S_1 foliation (Nelis et al., 1989). Thus, the mylonites, F_1, S_1, and all subsequent fold generations in the Packsaddle domain formed after 1239 +5/–3 Ma. The youngest (1232 ± 4 Ma; Walker, 1992) deformed metamorphic rock, located in the Valley Spring domain in northeastern uplift, further constrains the timing of penetrative deformation. An undeformed, regionally extensive rhyolitic dike dated as 1098 +10/–6 Ma (Walker, 1992) crosscuts all structures, providing an upper limit on the deformation (Nelis et al., 1989).

Outside of the eastern uplift, rocks mapped as Packsaddle Schist and Valley Spring Gneiss show an equally complex deformational history. Preliminary detailed mapping (Hunt, 1996; M. A. Helper, S. Mosher, S. Anderson, unpublished mapping) and examination of previous work (Mutis-Duplat, 1972; Droddy, 1978) in the western uplift indicate that early structures generally trend northeast to east and some southeast-trending structures verge southwestward. Thus, this area may record a different kinematic history with east- to northeast-trending structures playing a more significant role.

Metamorphism

The metamorphic rocks in all three domains record a complex polymetamorphic history (reviewed by Carlson and Schwarze, 1997; Carlson, 1998). An early dynamothermal, high- to moderate-pressure, amphibolite to granulite (transitional to medium-temeperature eclogite) facies regional metamorphism was overprinted by a low-pressure, generally static, mid-amphibolite facies metamorphism (Wilkerson et al., 1988; Carlson, 1998; Carlson and Schwarze, 1997, and references therein), both of which affect all three domains. Metamorphic conditions for the dynamothermal event do not change abruptly across domain boundaries, consistent with the metamorphic foliation, S_2, affecting all three domains.

Pressure-temperature (*P-T*) conditions for the dynamothermal metamorphism decrease from a high in the western uplift northeastward parallel to the direction of tectonic transport documented for the southeastern uplift (Reese, 1995; Carlson and Schwarze, 1997). The highest *P-T* conditions of 750 ± 50 °C and ~15 kbar are recorded by medium-*T* eclogites (pyropic garnet + sodic clinopyroxene + pargasitic amphibole + rutile ± orthopyroxene) in the western uplift (Wilkerson et al., 1988; Davidow, 1996; Carlson and Schwarze, 1997; Carlson, 1998). Temperatures are determined from cation-exchange thermometry (Fe-Mg exchange for garnet-clinopyroxene, garnet-orthopyroxene, garnet-hornblende pairs and Ca-Mg exchange for orthopyroxene-clinopyroxene) and pressures are estimated based on Al content of orthopyroxene equilibrated with garnet (see Carlson and Schwarze, 1997, for discussion). An in situ origin for the eclogitic rocks is supported by field relations and totally homogenized (flat) garnet growth zoning profiles from the surrounding rocks (to 5 km away). In the northern uplift, a garnetiferous amphibolite, showing relict eclogitic textures, records temperatures of ~585 °C, on the basis of Fe-Mg exchange thermometry on omphacite inclusions and inclosing garnet, and pressures of 6–8 (?) kbar, estimated from inclusion suites within garnets (Carlson and Johnson, 1991; Carlson and Schwarze, 1997). Garnets from the northern uplift have steep internal compositional gradients, again supporting an in situ origin for the eclogitic rocks (Carlson and Schwarze, 1997). In the southeastern uplift, peak conditions of ~700 °C and ~7 kbar have been estimated based on phase equilibria using an incomplete reaction between Fe-rich, high-H staurolite + quartz producing almandine and sillimanite in Al- and Fe-rich pelitic rocks of the Packsaddle domain (Carlson and Reese, 1994; Carlson, 1998). Garnet growth zoning profiles in this area are consistent with these conditions (Carlson and Schwarze, 1997). The Fe-rich, high-H staurolite is aligned parallel to S_2 (Carlson and Reese, 1994), and nearby, high-H staurolite occurs as inclusions in garnet that overgrows S_2 and S_3, but not S_4 and S_5 (Carlson and Nelis, 1986). Thus, in the Packsaddle domain, the high-*P*, high-*T* metamorphism was synchronous with the early phases of deformation. In the Coal Creek domain, a relict metamorphic assemblage of enstatite + forsterite ± anthophyllite in the serpentinite suggests temperatures of ~710 °C or higher (Garrison, 1981a, 1981b) and pressures at 8–10 kbar, if anthophyllite grew during prograde metamorphism (Gillis and Mosher, unpublished data), consistent with the metamorphic conditions in the Packsaddle domain. The fosterite, and locally enstatite, define a tectonic foliation interpreted to be correlative with S_2 in the rest of the Coal Creek domain (Gillis, 1989), further suggesting that it underwent the same dynamothermal history as the rest of the uplift.

Timing of the high-*P*, dynamothermal metamorphism has been further constrained by dating of metamorphic minerals (Roback, 1996b; Roback and Carlson, 1996). Metamorphic zircon from eclogitic rocks yields ages of 1147 ± 4 to 1128 ± 6 Ma, and the syntectonic staurolite used to determine *P-T* conditions in the Packsaddle domain yields preliminary $^{207}Pb/^{206}Pb$ ages of 1134 to 1102 Ma (Roback, 1996b; Roback and Carlson, 1996; Table 1). These ages may record a high-*T* part of the prograde path, however, rather than the highest *P* conditions. U-Pb titanite, rutile, and monazite ages from across the entire uplift (all domains), except adjacent to or from post-tectonic plutons, yield ages of 1115 ± 6 Ma (Roback, 1996b) (Table 1). These ages are 25–45 m.y. older than the crystallization ages for the undeformed, post-tectonic plutons (1091 +4/–3 to 1070 ± 2 Ma; Walker, 1992). Thus, they are not the result of an associated thermal event or contact metamorphism and record different parts of the retrograde path. These ages are compatible with the protolith age constraints for deformation in the Packsaddle and Valley Spring domains (1232 ± 4 to 1098 +3/–2 Ma). Taken together, these data indicate that dynamothermal metamorphism occurred in the ca. 1150 to 1115 Ma range with the most penetrative deformation prior to ca. 1119 Ma, the age of the oldest dated late syntectonic granites. Deformation could have commenced somewhat earlier (but <1232 Ma) because the zircons may not record peak pressure conditions. The narrow age range for minerals with distinctly different blocking temperatures (monazite, 640–730 °C; titanite, 500–670 °C; rutile 380–420 °C; Mezger et al., 1989, Mezger et al., 1991) indicates rapid cooling (Roback, 1996b), probably associated with rapid uplift and exhumation. The late syntectonic granites that were generated during the same time period (1119 +6/–3 to 1116 +6/–4 Ma) show both contractional deformation and low-*P* aureoles, indicating that contraction was still under way during uplift.

The Coal Creek domain also records earlier metamorphic events (Table 1). The 1326 ± 2 to 1301 +2/–1 gray tonalitic gneisses (Big Branch Gneiss) underwent dynamothermal metamorphism prior to intrusion of the 1286 +6/–4 to 1275 +2/–1 Ma dioritic to tonalitic plutonic suite, probably during the formation of anatectic melts dated as 1292 +3/–2 Ma (Roback, 1996a). Amphibolites intruded by these anatectic melts contain metamorphic zircons yielding ages of 1256 +2/–1 (Roback, 1996a).

Regional dynamothermal metamorphism has been overprinted by a primarily static, mid-amphibolite facies metamorphism throughout the uplift. Isotopic evidence indicates that reheating and hydration are genetically related to post-tectonic granite pluton emplacement (Bebout and Carlson, 1986). Temperatures ranged from ~475 to ~625 °C, and pressures ranged from 2.2 to 3.2 kbar (Wilkerson et al., 1988; Carlson, 1992; Letargo and Lamb, 1993; Letargo et al., 1995; Carlson and Schwarze, 1997).

Tectonic Evolution

Mesoproterozoic orogenic activity recorded in central Texas spanned ~300 m.y. and apparently culminated with the collision of a long-lived (~50 m.y.) island arc terrane with a continental block that may represent the southern margin of Laurentia. The presence of medium-*T* eclogites, characteristic of A-type subduction, indicates collision of a continental block as well.

The Valley Spring domain and Packsaddle domain rocks overlap in age and probably represent a continuum from a continental to marine environment with intermittent volcanism and plutonism along the continental margin prior to collision. The Valley Spring domain arkosic and quartzofeldspathic sedimentary rocks show continental affinities, and the Packsaddle domain contains fewer quartzofeldspathic rocks and a wider variety of supracrustal rock types indicative of a continental margin shelf and slope deposit. The associated felsic volcanic and plutonic rocks in the Valley Spring and Packsaddle domains could be arc related, with the clastic rocks representing eroded arc material interlayered with marine sediments along a continental margin. If so, the almost uniformly granitic compositions of the rocks in the northeastern uplift suggest that the arc is most likely located north of or within the northeastern uplift. Alternatively, these rocks could be part of a continental rift sequence; no geochemical data are available to help constrain their origin.

The Coal Creek domain represents the base of an ensimatic arc that evolved separately from the rest of the Llano uplift (Roback, 1996a). Magmatism ranged from 1326 ± 2 Ma to 1275 +2/–1 Ma. The arc may have continued to be active after that time, but thorough and systematic dating of the preserved portion has not yielded younger protolith ages. In the rest of the uplift, felsic plutonism and volcanism occurred from about 1255 +11/–4 Ma to about 1232 ± 4 Ma. The lack of similar igneous activity at this time in the Coal Creek domain suggests that it was not yet accreted, although it was probably no longer active, as implied by a metamorphic zircon age of 1256 +2/–1 Ma.

Accretion of the island arc (Coal Creek domain) occurred before 1119 +6/–3 Ma, on the basis of stitching plutons (Town Mountain Granite) that intrude all domains, and after 1275 +2/–1 Ma, the youngest age for rocks of the Coal Creek domain igneous complex. Mylonites formed at the Coal Creek domain and Packsaddle domain boundary after 1238 +8/–6 Ma, and mylonitization, intense strain, and transposition by polyphase folding occurred within the Packsaddle domain after 1239 +5/–3 Ma. Thus, although accretion may have begun earlier, most of the collision-related deformation and metamorphism occurred between 1238 +8/–6 Ma and 1119 +6/–3 Ma. Dating of the dynamothermal metamorphism (Roback, 1996b) narrows this window to ca. 1150–1119 Ma with waning stages of deformation continuing until ca. 1115 Ma.

The genesis of the late syntectonic and post-tectonic plutons is unknown. The oldest (1119 +6/–3 to 1116 +6/–4 Ma) formed during contraction and rapid uplift, as shown by the overlap in ages with U/Pb dates for titanite, monazite, and rutile. The juvenile Nd signature of both late syntectonic and post-tectonic plutons suggests they could be related to extension collapse of the orogen or delamination following collision, but further work is needed.

WEST TEXAS EXPOSURES

The Mesoproterozoic continental margin is exposed in west Texas near Van Horn (Fig. 1), where polydeformed metamorphosed supracrustal and minor intrusive rocks (Carrizo Mountain Group) are thrust onto Mesoproterozoic carbonates (Allamoore Formation), volcanic rocks (within Allamoore and Tumbledown Formations), and synorogenic conglomerates and sandstones (Hazel Formation) along the west-northwest–trending Streeruwitz thrust (King and Flawn, 1953) (Fig. 4). The associated fold-and-thrust belt is only 3–5 km wide and is interpreted to have formed as a result of transpression (Soegaard and Callahan, 1994). These rocks are undeformed immediately to the north, as are correlative carbonate (Castner Marble) and volcanic rocks (Mundy Breccia and within the Castner Marble) to the west in the Franklin Mountains, near El Paso (King and Flawn, 1953; McLelland et al., 1995) (Fig. 1). These rocks are unconformably overlain by undeformed, Neoproterozoic to Cambrian sedimentary rocks (Van Horn Sandstone; King and Flawn, 1953). Thus, this thrust belt marks the northernmost extent of Grenville age deformation along the southern margin of Laurentia.

The sedimentary rocks north of the Streeruwitz thrust in the Sierra Diablo foothills consist of both preorogenic and synorogenic rocks (Fig. 4). Preorogenic rocks are thin-bedded, laminated carbonates interlayered with chert, subaqueous or subaerial basalt flows, mafic pyroclastic rocks, volcaniclastic sedimentary rocks, and felsic tuffs dated as 1247 ± 4 and 1256 ± 5 Ma (Glahn et al., 1996) (Table 1). The carbonates contain stromatolites indicative of a shallow subtidal or intertidal environment (Nyberg and Schopf, 1981; Toomey and Babcock, 1983). Trace element geochemical data for volcanic rocks in the Allamoore Formation show unaltered felsic tuffs (<1 m to 18 m thick) plotting in the volcanic-arc granite field and slightly altered basalts (37 m thick) plotting in the island-arc tholeiite field on tectonic discrimination diagrams (Table 2) (Roths, 1993). Unaltered basalts of the Tumbledown Formation (~100 m thick) fall along the boundary between within-plate and mid-oceanic-ridge basalt (MORB) fields on the same discrimination diagrams (Roths, 1993), although basalts from both formations show a strong Nb depletion, suggesting a subduction-related setting (Roths, 1993) (Table 2). The trace elements used, with the exception of Rb, most likely reflect the original chemistry of these unaltered and slightly altered rocks. In particular, the significantly lower Nb relative to La and Th values should be characteristic of the original basalts. An angular unconformity separates the preorogenic and synorogenic units and shows evidence of an irregular topography and karst formation (King and Flawn, 1953; Roths, 1993).

The synorogenic conglomerates and sandstones overlying the preorogenic rocks were deposited in alluvial fans with a southern source and interfinger with a northern eolian dune sandstone facies (Soegaard and Callahan, 1994). The immature conglomerate is predominately composed of clasts from the preorogenic rocks; there are none from the metamorphic rocks (Carrizo Mountain Group) located to the south (King and Flawn, 1953; Soegaard and Callahan, 1994). Less-abundant granite and porphyritic rhyolite clasts, found in the upper part of the section (Soegaard and Callahan, 1994), have been dated as 1123 ± 29 Ma (Roths, 1993). These clasts are similar in composition, texture, and age to those that crop out farther west in the Franklin and Hueco Mountains and Pump Station Hills (see following; Fig. 1). Paleomagnetic pole positions for the synorogenic rocks support deposition between ca. 1100 and 1080 Ma (Elston and Clough, 1993; also see discussion in Soegaard and Callahan, 1994), which is consistent with the maximum age constraint provided by the ca. 1123 Ma clasts. Syndepositional deformation caused structural imbrication of the preorogenic and synorogenic rocks and subsequent folding (Reynolds, 1985; Soegaard and Callahan, 1994). Vertical east-trending mylonites in carbonates show horizontal stretching lineations, suggesting strike-slip zones (Soegaard and Callahan, 1994). Rocks adjacent to the thrust are very low grade, containing chlorite, epidote, and talc, with alteration attributed to hydrothermal flow (King and Flawn, 1953). All evidence of deformation and alteration dies out within ~7 km of the Streeruwitz thrust.

South of the Streeruwitz thrust, metamorphosed supracrustal and minor intrusive rocks (Carrizo Mountain Group) (Fig. 4) increase in grade southward from greenschist to middle to upper amphibolite facies (Mosher, 1993). The Carrizo Mountain Group rocks consist of quartzites, feldspathic quartzite, metaarkose, rare conglomerate, pelitic schist, and metacarbonate interlayered with voluminous, peraluminous metarhyolite flows and welded ash-flow tuffs ranging in age from 1380 ± 20 to 1327 ± 28 Ma (Copeland and Bowring, 1988, unpublished data; Roths, 1993; Soegaard et al., 1996) (Table 1). Intrusive rocks are pretectonic (Grimes, 1996) and include ~1–600-m-thick metadiabase sills, granodiorite bodies, and a few rhyolitic dikes. In northern low-grade exposures (northern Carrizo Mountains), primary sedimentary and igneous structures are preserved, allowing the determination of protoliths. These rocks can be correlated with the higher grade equivalents in southern exposures (southern Carrizo, Eagle, Wylie, Van Horn Mountains; Fig. 4) except for some amphibolites with apparent sedimentary protoliths and iron-rich metacherts in the southernmost exposures (northwest Van Horn Mountains; King and Flawn, 1953; Mosher 1993). On tectonic trace element discrimination diagrams (Table 2), geochemical data for the low-grade metarhyolites plot in the within-plate (Rudnick, 1983; Roths, 1993) or extensional basin fields (Rudnick, 1983; Norman et al., 1987). Sm-Nd isotopic data yield model ages of 1560 to 1320 Ma (e_{Nd} +2.8 to +5.7; Patchett and Ruiz, 1989). The Sm-Nd isotopic data, age, and geochemistry of these metarhyolites are similar to those of the southern Granite rhyolite terrane (cf. Van Schmus et al., 1996). The diabase sills, which intrude the supracrustal rocks, are chemically similar to low-K_2O tholeiites with rare earth element patterns and trace-element ratios appropriate for type II MORB ocean-floor basalts (Rudnick, 1983). Trace element geochemical data for the low-grade diabase sills overlap the island-arc, within-plate, and MORB fields on tectonic discrimination diagrams (Table 2) (Rudnick, 1983; Roths, 1993; Norman et al., 1987). On a MORB-normalized incompatible-element distribution diagram (Pearce, 1983), the diabase data show distributions consistent with continental margin arc or evolved island arcs (progressive increase from Yb to Ce and small Ta anomaly) (Rudnick, 1983; Norman et al., 1987). Rudnick (1983) concluded, based on igneous interelement correlations, that all of the preceding elements, except Rb, were immobile during the low-grade metamorphism that affected the analyzed samples.

Polyphase deformation synchronous with metamorphism has affected the Carrizo Mountain Group. Both the complexity and intensity of deformation and metamorphic grade increase southward. The southern exposures (Van Horn to southern Carrizo Mountains) show four to five generations of noncoaxial folds, the first three of which have associated penetrative metamorphic fabrics (Bristol and Mosher, 1989; Grimes, 1996). Peak metamorphic conditions were synchronous with S_2 foliation formation (Bristol and Mosher, 1989; Grimes, 1996). Garnet-biotite Fe-Mg exchange thermometry on pelitic schists yield peak temperatures of 640º ± 50º C in the southernmost exposures (northwest Van Horn Mountains) (Bristol and Mosher, 1989) decreasing to ~500 ºC northward in the southern Carrizos Mountains (Grimes, 1996). Subsequent structural generations formed at decreasing temperatures. In the central and northern Carrizo Mountains, two generations of coaxial folds and mylonites that show northwestward transport dominate (Grimes and Mosher, 1996; DuBois and Nielsen, 1996). Peak metamorphic conditions are associated with S_2 foliation formation and decrease to biotite grade near the thrust. DuBois and Nielsen (1996) reported evidence of later, lower temperature, left-lateral and northwestward thrust movement on the Mineral Creek fault (Fig. 4). No post-tectonic plutonic bodies intrude the Carrizo Mountain Group, although large pegmatites cross cut all structures in the southernmost exposure (northwest Van Horn Mountains) (King and Flawn, 1953; Bristol and Mosher, 1989).

The timing of synmetamorphic deformation of the Carrizo Mountain Group and the relationship to thrusting within and over the sedimentary rocks are poorly constrained. The Carrizo Mountain Group was metamorphosed and polydeformed after ca. 1300 Ma and prior to thrusting over the foreland sediments. Thrusting within the sedimentary rocks occurred after ca. 1123 Ma (age of clast in synorogenic conglomerate; Roths, 1993), and perhaps between 1100 and 1080 Ma based on paleomagnetic data from the synorogenic sedimentary rocks (Elston and Clough, 1993). Muscovite from mylonites near the thrust give $^{40}Ar/^{39}Ar$ ages of 1020 ± 20 Ma (Bickford et al., 1995), and post-tectonic pegmatites give Rb-Sr ages mineral ages of 1100 to 1020 Ma (Wasserburg et al., 1962). Several lines of evidence suggest that polyphase deformation of the Carrizo Mountain Group and thrusting of the foreland sedimentary rocks and synorogenic sedimentation are part of a progressive deformation that culminated in their juxtaposition along the Streeruwitz thrust. (1) Within the Carrizo Mountain Group, temperatures decrease with structural generation (time) and toward the Streeruwitz thrust. (2) The decrease in metamorphic grade continues across the thrust, going from low grade immediately below to the thrust to unmetamorphosed farther north. (3) The northwestward tectonic transport direction within the Carrizo Mountain Group is compatible with transpressional deformation of the foreland sedimentary rocks along the generally east-trending faults. On the basis of present data, however, it is equally possible that these represent two unrelated events widely separated in time.

In the Franklin Mountains near El Paso (Fig. 1), rocks correlative with the preorogenic sedimentary rocks north of the Streeruwitz thrust crop out and are overlain by noncorrelative sandstones and volcanic rocks. The entire sequence is undeformed, but has been intruded by plutonic rocks and contact metamorphosed to albite-epidote or hornblende hornfels facies. Correlative rocks include carbonates (Castner Marble), which contain felsic volcanic ash layers dated as 1260 ± 20 Ma (Pittenger et al., 1994), and an overlying basalt breccia (Mundy Breccia). The carbonates formed on a northwest-trending, low-energy carbonate ramp, based on stromatolite orientations and other

TABLE 2. GEOCHEMISTRY FOR WEST TEXAS EXPOSURES

Location	Rock type	Tectonic environment	Diagram and explanation	Reference
Carrizo Mountain Group 1380 ± 20 to 1327 ± 28 Ma	Metarhyolites (low grade)	Within plate	Nb vs. Y Rb vs. Y + Nb (Pearce et al., 1984)	Rudnick, 1983 and Roths, 1993
		Extensional basin	La/Yb vs. Yb	Rudnick, 1983 and Norman et al., 1987
		Th-rich part of calc alkaline subduction-related field*	Hf-Ta-Th (Woods, 1980)	Rudnick, 1983 and Norman et al., 1987
	Diabase sills (low grade)	Continental margin arc; evolved island arcs	Incompatible-element distribution; MORB normalized (Pearce, 1983)	Rudnick, 1983 and Norman et al., 1987
		Overlaps island arc, within plate, MORB	TiO_2 vs. Zr Zr/Y vs. Zr. (Pearce and Cann, 1973)	Rudnick, 1983 and Roths, 1993
		Between island arc, MORB	Hf-Ta-Th (Woods, 1980)	Rudnick, 1983 and Norman et al., 1987
Allamoore Formation 1256 ± 5, 1247 ± 4	Felsic tuffs (unaltered)	Volcanic arc granite	Nb vs. Y (Pearce et al., 1985)	Roths, 1993
			Rb vs. Y + Nb (Pearce et al., 1985)	Roths, 1993
	Basalts (altered-clay, chlorite, epidote)	Island arc tholeiite	TiO_2 vs. Zr Zr/Y vs. Zr (Pearce and Cann, 1973)	Roths, 1993
		Subduction component	Nb depletion (Thompson et al., 1984)	
Tumbledown Formation	Basalts (unaltered)	Within plate/MORB	TiO_2 vs. Zr Zr/Y vs. Zr. (Pearce and Cann, 1973)	Roths, 1993
		Subduction component	Nb depletion (Thompson et al., 1984)	
Franklin Mountains				
Mundy Breccia 1260 ± 120 Ma	Basalts	Overlap island arc/MORB	TiO_2 vs. Zr Zr/Y vs. Zr (Pearce and Cann, 1973)	Roths, 1993
Red Bluff Granite 1120 ± 35 to 1086 ± 5 Ma	Granite	Continental rift	La/Yb vs. Yb Nb vs. Y	Norman et al., 1987 Shannon et al., 1997
Cerro el Carrizalillo				
	Trondhjemite Granite	Partial melting of amphibolites	Comparison of field relations, bimodal rock associations, geochemistry with other trondhjemites	Blount, 1993
Sierra del Cuervo				
1333 +10/–8 Ma	Metagabbros Metadiorites	Base of over-thickened island arcs; continental margin arcs	HREE-depleted low Y content; (Gill, 1981)	Blount, 1993
1274 +6/–5 Ma	Granite	Arc setting? Partial melting of granitic material	Low REE; no continuous fractionation series	Blount, 1993
	Metabasaltic	Mixed MORB/island arc	TiO_2 vs. Zr Zr/Y vs. Zr (Pearce and Cann, 1973) V vs. Ti (Shervais, 1982) Zr-Ti-Y (Pearce and Cann, 1973) Zr-Nb-Y (Meschede, 1986)	Blount, 1993
	Metadiabase	Within plate	Same five as metabasalts	Blount, 1993
1080 ± 5 Ma	Trondhjemites	Partial melting of amphibolites	See Cerro El Carrozalillo	Blount, 1993

Note: Dates given for reference; see Table 1. MORB—mid-oceanic-ridge basalt; REE—rare earth element; HREE—heavy rare earth element.
*Not uncommon for continental within-plate volcanic rocks (Condie, 1989, p. 221).

paleocurrent indicators, and change in facies from intertidal to subtidal, recording a marine transgression (Pittenger et al., 1994). The overlying olivine tholeiitic basalt represents a submarine eruption (Thomann and Hoffer, 1985; Pittenger et al., 1994). The carbonate-basalt contact is characterized by polymictic megabreccias consisting of thin-bedded carbonate blocks and basalt clasts and intrusions in a muddy, flat-pebble conglomerate matrix. This evidence for syneruptive mixing of the basaltic breccia and carbonate indicates that the basalt is of approximately the same age (Pittenger et al., 1994). Limited geochemical data for these basalts are available; two analyses plot in the area of overlap between the island-arc and MORB thoeliite fields on tectonic trace element discrimination diagrams (Table 2) (Roths, 1993). The overlying, noncorrelative, thick sandstones represent a tide-dominated inner shelf deposit (Seeley, 1990). The sedimentary rocks are overlain by trachyte flows and rhyolitic ignimbrites dated as 1111 ± 43 Ma and are intruded by a comagmatic alkalic and granitic suite dated as 1120 ± 35 Ma and 1086 ± 5 Ma (Thomann, 1981; Roths, 1993;

Shannon et al., 1997) (Table 1). Similar granites crop out farther east (Hueco Mountains and Pump Station Hills; Fig. 1).

The intrusive suite records five compositionally distinct stages of intrusion, which range continuously in composition from quartz syenite to leucogranite, plus late stage ferrobasalt dikes (Shannon et al., 1997). Geochemical, petrologic, and isotopic studies (Norman et al., 1987; Shannon et al., 1997) agree that the magmas most likely resulted from fractional crystallization of slightly alkaline basaltic, mantle-derived source with some crustal contamination. The trace element geochemistries of the volumetrically most abundant felsic rocks indicate a continental rift environment on tectonic discrimination diagrams (Table 2) (Norman et al., 1987; Shannon et al., 1997). The data, however, have been used to support conflicting interpretations for the tectonic setting of this suite (Anderson, 1983; Norman et al., 1987; Shannon et al., 1997). Norman et al. (1987) proposed a continental-margin arc and backarc basin setting based on the association of these rocks with possible arc-related basalts (probably Mundy Breccia) and comparison with the Carrizo Mountain Group (Van Horn) and Coal Creek domain Llano uplift rocks, all of which are now known to be much older. The generally A-type magmatism and the presence of nearly contemporaneous extension farther east in the Central basin platform (see following) led Shannon et al. (1997) to propose a continental extensional origin. The lack of an arc of this age in the region supports the latter interpretation.

Tectonic Setting

Three separate depositional environments of different ages are preserved in west Texas. In the Carrizo Mountain Group (ca. 1380 ± 20 to 1327 ± 28 Ma), the association of immature clastic rocks, rhyolitic (within plate) volcanism, and minor carbonates suggests deposition in a shallow-water, active continental rift environment (Grimes, 1996). If the Carrizo Mountain Group is part of a backarc sequence, as previously proposed by Rudnick (1983) based on the intrusive diabase geochemistry, the plutonic part of the arc is not currently exposed in west Texas, and the postulated arc in central Texas is now known to be too young. A continental margin arc of this age has been proposed for Sierra Del Cuervo, Mexico (see following; Blount, 1993), however, so this possibility cannot be discounted. In terms of age, chemistry, and isotopic character, the rocks appear to be deformed and metamorphosed equivalents of the Granite Rhyolite terrane; however, their location south of younger marine deposits and the Llano front would require early rifting and later reattachment. The possibility that the Carrizo Mountain Group is exotic to North America cannot be discounted.

The younger carbonate and volcanic rocks (1260 ± 20 to 1247 ± 4 Ma) near Van Horn and El Paso formed in a marine intertidal to subtidal environment along a continental margin or in an elongate marine basin. The carbonates are similar in age and character to the Mescal Limestone of central Arizona (Link et al., 1993), suggesting that the continental margin may have extended westward instead of curving to the south, as proposed by Mosher (1991). If so, active tectonism did not affect the margin west of Van Horn during Mesoproterozoic time. Alternatively, these rocks could have formed in an extensional or transtensional cratonic basin (Pittenger et al., 1994; Bickford et al., 1995; McLelland et al., 1995; Marsaglia et al., 1996) connected to an eastern ocean. The combination of bimodal volcanism and an arc-related geochemical signature for the volcanic rocks (Table 2) is compatible with rifting in a backarc basin environment. For the basalts near Van Horn, the observed change with time from an island-arc to MORB tholeiite (but with a subduction component; Table 2) is common during the evolution of backarc basins (Condie, 1989, p. 271). In the Franklin Mountains, marine deposition continued. Near Van Horn, no record of the interval between carbonate deposition and tectonism remains, and the presence of an irregular and karst topography indicates a period of subaerial exposure and erosion.

More than 125 m.y. later (post 1123 Ma, possibly between 1100 and 1080 Ma), the carbonates currently near Van Horn were thrust northward in an active transpressional setting (Soegaard and Callahan, 1994). The emerging thrusts were eroded to form alluvial fans with a southerly source, which were subsequently overridden by the thrust sheets and ultimately the Carrizo Mountain Group metamorphic rocks. The lack of Carrizo Mountain Group metamorphic rocks as clasts in the synorogenic conglomerate requires that the Carrizo Mountain Group was either not exhumed or not proximal during thrust-related sedimentation. The lack of volcanism and plutonism at this time and of significant tectonism of the sedimentary rocks makes it unlikely that the Streeruwitz thrust marks the location of a large ocean closure. Instead, collapse of a small ocean basin is more likely. The increase in metamorphic grade and deformation intensity and complexity across and southward in the Carrizo Mountain Group away from the Streeruwitz thrust suggests progressive deformation of the Carrizo Mountain Group and foreland sedimentary rocks and collision of a southern continental block (Mosher, 1993). The last stages of this collision could result in closing a small ocean basin, deformation of the sedimentary rocks, and finally thrusting of the metamorphic (Carrizo Mountain Group) rocks over the sedimentary rocks.

MEXICAN EXPOSURES

Two small exposures of Mesoproterozoic amphibolite facies, metamorphic rocks are found in Chihuahua, Mexico (Fig. 1); the results of an extensive geochemical study (Blount, 1993) are outlined in the following. The eastern exposure of Cerro El Carrizalillo contains mafic schists intruded by trondhjemite and granite dikes and sills, which are all multiply deformed and cut by late tectonic tonalite, trondhjemite, and granite dikes. Comparison of the field relations, bimodal rock associations, and geochemistry with better constrained occurrences of trondhjemites (type locality, Trondheim, Norway, Size, 1979; Twillingate region, Newfoundland, Payne and Strong, 1979) indicates that the generally low-K, peraluminous granitoids have most likely resulted from partial melting of amphibolites during orogenesis. It should be noted, however, that the ages of the mafic schists and granitoids are unknown, and thus the implied association may be invalid. Blount (1993) suggested a correlation with the Coal Creek domain of the Llano uplift, although again age constraints are lacking.

Approximately 100 km to the west, the Sierra Del Cuervo exposure primarily consists of metagranites with lesser amounts of granitic gneisses, metagabbro, and metadiorite. Except for the early gneisses, none of the Sierra Del Cuervo rocks are pervasively foliated, although all have been metamorphosed to amphibolite facies. Contact relationships show that metagranites both predate and postdate the metadiorite and metagabbro; presumably the granitic gneisses are the oldest rocks present. U/Pb zircon dates of 1333 +10/–8 Ma (metagabbro), 1274 +6/–5 Ma (metagranite) and 1080 ± 5 Ma (crosscutting pegmatitic trondhjemites) confirm that these are Mesoproterozoic rocks (Blount, 1993) (Table 1). The medium-K, calc-alkaline metagabbros and metadiorites have compatible major and trace element trends, including those for the incompatible and relatively immobile high field strength elements (HFSE) (REE [rare earth element], Y, Nb, P, and Zr), typical of igneous melts. These rocks are depleted in heavy REE and have a low Y content similar to those observed in magmas generated at the base of mature, overthickened island arcs or continental margin arcs (Gill, 1981). Two samples of metagranite show a major and trace element geochemistry consistent with generation by partial melting of granitic material, although their peraluminous character may be the result of metamorphism. One granite has low REE concentrations inconsistent with fractionation from a mafic or intermediate melt, and no continuous fractionation series is observed in the area. Blount (1993) suggested that they may have formed in an arc-related setting. These rocks are cut by metabasaltic dikes that show mixed MORB and island-arc chemistries on five trace element tectonic discrimination diagrams (Table 2), which Blount (1993) attributed to a backarc basin setting. Younger, crosscutting, late-tectonic metadiabase dikes fall in the within-plate field on the same five tectonic discrimination diagrams (Table 2). Crosscutting garnetiferous trondhjemites and 1080 ± 5 Ma pegmatitic trondhjemites apparently formed from partial melting of amphibolites during orogenesis.

CENTRAL BASIN PLATFORM

A mafic to ultramafic layered (Nellie) intrusion, dated as 1163 ± 4 Ma (Keller et al., 1989), is located in the subsurface in the Central basin platform, ~210 km east of Van Horn (Fig. 1). Petrologic and geochemical investigations of well cuttings indicate that parental magmas were subalkaline and tholeiitic and not arc related (Kargi and Barnes, 1995). Gravity, magnetic, and well data indicate that this body has a north-northwest–trending, narrow, elongate shape, which Adams and Keller (1994) interpret as a rift.

The tectonic settings of the igneous rocks in the Central basin platform, Franklin Mountains, Sierra Del Cuervo, and Llano uplift from 1163 ± 4 to 1070 ± 2 Ma were highly variable. The mafic layered intrusion in the Central basin platform and the granites and rhyolites in the Franklin Mountains and surrounding eastern area are compatible with regional extension between 1163 ± 4 Ma and 1086 ± 5 Ma. Minor trondhjemites (1080 ± 5 Ma) in the Sierra Del Cuervo resulted from orogenesis. During the same time (1119 +6/–3 to 1070 ± 2 Ma), granite plutonism occurred in the Llano uplift, both during the waning stages of the contractional deformation and after orogenesis. Petrology and geochemistry of one postorogenic Llano pluton confirm that even the postorogenic plutons formed under different tectonic conditions than those of the Franklin Mountain granites (Smith et al., 1997).

CORRELATION AND MODELS

The exposed rocks across central and west Texas show evidence for three distinct periods of activity: 1380 to 1320 Ma, 1288 to 1232 Ma (primarily ca. 1260 to 1232 Ma), and 1163 to 1070 Ma. Despite differences in structural level, striking similarities in tectonic settings and events are observed along the southern margin of Laurentia (Fig. 5). When taken together, these exposures record more than 300 m.y. of tectonic activity

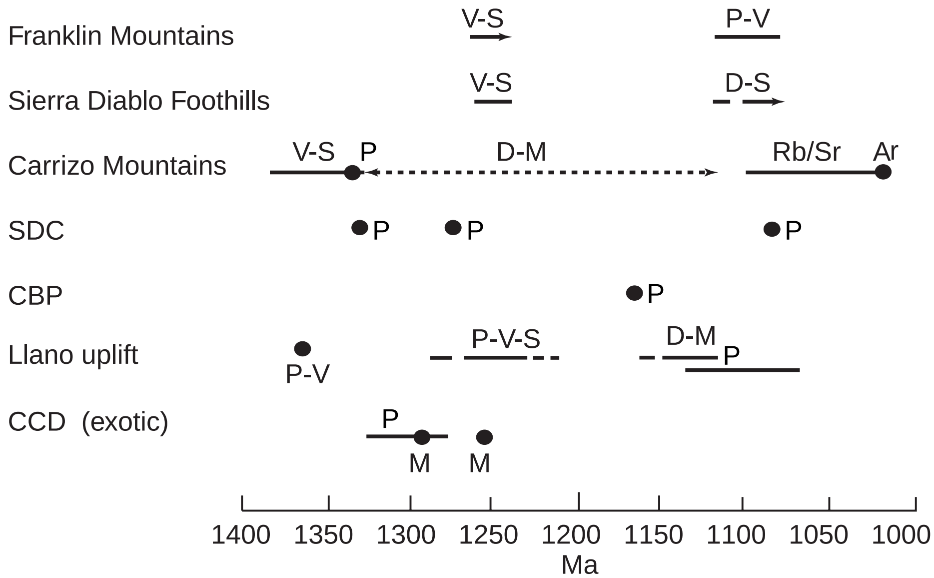

Figure 5. Relative timing of Mesoproterozoic events along the southern margin of Laurentia. V—volcanism; S—sedimentation; P—plutonism; D—deformation; M—metamorphism; Rb/Sr—ages for pegmatites; Ar—$^{40}Ar/^{39}Ar$ muscovite cooling age. Carrizo Mountains includes all Carrizo Mountain Group exposures. SDC—Sierra Del Cuervo; CBP—Central basin platform; CCD—Coal Creek domain.

and give evidence for a consistent tectonic setting along this margin that evolved with time (Figs. 6–10). Previous attempts at comparing igneous tectonic environments along the margin (e.g., Norman et al., 1987; Rudnick, 1983; Garrison, 1985) lacked the present age constraints and treated rocks of widely different ages as time equivalent.

In west Texas, the earliest rocks (1380 ± 20 to 1327 ± 28 Ma; Carrizo Mountain Group) record rifting of continental crust (Fig. 10A). Without evidence of an arc at this time, the best interpretation of the tectonic setting is a continental rift that ultimately evolved into a completely rifted margin. The presence of 1333 +10/–8 Ma arc-related rocks in the Mexican Sierra Del Cuervo exposure, however, strongly suggests that rifting is at least partially in response to backarc spreading. This interpretation is also supported by the geochemistry (arc related) of the west Texas diabase rocks of this age (Table 2). Alternatively, the arc-related rocks (Sierra Del Cuervo) could be part of a mature island arc and exotic, similar to the roughly contemporaneous Llano Coal Creek domain. The Sierra Del Cuervo gabbros and diorites intrude granites and granitic gneisses, however, further supporting the continental margin–arc hypothesis. The proposed evolution of this area is shown in Figure 6. Between about 1400 and 1350 Ma, continental rifting resulted in the deposition of immature clastic sediments in a shallow-water rift and extrusion of peraluminous (within plate) rhyolites. At some point subduction initiated, and a continental margin arc formed at least locally. Rifting behind the arc continued between about 1350 and 1300 Ma, forming a backarc basin. Deposition of clastic sediments and rhyolitic flows and tuffs continued, and widespread intrusion of diabase and granodiorite sills occurred (Fig. 6B).

For the next time period, 1288(?) to 1232 Ma, shown in Figure 7A, rocks of the Llano uplift are postulated to represent an arc and a forearc basin, and the west Texas rocks represent an associated backarc basin. In the Llano uplift, the extensive igneous activity, including plutonism and volcanism, concurrent with extensive weathering and deposition of arc-flank, shelf-slope facies sediments, points to a continental margin arc ca. 1260 to 1232 Ma (Fig. 9B). The dominance of granitic gneisses in the northeastern uplift and the more variable volcanic and sedimentary protoliths in the western and southeastern uplift suggest that the arc was located to the north of the present uplift. Thus, much of the Valley Spring and Packsaddle domains would represent forearc and arc-flank deposits, and part of the main arc would be represented by granitic gneisses. Dates as old as 1288 ± 2 Ma on felsic igneous rocks in the Valley Spring domain suggest that subduction could have started even earlier (Fig. 9A). In west Texas,

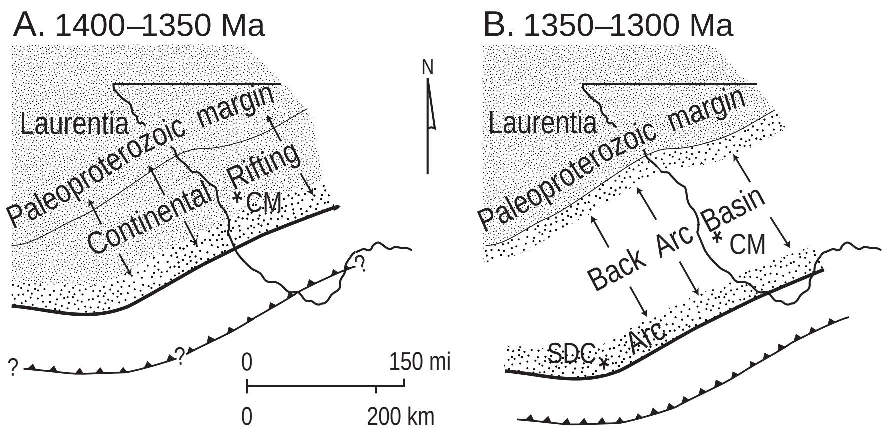

Figure 6. Tectonic setting of west Texas. (A) Continental rifting at 1400 to 1350 Ma resulting in rhyolite flows, welded ash-flow tuffs, and clastic sedimentation in shallow sea; possible subduction zone is shown (CM—Carrizo Mountains). (B) Continued extension in a probable backarc basin setting at 1350 to 1300 Ma resulting in diabase and granodiorite intrusions along with felsic volcanism and shallow-marine sedimentation. Change from continental rifting to backarc spreading is suggested by diabase intrusion geochemistry and postulated arc at Sierra Del Cuervo (SDC), although the proximity of this arc to Laurentia at that time is speculative.

the coeval shelf carbonates and felsic and mafic volcanic rocks best fit a backarc basin setting with wind-blown felsic volcanic ash in the Franklin Mountains supplied by the Llano arc. This second backarc basin formed near the continental margin along the northern boundary of the earlier Carrizo Mountain Group basin (Figs. 7A and 10B). Granites of this general age (1274 +6/–5 Ma) in the Mexican Sierra Del Cuervo suggest that the arc may have been active southwest of the Van Horn exposures. The younger, undated, metabasalt and metadiabase dikes in the Sierra Del Cuervo are geochemically similar to basalts within the west Texas carbonates (Table 2) and are compatible with the proposed backarc setting.

An alternative explanation for the 1255 +11/–6 to 1232 ± 4 Ma felsic igneous activity in the Llano uplift is that it is related to arc (Coal Creek domain) collision (Reese, 1995; Roback, 1996b). If the arc was accreted at about this time and overrode the Packsaddle and Valley Spring domains, crustal thickening could give rise to melts. The presence of 1248 ± 3 to 1244 ± 5 Ma volcanic rocks interlayered with the Packsaddle domain sedimentary rocks, however, makes this possibility highly improbable. Also, the distribution of these felsic igneous rocks would require most of the uplift be covered by this block, yet no erosional remnants of this arc have been found outside the southeastern uplift. Instead, the widespread distribution of these felsic igneous rocks throughout the uplift, except in the Coal Creek domain, argues against the Coal Creek domain being accreted at that time. The presence of volcanic rocks of this age all along the southern margin of Laurentia, coupled with the subduction-related geochemical signature of volcanic rocks in west Texas (Table 2) and plutonism in Llano, strongly favors Llano being a continental margin arc at that time.

Elsewhere, the Coal Creek arc evolved from 1326 ± 2 to 1275 +2/–1 Ma as an ensimatic arc exotic to Laurentia (Figs. 7B and 9A). The record of magmatism ceased about the time magmatism started in the rest of the Llano uplift, and the rocks were metamorphosed at 1256 +2/–1 Ma, when the largest pulse of igneous activity started in the rest of the Llano uplift. One possible model is that subduction with a southward polarity generated the Coal Creek domain arc and led to the eventual collision of the arc with the continent (Reese, 1995). Such a model is supported by the northeastward structural vergence in the southeastern uplift and increase in P-T conditions toward the southwest. The new age constraints, however, make this unlikely. Regional metamorphism and deformation occurred between ca. 1150 and 1120 Ma, and the intensity of deformation and degree of transposition in the Packsaddle domain decrease away from the boundary with the Coal Creek domain, strongly indicating that the deformation is related to the juxtaposition of these two domains. The rocks within the Packsaddle domain adjacent to this boundary show no evidence of older structures, and thus argue against a reactivated boundary. In addition, the temperature of metamorphism of the Coal Creek domain is comparable to that of the adjacent Packsaddle domain, and metamorphic minerals yield similar ages. Therefore it is most likely that the deformation and metamorphism were caused by collision of the arc or arc and a southern continent with Laurentia. Thus, subduction with a south-dipping polarity, when coupled with the new age constraints, requires the arc to have been active about 125 m.y. longer than recorded in the Coal Creek domain. For this reason, I have shown the formation of the Coal Creek domain arc to be related to north-dipping subduction unrelated to the Laurentian plate margin (Figs. 7B and 9A). The mafic schists in the Mexican Cerro El Carrizalillo may be equivalent, as suggested by Blount (1993) and as shown in Figures 7B and 10B, but age constraints are lacking.

Collision of the arc (Coal Creek domain) and a southern continent with Laurentia occurred between about 1150 and 1120 Ma, producing the polyphase deformation and high-P metamorphism observed in the Llano uplift (Figs. 8 and 9C). Continent-continent collision and A-type subduction is indicated by the presence of medium-T eclogites recording burial to depths of ~50 km. It seems likely that the arc and southern continent collided earlier and were accreted together as a package (Fig. 9B) for several reasons. The Coal Creek domain appears to have ceased activity shortly after 1275 +2/–1 Ma and was metamorphosed at 1256 +2/–1 Ma. Yet accretion of the Coal Creek domain did not occurr until ca. 1150 and 1120 Ma. Collision of the arc with the southern continent would stop activity of the arc, and the metamorphism could be related to this collision. Also, the arc rocks (Coal Creek domain) are not penetratively deformed and preserve original igneous textures and crosscutting relationships, in marked contrast to the adjacent, highly transposed Packsaddle domain rocks. The difference in degree of deformation could be due solely to rheological differences between a microcline-rich, layered, supracrustal sequence and an unlayered igneous complex with plagioclase as the dominant feldspar. However, the contrast between the amount of deformation recorded by the Coal Creek domain and Packsaddle domain rocks over less than 1 km is striking. If the arc was still (or recently) active, it is unlikely that the base (and hottest part) of the arc would be essentially undeformed immediately adjacent to the most deformed rocks in the uplift. It would be easier to explain if the arc were already cold, old, and accreted onto the margin of another continent. During the earlier collision of the Coal Creek domain arc with a southern continent, deformation would be relatively minor because subduction of the southern continent crust would jam the subduction zone (cf. Cloos, 1993). This collision might also trigger the initiation of subduction under the Laurentian margin, causing formation of a continental margin arc and possibly some early metamorphism and/or deformation of older Valley Spring domain and Packsaddle domain rocks (Fig. 9B). Alternatively, if subduction was already active (Fig. 9A), a change in plate motion as a consequence of the collision could have caused a change in the rate (or dip) of subduction, resulting in more igneous activity. This subduction ultimately led to the collision of the southern continent and accreted arc between ca. 1150 and 1120 Ma (Fig. 9C), causing the high-*P* metamorphism of the entire uplift and the polyphase deformation along discrete zones within the Coal Creek domain and of the entire Valley Spring and Packsaddle domains. The *P-T* conditions increase toward the southwest approaching the core of the orogen.

The proposed subduction polarity does not match the northeastward structural vergence in the southeastern uplift, although this is not uncommon in modern settings (e.g., Silver and Reed, 1988). The polarity of subduction could have reversed prior to collision in the Llano area during the apparent hiatus in igneous activity between 1232 and 1119 Ma, perhaps when the southern continent reached the subduction zone in west Texas. Also, the structural trend and vergence near the Coal Creek domain may be a local boundary effect of the accreted arc. In the western uplift, some folds have an apparent southwestward vergence, and many early folds have east to northeast trends, similar to F_4 in the southeastern uplift. These folds are overprinted by more open northwest-trending structures. Thus, different generation structures across the uplift may record a variable and changing regional stress field during overall northward convergence and collision, as a consequence of an irregular margin (Fig. 8).

The collision of the same southern continent in west Texas could have caused polyphase deformation and metamorphism of the 1380 ± 20 to 1327 ± 28 Ma Carrizo Mountain Group (Fig. 10C) and ultimately (post 1123 ± 29 Ma) thrusting of the Carrizo Mountain Group onto the 1256 ± 5 to 1247 ± 4 Ma carbonate and volcanic rocks, and deposition of the synorogenic sediments (Fig. 10D). The deformational and metamorphic history of the high grade rocks in west Texas is quite similar to that of the Llano uplift, and the need for a continent-continent collision to generate the polyphase deformation and amphibolite facies metamorphism is compelling. It is likely that this tectonism is roughly correlative in time to that documented for the Llano uplift and led to the collapse of the ca. 1250 Ma backarc basin in west Texas. This correlation is unconfirmed, however, until the timing of the metamorphism and deformation of the Carrizo Mountain Group is better constrained. In the Mexican exposures,

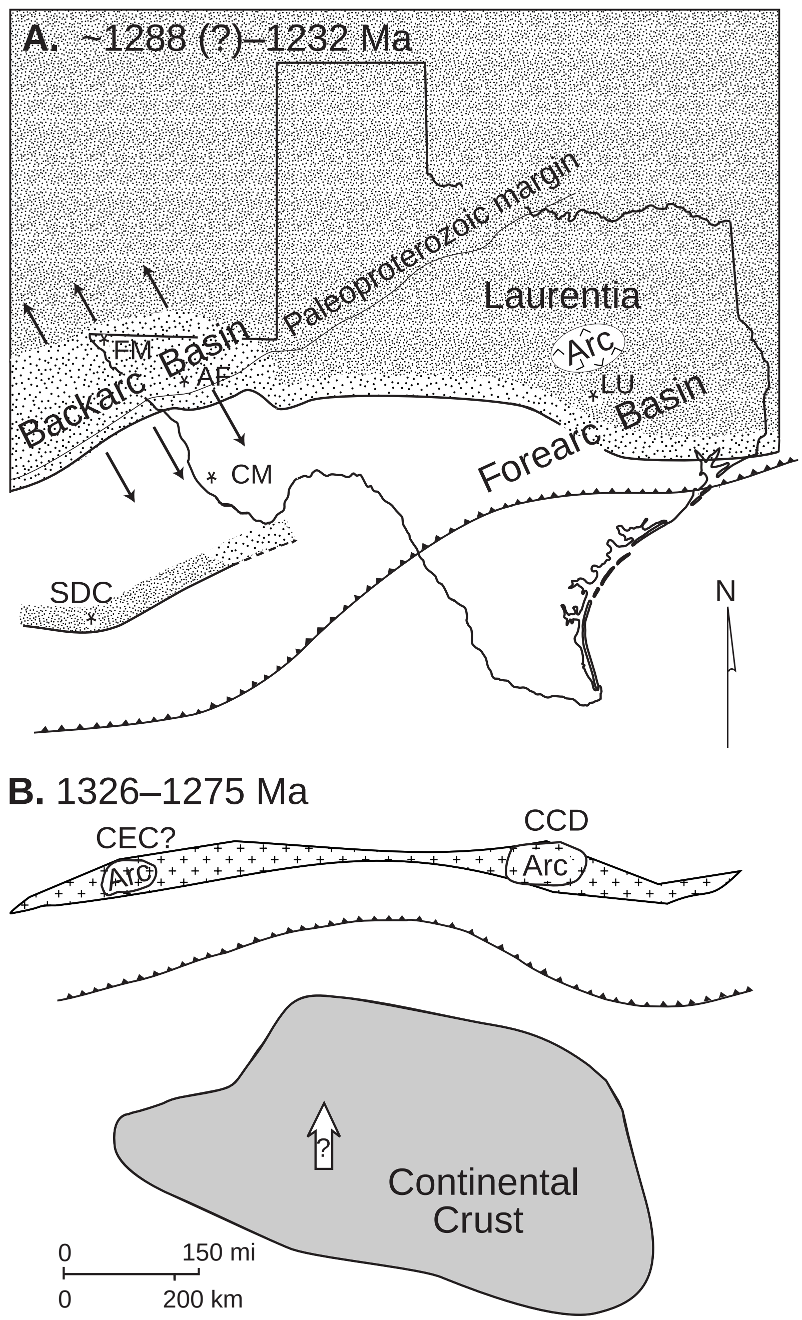

Figure 7. (A) Tectonic setting of southern margin of Laurentia. North-dipping subduction results in a continental margin arc and forearc basin in Llano uplift area (LU), represented by part of the Valley Spring domain and Packsaddle domain, and a backarc basin in west Texas represented by the Allamoore Formation (AF) in the Sierra Diablo foothills and Castner Marble–Mundy Breccia in the Franklin Mountains (FM). Main igneous activity is observed from 1260 to 1232 Ma. Granites (1274 +6/–5 Ma) in the Sierra Del Cuervo (SDC) may correspond to an arc in this area. Approximate location of Carrizo Mountain rocks (CM) is shown for reference. (B) Tectonic setting of exotic terranes 1326 to 1275 Ma. Probable position relative to Laurentia is shown, but size of separating ocean is unknown. North-dipping subduction results in formation of an island arc (Coal Creek domain—CCD) and possibly correlative Cerro El Carrizalillo—CEC). This subduction may have ceased before initiation of subduction under Laurentia (see text for discussion).

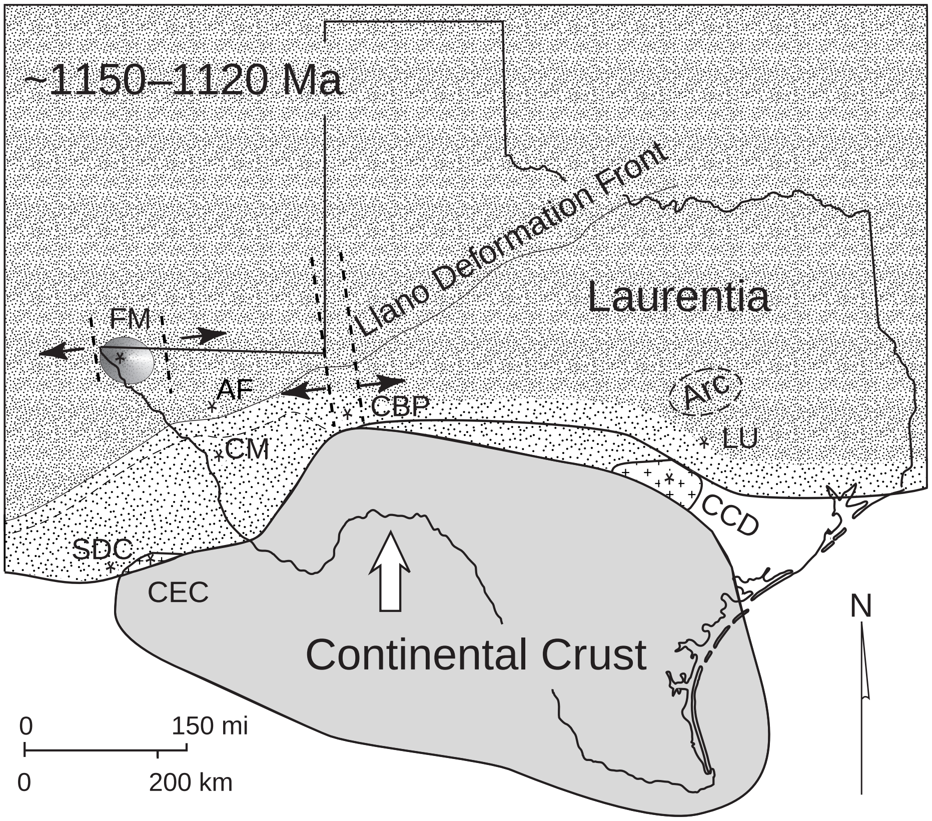

Figure 8. Collision of southern continent with Laurentia at ca. 1150 to 1120 Ma, causing polyphase deformation and metamorphism along margin. In Llano uplift area (LU), doubling of crust and collision of Coal Creek domain (CCD) arc occurred. Polarity of subduction zone may have changed between 1232 Ma (Fig. 7) and 1150 Ma, perhaps when the southern continent reached the subduction zone in west Texas. Llano arc is inactive. Irregular boundary results in different local transport directions in west and central Texas. Paleoproterozoic margin is reactivated and forms the northern extent of Grenville deformation (Llano deformation front). Rift forms perpendicular to collision margin (ca. 1163 Ma) in Central basin platform (CBP). Volcanism and plutonism initiates in far west Texas Franklin Mountains (FM) and continues until ca. 1086 Ma, probably as a result of extension. Further shortening from 1123 to 1080 Ma (not shown) results in thrusting of the Allamoore Formation (AF), synorogenic deposition of the Hazel Formation, and thrusting of Carrizo Mountain rocks (CM) over these sedimentary rocks in a transpressional setting. CEC—Cerro El Carrizalillo; SDC—Sierra Del Cuervo.

however, the polydeformed and late tectonic granitoids at Cerro El Carrizalillo and the 1080 ± 5 Ma trondhjemite dikes at Sierra Del Cuervo, all of which are interpreted to have formed from partial melting of amphibolites during orogenesis (Blount, 1993), support collisional orogenesis at that time. Thus, I conclude that the same continent-continent collision is recorded in west Texas, first affecting the 1380 ± 20 to 1327 ± 28 Ma Carrizo Mountain Group and then closing the ca. 1250 Ma backarc basin.

Thrusting within the west Texas sedimentary rocks did not occur until after 1123 ± 29 Ma and probably between 1100 and 1080 Ma, when orogenesis in the core of the orogen (Llano uplift) was waning. The deformation in a transpressional setting represents closure of a small ocean (backarc) basin (Fig. 10, C and D), with subduction absent or insufficient to produce an arc. Deformation is not observed in the Franklin Mountains or further west in possibly correlative rocks. In the Mexican exposures, the eastern Sierra Del Cuervo shows only amphibolite facies metamorphism with little tectonism, whereas the western Cerro El Carrizalillo is polydeformed. Thus, I have not shown a colliding southern continent west of the Van Horn area (Fig. 8).

The igneous activity between 1119 +6/–3 to 1070 ± 2 Ma, records different local tectonic environments along this margin. In Llano, the earliest of these plutons (1119 +6/–3 to 1116 +6/–4 Ma) are syncollisional, having formed and deformed in the waning stages of orogenesis. The subsequent post-tectonic (1091 +4/–3 to 1070 ± 2 Ma) plutons formed in the orogenic core, and their genesis, although unknown, most likely reflects this location. In west Texas near van Horn, plutonism of this age is not observed, except for large pegmatites in the southernmost exposures, which suggests that such plutonism might have been present farther south in the core of the orogen. The late-tectonic granitoids (Cerro El Carrizalillo) and the 1080 ± 5 Ma trondhjemite dikes (Sierra Del Cuervo) in Mexico support this suggestion. The 1163 ± 4 Ma layered mafic to ultramafic intrusion in the Central basin platform between the Llano and Van Horn exposures appears to have formed in a rift perpendicular to this collisional margin (Fig. 8) and most likely formed in response to collision similar to the Rhine graben north of the Alps (impactogen; Sengör et al., 1978; Adams and Keller, 1996) or to the grabens north of the Himalayas (e.g., spreading of overthickened crust; England and Houseman, 1988). The 1120 ± 35 to 1086 ± 5 Ma continental rift-related plutonism and volcanism in the Franklin Mountains (Fig. 8) occurred prior to transpressional deformation of the carbonates near Van Horn, although not necessarily prior to collision to the south that deformed the Carrizo Mountain Group. These igneous rocks are located at the edge of the collisional orogen, perhaps in an intercratonic setting. This unusual tectonic location may have led to extensional stresses at this time and may help explain the anomalous geochemistry.

SIGNIFICANCE OF THE LLANO FRONT

Any plate models for the southern margin of Laurentia during Mesoproterozoic time must include an explanation for the Llano front (Fig. 1). Van Schmus et al. (1996) postulated that it may be the southern continuation of the late Paleoproterozoic continental margin of Laurentia (Fig. 7), based on Nd model ages that are all <1550 Ma south of the proposed margin. If so, all crust south of margin must have formed in Mesoproterozoic time, and this part of the southern Granite Rhyolite terrane formed from this crust. The crust could be accreted juvenile terranes, as suggested by Van Schmus et al. (1996), which would require the Llano front be a suture or, alternatively, could have been added as the result of subduction-related magmatism (Nelson and DePaolo, 1985). Regardless of the origin of this Mesoproterozoic crust, it was likely part of Laurentia prior to the formation of the 1400–1300 Ma southern Granite Rhyolite terrane. The latter is the result of either regional extension or orogenic and accretionary activity (Van Schmus et al., 1996). The 1380 ± 20 to 1327 ± 28 Ma Carrizo Mountain Group in west Texas may be an exposed equivalent and best fits an extensional or rift environment (probably later associated with backarc spreading). In addition, the layered nature of the Carrizo Mountain Group is similar to the well layered sequence indicated by seismic reflection data for the southern Granite Rhyolite terrane (Pratt et al., 1989). Thus, the rifting in west Texas may be part of regional extension, perhaps related partially to subduction, that formed the southern Granite Rhyolite terrane.

Another possible explanation for the Llano front is that the Abilene gravity minimum, the northern boundary of which corresponds to the Llano front, is a batholith formed during Mesoproterozoic subduction (Adams and Keller, 1996). The postulated batholith could be the result of subduction-related magmatism related to the formation of Mesoproterozoic crust or to later (1400–1300 Ma) orogenic and accretionary processes, as favored by Adams and Keller (1996). Alternatively, it could represent the ca. 1250 Ma continental margin arc north of the Llano uplift.

The Llano front also separates undeformed and deformed rocks, suggesting that it is the northern extent of Grenville age deformation (Fig. 8), similar to the Grenville front in Canada (Rivers et al., 1989). Its apparent expression in west Texas as a narrow fold and thrust belt under the Streeruwitz thrust further supports this interpretation. The orientation of the boundary is problematic, however, because the tectonic transport documented for the southeastern Llano uplift is northeastward, nearly parallel to the Llano front. As suggested herein, the transport direction in this part of the uplift may be a local boundary effect controlled by shape of the accreted arc, and the bulk transport direction of the colliding continent may have been northward. Further work is needed to test this hypothesis. The location and orientation of the Llano front are probably controlled by a preexisting crustal-scale structure, however, such as the late Paleoproterozoic Laurentian margin and/or a preexisting suture. Further work on the basement in the Texas subsurface is needed to define the nature and significance of the Llano front.

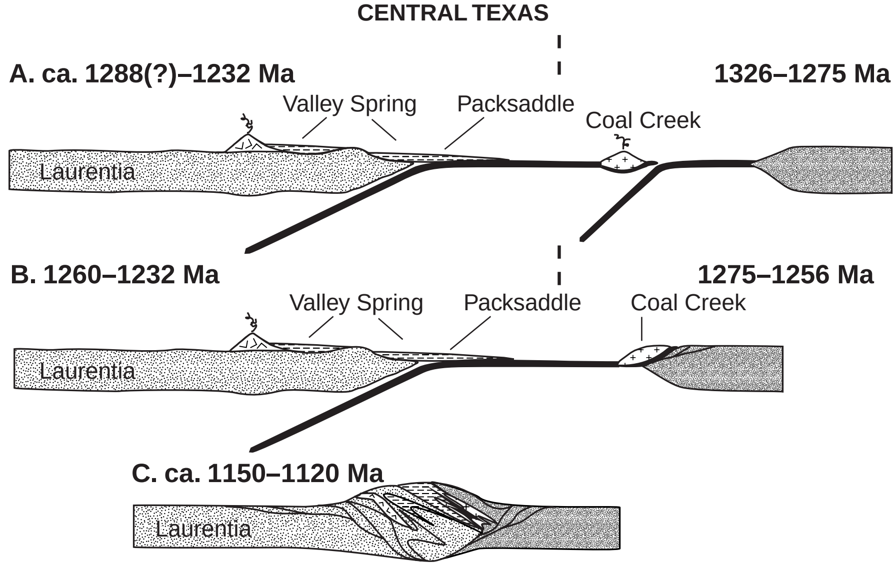

Figure 9. Cross sections showing evolution of central Texas. (A) From ca. 1326 to 1275 Ma, Coal Creek domain (CCD) island arc forms exotic to Laurentia. Subduction under Laurentia may have started as early as ca. 1288 Ma. (B) From ca. 1260 to 1232 Ma, subduction under Laurentia results in a continental margin arc and forearc basin. Valley Spring domain and Packsaddle domain rocks represent a continuum from arc flank and forearc material, to marine environment, respectively. The Valley Spring domain also contains older basement and possibly part of the arc. Between 1275 and 1256 Ma, the CCD island arc ceases activity, perhaps due to collision with southern continent. (C) Collision between ca. 1150 and 1120 Ma causes polyphase deformation, high-P metamorphism, and doubling of the crust. A change in subduction polarity between (B) and (C) is probable based on a gap in igneous activity between 1232 and 1119 Ma.

DISCUSSION

The Mesoproterozoic evolution of the southern margin of Laurentia, as documented for the Texas basement, is strikingly similar to that of the Canadian Grenville orogen (e.g., Gower, 1996, Fig. 4) and its extension in the Adirondack massif of New York State (McLelland et al., 1993). This similarity indicates that both the eastern and southern margins of Laurentia underwent a comparable tectonic evolution that culminated in the collision of another continent. The collision recorded in the Llano uplift that caused the doubling or partial subduction of the crust to produce burial depths of ~50 km or higher is on the same order of magnitude as the collision of South America (or Africa or Baltica) with the northeastern margin of Laurentia.

Recent plate models have focused on the eastern Laurentian margin and on possible along-strike continuations of the southern margin orogenic belt (Dalziel, 1991; Moores, 1991; Borg and DePaolo, 1994; Unrug, 1996). None has addressed the question of which continent was adjacent to the Texas portion of the southern Laurentian margin at the end of Mesoproterozoic time. Moores (1991) speculated that Baltica might lie in this position, but this is unlikely based on paleomagnetic data (cf. Dalziel, 1997). Dalziel's (1997) model shows a highly extended piece of continental crust, his Texas plateau, attached to this margin, which currently may be part of the Argentine Precordillera. These proposed small remnants of continental crust are not sufficient, however, to cause the orogenesis observed in the Texas Grenville-age rocks. The presence of this collisional orogen along the southern margin of Laurentia is now well documented (Wilkerson et al., 1988; Mosher, 1993; Reese, 1995; Roback, 1996a; Carlson, 1998, and this study) and requires collision of a southern continent with the southern margin of Laurentia during the assembly of Rodinia at the end of Mesoproterozoic time.

CONCLUSIONS

The Grenvillian orogenic belt along the southern margin of Laurentia records more than 300 m.y. of tectonic activity including both arc-continent and continent-continent collision. Although along-strike variations in style, nature, and timing of orogenesis are observed, the Texas basement reveals a consistent, but evolving tectonic setting for this margin during Mesoproterozoic time. The

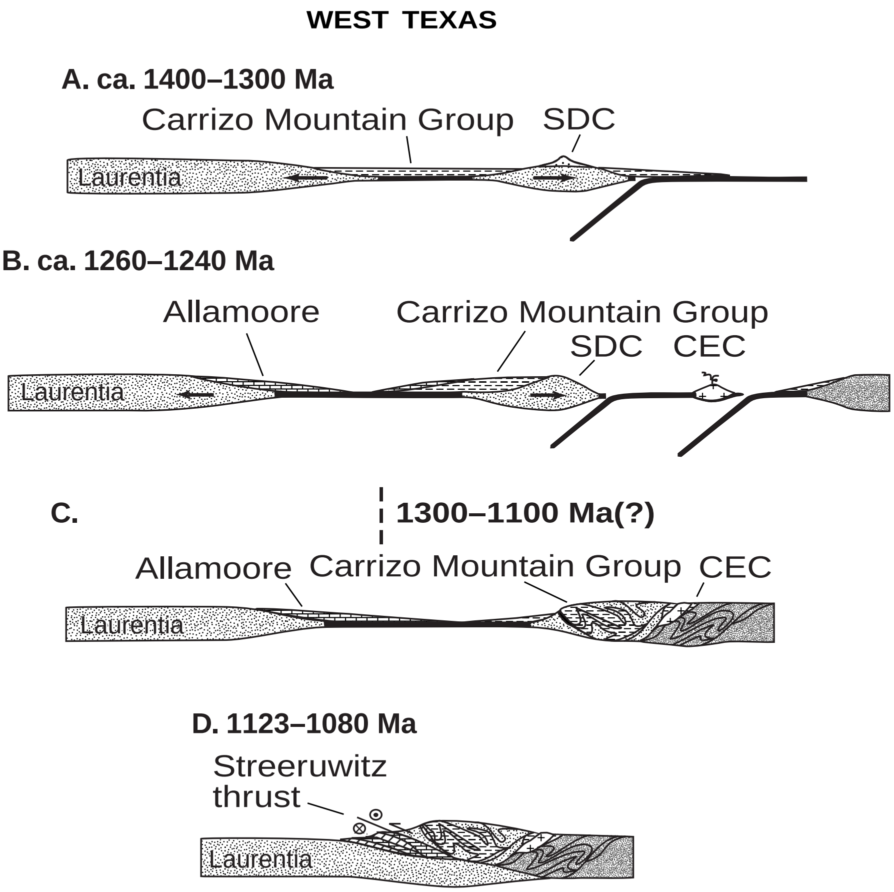

Figure 10. Cross sections showing evolution of west Texas near Van Horn. (A) From ca. 1400 to 1300 Ma extension of the Laurentian margin resulted in continental rifting and deposition of the Carrizo Mountain Group (CMG). Rifting probably evolved into backarc spreading upon the establishment of a subduction zone and arc at Sierra Del Cuervo (SDC; 1333 +10/–8 Ma). (B) From ca. 1260 to 1240 Ma a second backarc basin formed behind the Llano arc. A possible continuation of that arc is found at SDC (1274 +6/–5 Ma granites), but is not observed in the CMG. An island arc, representing the Cerro El Carrizalillo (CEC) is shown, but may be older and have accreted to a southern continent by that time, similar to the Coal Creek domain in central Texas. (See text for discussion.) (C) Timing of collision of a southern continent and the CMG rocks, causing polyphase deformation and metamorphism, is unconstrained between 1300 and 1100 Ma. (D) From ca. 1123 to 1080 Ma, thrusting within the Allamoore Formation, deposition of the synorogenic Hazel Formation, and ultimately thrusting of the CMG metamorphic rocks over the sedimentary rocks (Allamoore and Hazel Formations) along the Streeruwitz thrust occurred in a transpressional setting.

orogenic history is strikingly similar to that of the Canadian Grenville orogen and necessitates a reevaluation of recent global plate reconstructions.

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REFERENCES CITED

Adams, D. C., and Keller, R. G., 1994, Possible extension of the mid-continent rift in west Texas and eastern New Mexico: Canadian Journal of Earth Sciences, v. 31, p. 709–720.

Adams, D. C., and Keller, R. G., 1996, Precambrian basement geology of the Permian Basin region of west Texas and eastern New Mexico: A geophysical perspective: American Association of Petroleum Geologists, v. 80, p. 410–431.

Anderson, J. L., 1983, Proterozoic anorogenic granite plutonism of North America, *in* Medaris, L. G., Byers, C. W., Mickelson, D. M., and Shanks, W. C., eds., Proterozoic geology: Selected papers from an international Proterozoic symposium: Geological Society of America Memoir 161, p. 133–154.

Barker, D. S., Muehlberger, W. R., and Reed, R. M., 1996, Coarse-grained granite at Wirtz Dam, *in* Mosher, S., ed., Guide to the Precambrian geology of the eastern Llano uplift (Geological Society of America, 30th annual South-Central Section meeting guidebook): Austin, Department of Geological Sciences, University of Texas, p. 33–40.

Barnes, V. E., 1981, Geologic atlas of Texas—Llano sheet: Austin, University of Texas Bureau of Economic Geology, scale 1:250 000.

Barnes, V. E., 1988, The Precambrian of central Texas, *in* Hayward, O. T., ed., Centennial field guide, Volume 4: Boulder, Colorado, Geological Society of America, p. 361–368.

Bebout, G. E., and Carlson, W. D., 1986, Fluid evolution and transport during metamorphism: Evidence from the Llano Uplift, Texas: Contributions to Mineralogy and Petrology, v. 92, p. 518–529.

Bickford, M. E., McLelland, J., Soegaard, K., and Nielsen, K. C., 1995, Oblique convergent tectonism in the Grenville of west Texas: A model: Geological Society of America Abstracts with Programs, v. 27, no. 7, p. A162.

Bird, J. M., and Dewey, J. F., 1970, Lithosphere plate: Continental margin tectonics and the evolution of the Appalachian orogen: Geological Society of America Bulletin, v. 81, p. 1031–1060.

Blount, J. G., 1993, The geochemistry, petrogenesis, and geochronology of the Precambrian meta-igneous rocks of Sierra Del Cuervo and Cerro El Carrizalillo, Chihuahua, Mexico [Ph.D. dissert.]: Austin, University of Texas at Austin, 242 p.

Borg, S. G., and DePaolo, D., 1994, Laurentia, Australia, and Antarctica as a Late Proterozoic supercontinent: Constraints from isotopic mapping: Geology, v. 22, p. 307–310.

Bristol, D., A., and Mosher, S., 1989, Grenville-age polyphase deformation of Mid-Proterozoic basement, NW Van Horn Mountains, Trans-Pecos, Texas: Journal of Geology, v. 97, p. 25–43.

Carlson, W. D., 1992, Polymetamorphism in the Llano Uplift: Geological Society of America Abstracts with Programs, v. 24, no. 1, p. A6.

Carlson, W. D., 1998, Petrologic constraints on the tectonic evolution of the Llano Uplift, *in* Gilbert, M. C., and Hogan, J. P., eds., Basement tectonics 12: Dordrecht, Netherlands, Kluwer Academic Press, p. 3–27.

Carlson, W. D., and Johnson, C. D., 1991, Coronal reaction textures in garnet amphibolites of the Llano uplift: American Mineralogist, v. 76, p. 756–772.

Carlson, W. D., and Nelis, M. K., 1986, An occurrence of staurolite in the Llano uplift, central Texas: American Miner-

alogist, v. 71, p. 682–685.
Carlson, W. D., and Reese, J. F., 1994, Nearly pure iron staurolite in the southeastern Llano uplift, Texas and its petrologic significance: American Mineralogist, v. 79, p. 154–160.
Carlson, W. D., and Schwarze, E., 1997, Petrological significance of prograde homogenization of growth zoning in garnet: An example from the Llano uplift: Journal of Metamorphic Geology, v. 15, p. 631–644.
Carter, K. E., 1989, Grenville orogenic affinities in the Red Mountain area, Llano uplift, Texas: Canadian Journal of Earth Sciences, v. 26, p. 1124–1135.
Carter, K. E., Reese, J., and Helper, M. A., 1993, Precambrian extension in the Llano uplift: Geological Society of America Abstracts with Programs, v. 25, no. 1, p. A5.
Cloos, M., 1993, Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts: Geological Society of America Bulletin, v. 105, p. 715–737.
Condie, K. C., 1989, Plate tectonics and crustal evolution (third edition): Oxford, Pergamon Press, 476 p.
Connelly, J. N., Rivers, T., and James, D. T., 1995, Thermotectonic evolution of the Grenville Province of western Labrador: Tectonics, v. 124, p. 202–217.
Cook, L. P., DeLong, S. E., Illich, H. A., and Jordan, M. A., 1976, Granitic rocks of the Baldwin Quarry, Llano County, Texas: Texas Journal of Science, v. 27, p. 73–85.
Copeland, P., and Bowring, S. A., 1988, U-Pb zircon and $^{40}Ar/^{39}Ar$ ages from Proterozoic rocks, west Texas: Geological Society of America Abstracts with Programs, v. 20, p. 95–96.
Culotta, R. C., Pratt, T., and Oliver, J., 1990, A tale of two sutures: COCORP'S deep seismic surveys of the Grenville Province in the eastern U.S. mid-continent: Geology, v. 18, p. 646–649.
Dalziel, I. W. D., 1991, Pacific margin of Laurentia and east Antarctica–Australia as a conjugate rift pair: Evidence and implications for an Eocambrian supercontinent: Geology, v. 19, p. 598–601.
Dalziel, I. W. D., 1992, Antarctica: A tale of two supercontinents?: Annual Review of Earth and Planetary Sciences, v. 20, p. 501–526.
Dalziel, I. W. D., 1997, Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation: Geological Society of America Bulletin, v. 109, p. 16–42.
Davidow, J. S., 1996, Proterozoic evolution of the Llano Uplift, central Texas: Evidence for high-pressure metamorphism from the Oxford mafic body [Master's thesis]: Austin, University of Texas at Austin, 172 p.
Davidson, A., 1986, New interpretation of the southwestern Grenville Province, *in* Moore, J. M., Jr., Davidson, A., and Baer, A. J., eds., The Grenville province: Geological Association of Canada Special Paper 31, p. 61–74.
Denny, J. H., and Gobel, V. W., 1986, Structural-geologic framework and emplacement of Late Proterozoic Lone Grove and northern Granite Mountain plutons, northeastern Llano uplift, central Texas: (Geological Society of America annual meeting guidebook, Field Trip 13): San Antonio, University of Texas, p. 21–39.
Droddy, M. J., Jr., 1978, Metamorphic rocks of the Fly Gap quadrangle, Mason County, Texas [Ph.D. dissert.]: Austin, University of Texas at Austin, 178 p.
DuBois, P. F., and Nielsen, K. C., 1996, Sequential emplacement history of the Mineral Creek fault zone, Carrizo Mountains, Texas: A kinematic analysis: Geological Society of America Abstracts with Programs, v. 28, no. 6, p. A245.
Elston, D. P., and Clough, G. A., 1993, Paleomagnetic correlations of Middle Proterozoic Hazel Formation with Keweenawan-age rocks, and correlations of compressional folding phases with episodes of Grenville tectonism, Van Horn, west Texas, *in* Soegaard, K., Nielsen, K. C., Marsaglia, K. M., and Barnes, C. G., eds., Precambrian geology of Franklin Mountains and Van Horn area, Trans-Pecos Texas (Geological Society of America South-Central Section meeting guidebook): Dallas, University of Texas, p. 36–49.
England, P. C., and Houseman, G. A., 1988, The mechanics of the Tibetan Plateau: Royal Society of London Philosophical Transactions, ser. A, v. 326, p. 301–320.
Farmer, R. B., 1977, Pillow basalts and plate tectonic setting of the Precambrian Packsaddle Schist, southeastern Llano County, Texas [M.S. thesis]: Monroe, Northeast Louisiana University, 88 p.
Garrison, J. R., Jr., 1981a, Coal Creek Serpentinite, Llano uplift: A fragment of a Precambrian ophiolite: Geology, v. 9, p. 225–230.
Garrison, J. R., Jr., 1981b, Metabasalts and metagabbros from the Llano uplift, Texas: Petrologic and geochemical characterization with emphasis on tectonic setting: Contributions to Mineralogy and Petrology, v. 78, p. 459–475.
Garrison, J. R., Jr., 1985, Petrology, geochemistry, and origin of the Big Branch and Red Mountain Gneisses, southeastern Llano uplift, central Texas: American Mineralogist, v. 70, p. 1151–1163.
Garrison, J. R., Jr., Long, L. E., and Richmann, D. L., 1979, Rb-Sr and K-Ar geochronologic and isotopic studies, Llano Uplift, central Texas: Contributions to Mineralogy and Petrology, v. 69, p. 361–374.
Gill, J., 1981, Orogenic andesites and plate tectonics: Berlin, Springer-Verlag, 367p.
Gillis, G., 1989, Polyphase deformation of the Middle Proterozoic Coal Creek Serpentinite, Llano Uplift, Texas [Master's thesis]: Austin, University of Texas at Austin, 88 p.
Glahn, J. E., Nielsen, K. C., and Soegaard, K., 1996, Tumbledown Formation, Van Horn, far west Texas: A series of Grenville-age transpressive basins, Geological Society of America Abstracts with Programs, 28, no. 1, p. 15.
Gower, C. F., 1996, The evolution of the Grenville Province in eastern Labrador, Canada, *in* Brewer, T. S., ed., Precambrian crustal evolution in the North Atlantic region: Geological Society [London] Special Publication 112, p. 197–218.
Gower, C. F., Ryan, B., and Rivers, T., 1990, Mid-Proterozoic Laurentia-Baltica: An overview of its geological evolution and a summary of the contributions made by this volume, *in* Gower, C. F., Rivers, T., and Ryan, B., eds., Mid-Proterozoic Laurentia-Baltica: Geological Association of Canada Special Paper 38, p. 1–20.
Grimes, S. W., 1996, Mid-crustal Grenvillian orogenesis in west Texas: A detailed structural and metamorphic study of the Carrizo Mountain Group, *in* Gower, C. F., ed., Proterozoic evolution in the North Atlantic realm, COPENA-ECSOOT-IBTA conference, Goose Bay, Labrador, Program and Abstracts: St. Johns, Newfoundland, Geological Survey of Canada, p. 74–75.
Grimes, S. W., and Mosher, S., 1996, Carrizo Mountain Group, west Texas: The Grenville orogen's metamorphic core at its southwestern terminus in Laurentia: Geological Society of America Abstracts with Programs, v. 28, no. 7, p. A377.
Hatcher, R. D., Jr., 1987, Tectonics of the southern and central Appalachian internides: Annual Review of Earth and Planetary Sciences, v. 15, p. 337–362.
Helper, M. A., 1996, Inks Lake State Park, Valley Spring Gneiss at Spring Creek, *in* Mosher, S., ed., Guide to the Precambrian geology of the eastern Llano uplift (Geological Society of America, 30th annual South-Central Section meeting guidebook): Austin, Department of Geological Sciences, University of Texas at Austin, p. 30–31.
Helper, M. A., Gose, W. A., and Roback, R. C., 1996, Virtual geomagnetic pole positions from 1.1 Ga intrusive rocks of the Llano Uplift, central Texas: Geological Society of America Abstracts with Programs, v. 28, no. 1, p. 18.
Hess, M., and Gobel, V. W., 1987, Occurrence and origin of Late Proterozoic manganese and barite mineralizations, north-central Llano Uplift, Texas: Geological Society of America Abstracts with Programs, v. 19, p. 170.
Hoffmann, P. G., 1991, Did the breakout of Laurentia turn Gondawanaland inside-out? Science, v. 252, p. 1409–1412.
Hunt, B. B., 1996, An investigation of the structural evolution of the Packsaddle domain along the Llano River [Bachelor's thesis]: Austin, University of Texas at Austin, 55p.
Indares, A., 1993, Eclogized gabbros from the eastern Grenville Province: Textures, metamorphic context and implications: Canadian Journal of Earth Sciences, v. 30, p. 159–173.
James, E. W., and Walker, N., 1992, Implications of initial Pb isotopic ratios for source characteristics of Proterozoic rocks in the Llano Uplift and Trans-Pecos Texas: Geological Society of America Abstracts with Programs, v. 24, no. 7, p. 189.
Kargi, H., and Barnes, C. G., 1995, A Grenville-age layered intrusion in the subsurface of west Texas: Petrology, petrography, and possible tectonic setting: Canadian Journal of Earth Sciences, v. 32, p. 2159–2166.
Keller, G. R., Hills, J. M., Baker, M. R., and Wallin, E. T., 1989, Geophysical and geochronological constraints on the extent and age of mafic intrusions in the basement of west Texas and eastern New Mexico: Geology, v. 17, p. 1049–1052.
King, P. B., and Flawn, P. T., 1953, Geology and mineral deposits of Pre-Cambrian rocks of the Van Horn area, Texas: University of Texas Bureau of Economic Geology Bulletin 5301, 218 p.
Letargo, C. M. R., and Lamb, W. M., 1993, P-T-X conditions of calc-silicate formation: Evidence from fluid inclusions and phase equilibria, Llano uplift, central Texas, U.S.A.: Journal of Metamorphic Geology, v. 11, p. 89–100.
Letargo, C. M. R., Lamb, W. M., and Park, J.-S., 1995, Comparison of calcite + dolomite thermometry and carbonate + silicate equilibria: Constraints on the conditions of metamorphism of the Llano uplift, central Texas, U. S. A.: American Mineralogist, v. 80, p. 131–143.
Link, P. K., Christie-Blick, N., Devlin, W. J., Elston, D. P., Horodyski, R. J., Levy, M., Miller, J. M. G., Pearson, R. C., Prave, A., Stewart, J. H., Winston, D., Wright, L. A., and Wrucke, C. T., 1993, Middle and Late Proterozoic stratified rocks of the western U. S. Cordillera, Colorado Plateau, and Basin and Range province, *in* Reed, J. C., Jr., Bickford, M. R. E., Houston, R. S., Link, P. K., Rankin, D. W., Sims, P. K., and Van Schmus, W. R., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. C-2, p. 463–595.
Marsaglia, K. M., Ballard, J. L., and Seeley, J. M., 1996, Tectonic and stratigraphic implications of the Middle Proterozoic sequence, Franklin Mountains, west Texas: Geological Society of America Abstracts with Programs, v. 28, no. 1, p. 52.
McGehee, R. V., 1979, Precambrian rocks of the southeastern Llano region, Texas: University of Texas Bureau of Economic Geology Circular 79–3, 36 p.
McLelland, J., Isachsen, Y., Whitney, P., Chiarenzelli, J., and Hall, L., 1993, Geology of the Adirondack Massif, New York, *in* Reed, J. C., Jr., Bickford, M. R. E., Houston, R. S., Link, P. K., Rankin, D. W., Sims, P. K., and Van Schmus, W. R., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. C-2, p. 338–353.
McLelland, J., Bickford, M. E., Soegaard, K., and Nielsen, K. C., 1995, Age and composition of the Tumbledown Formation: Constraints on Grenville belt of far west Texas: Geological Society of America Abstracts with Programs, v. 27, no. 6, p. A-162.
Meschede, M., 1986, A method of discriminating between different types of mid-ocean ridge basalts and continental tholeiites with the Nb-Zr-Y diagram: Chemical Geology, v. 56, p. 206–218.
Mezger, K., Hanson, G. N., and Bohlen, S. R., 1989, High-precision U-Pb ages of metamorphic rutile: Application to the cooling history of high-grade terranes: Earth and Planetary Science Letters, v. 96, p. 106–118.
Mezger, K., Rawnsley, C. M., Bohlen, S. R., and Hanson, G. N., 1991, U-Pb garnet, sphene, monazite, and rutile ages: Implications for the duration of high-grade metamorphism and cooling histories, Adirondack Mountains, New York: Journal of Geology, v. 99, p. 416–428.
Moores, E. M., 1991, Southwest U.S.–East Antarctic (SWEAT) connection: A hypothesis: Geology, v. 19, p. 425–428.
Mosher, S., 1991, The Texas Grenville orogenic belt: Geological Society of America Abstracts with Programs, v. 23, no. 4, p. A51.
Mosher, S., 1993, Western extensions of Grenville age Rocks, Texas, *in* Reed, J. C., Jr., Bickford, M. R. E., Houston, R. S., Link, P. K., Rankin, D. W., Sims, P. K., and Van Schmus, W. R., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. C-2, p. 366–378.
Mosher, S., ed., 1996, Guide to the Precambrian Geology of the eastern Llano uplift (Geological Society of America, 30th annual South-Central Section meeting guidebook): Austin, Department of Geological Sciences, University of Texas at Austin, 78 p.
Mutis-Duplat, E., 1972, Stratigraphic sequence and structure of Precambrian metamorphic rocks in Purdy Hill Quadrangle, Mason County, Texas [Ph.D. dissert.]: Austin, University of Texas at Austin, 152 p.
Nelis, M. K., Mosher, S., and Carlson, W. D., 1989, Grenville-age orogeny in the Llano uplift of central Texas: Deformation and metamorphism of the Rough Ridge Forma-

tion: Geological Society of America Bulletin, v. 101, p. 876–883.

Nelson, B. K., and DePaolo, D. J., 1985, Rapid production of continental crust 1.7–1.9 b.y. ago: Nd isotopic evidence from the basement of the North American midcontinent: Geological Society of America Bulletin, v. 96, p. 746–754.

Norman, D. I., Condie, K. C., Smith, R. W., and Thomann, W. F., 1987, Geochemical and Sr and Nd isotopic constraints on the origin of late Proterozoic volcanics and associated tin-bearing granites from the Franklin Mountains, west Texas: Canadian Journal of Earth Sciences, v. 24, p. 830–839.

Nyberg, A. V., and Schopf, J. W., 1981, Microfossils in stromatolitic cherts from the Proterozoic Allamoore Formation of west Texas: Precambrian Research, v. 16, p. 120–141.

Patchett, P. J., and Ruiz, J., 1989, Nd isotopics and the origin of Grenville-age rocks in Texas: Implications for Proterozoic evolution of the United States mid-continent region: Journal of Geology, v. 97, p. 685–695.

Payne, J. G., and Strong, D. F., 1979, Origin of the Twillingate Trondhjemite, north-central Newfoundland: Partial melting in the roots of an island arc, *in* Barker, F., ed., Trondhjemites, dacites and related rocks: Amsterdam, Elsevier Scientific, p. 289–513.

Pearce, J. A., 1983, Role of the subcontinental lithosphere in magma genesis at active continental margins, *in* Hawkesworth, C. J., and Norry, M. J., eds., Continental basalts and mantle xenoliths: Cheshire, United Kingdom, Shiva Press, p. 230–249.

Pearce, J. A., and Cann, J. R., 1973, Tectonic setting of basic volcanic rocks determined using trace element analyses: Earth and Planetary Science Letters, v. 19, p. 290–300.

Pearce, J. A., Harris, N. B. W., and Tindle, A. G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 2, p. 956–983.

Pittenger, M. A., Marsaglia, K. M., and Bickford, M. E., 1994, Depositional history of the Middle Proterozoic Castner Marble and basal Mundy Breccia, Franklin Mountains, west Texas: Journal of Sedimentary Research, v. B64, p. 282–297.

Pratt, T., Culotta, R., Hauser, E., Nelson, D., Brown, L., Kaufman, S., Oliver, J., and Hinze, W., 1989, Major Proterozoic basement features of the eastern midcontinent of North America revealed by recent COCORP profiling: Geology, v. 17, p. 505–509.

Ramsey, J. G, 1967, Folding and fracturing of rocks: New York, McGraw-Hill, 568 p.

Reed, R. M., 1995, A complex strain and intrusion fabric related to trans-solidus deformation: The Wolf Mountain intrusion, Llano uplift, Texas, *in* Brown, M. and Piccoli, P., eds., The origin of granites and related rocks (Third Hutton Symposium abstracts): U.S. Geological Survey Circular 1129, p. 124–125.

Reed, R. M., 1996a, Wolf Mountain intrusion and the Midway Granite sill, *in* Mosher, S., ed., Guide to the Precambrian geology of the eastern Llano uplift (Geological Society of America 30th annual South-Central Section meeting Guidebook): Austin, Department of Geological Sciences, University of Texas at Austin, p.25–33.

Reed, R. M., 1996b, Emplacement and deformation of late synorogenic to post-orogenic granites in the Grenvillian Llano Uplift, central Texas: A preliminary report: Geological Society of America Abstracts with Programs, v. 28, no. 1, p. 59.

Reed, R. M., and Helper, M. A., 1994, Evidence for solid-state deformation of ~1.1 Ga "anorogenic" granites in the Llano Uplift, Texas: Geological Society of America Abstracts with Programs, v. 26, no. 1, p. A25.

Reed, R. M., Roback, R. C., and Helper, M. A., 1995, Nature and age of ductile deformation associated with the "anorogenic" Town Mountain Granite, Llano uplift, central Texas 12th International Conference on Basement Tectonics '95: Norman Oklahoma, International Basement Tectonics Association, 68p.

Reed, R. M., Eustice, R. A., Rougvie, J. R., and Reese, J. F., 1996, Sedimentary structures, paleo-weathering, and protoliths of metamorphic rocks, Grenvillian Llano Uplift, Central Texas: Geological Society of America Abstracts with Programs, v. 28, no. 1, p. 59.

Reese, J. F., 1995, Structural evolution and geochronology of the southeastern Llano Uplift, central Texas. [Ph.D. dissert.]: Austin, University of Texas at Austin, 172 p.

Reese, J. F., Roback, R. C., and Walker, N. W., 1992, Reworked pre-Grenville crust and timing of Grenville orogenesis in the southeastern Llano Uplift, Texas: Results from U-Pb zircon geochronometry: Geological Society of America Abstracts with Programs, v. 24, no. 7, p. A92.

Reynolds, D. J., 1985, Deformation along the late Precambrian Streeruwitz thrust near Allamoore, Hudspeth County, Texas, *in* Dickerson, P. W., and Muelhberger, W. R., eds., Structure and tectonics of Trans-Pecos Texas: West Texas Geological Society Publication 85–811, p. 107–115.

Rivers, T., Martignole, J., Gower, C. F., and Davidson, A., 1989, New tectonic divisions of the Grenville Province, southeast Canadian shield: Tectonics, v. 8, p. 63–84.

Roback, R. C., 1996a, Characterization and tectonic evolution of a Mesoproterozoic island arc in the southern Grenville Orogen, Llano uplift, central Texas: Tectonophysics, v. 265, p. 29–52.

Roback, R., C., 1996b, Mesoproterozoic polymetamorphism and magmatism in the Llano Uplift, central Texas: Geological Society of America Abstracts with Programs, v. 28, no. 7, p. A377.

Roback, R. C., and Carlson, W. D., 1996, Constraining the timing of high-P metamorphism in the Llano uplift through geochronology of eclogitic rocks: Geological Society of America Abstracts with Programs, v. 28, no. 1, p. 60–61.

Roback, R. C., James, E. W., Whitefield, C., and Connelly, J. N., 1995, Tectonic assembly of "Grenville" terranes in the Llano Uplift, central Texas: Evidence from Pb and Sm-Nd isotopics: Geological Society of America Abstracts with Programs, v. 27, no. 6, p. A398.

Roths, P. J., 1993, Geochemical and geochronological studies of the Grenville-age (1250–1000 Ma) Allamoore and Hazel Formations, Hudspeth and Culberson counties, west Texas, *in* Soegaard, K., Nielsen, K. C., Marsaglia, K. M., and Barnes, C. G., eds., Precambrian geology of Franklin Mountains and Van Horn area, Trans-Pecos, Texas (Geological Society of America South-Central Section meeting guidebook): Dallas, University of Texas, p. 1–35.

Rougvie, J. R., 1993, Metamorphism and fluid flow in the Valley Spring Gneiss, Llano Uplift: Inferences from Rb-Sr and oxygen isotopic data [Master's thesis]: Austin, Texas, University of Texas, 93 p.

Rougvie, J. R., Carlson, W. D., Connelly, J. N., Roback, R. C., and Copeland, P., 1996, Late thermal evolution of Proterozoic rocks in the northeastern Llano uplift, central Texas: Geological Society of America Abstracts with Programs, v. 28, no. 7, p. A376.

Rudnick, R. L., 1983, Geochemistry and tectonic affinities of a Proterozoic bimodal igneous suite, west Texas: Geology, v. 11, p. 352–355.

Seeley, J. M., 1990, Stratigraphy, petrology, and depositional environment of the Middle Proterozoic Lanoria Formation, Franklin Mountains, El Paso County, Texas [Master's thesis]: Kingsville, Texas A & I University, 134 p.

Sengör, A. M. C., Burke, K., and Dewey, J. F., 1978, Rifts at high angles to orogenic belts; tests for their origin and the Upper Rhine Graben as an example: American Journal of Science, v. 278, p. 24–40.

Shannon, W. M., Barnes, C. G., and Bickford, M. E., 1997, Grenville magmatism in west Texas: Petrology and geochemistry of the Red Bluff Granitic Suite: Journal of Petrology, v. 38, p. 1279–1305.

Shervais, J. W., 1982, Ti-V plots and the petrogenesis of modern and ophiolitic lavas: Earth and Planetary Science Letters, v. 59, p. 101–118.

Silver, E. A., and Reed, D. C., 1988, Backthrusting in accretionary wedges: Journal of Geophysical Research, v. 93, p. 3116–3170.

Size, W. B., 1979, Petrology, geochemistry and genesis of the type area trondhjemite in the Trondheim region, central Norwegian Caledonides: Norges Geologiske Undersogelse, v. 351, p. 51–76.

Smith, D. R., Barnes, C. G., Shannon, W., Roback, R. C., and James, E., 1997, Petrogenesis of Mid-Proterozoic granitic magmas: Examples from central and west Texas: Precambrian Research, v. 85, p. 53–79.

Soegaard, K., and Callahan, D. M., 1994, Late Middle Proterozoic Hazel Formation near Van Horn, Trans-Pecos Texas: Evidence for transpressive deformation in Grenvillian basement: Geological Society of America Bulletin, v. 106, p. 413–423.

Soegaard, K., Nielson, K. C., and Bickford, M. E., 1996, Lithostratigraphy and chronometry of Middle Proterozoic Carrizo Mountain Group, west Texas: Geological Society of America Abstracts with Programs, v. 28, p. 64.

Thomann, W. F., 1981, Ignimbrites, trachytes and sedimentary rocks of Precambrian Thunderbird group, Franklin Mountains, El Paso, Texas: Geological Society of America Bulletin, v. 92, p. 94–100.

Thomann, W. F., and Hoffer, J. M., 1985, Petrology and geochemistry of the Precambrian Mundy Breccia, Franklin Mountains, Texas: Texas Journal of Science, v. 36, p. 71–80.

Thompson, R. N., Morrison, M. A., Dickin, A. P., and Hendry, G. L., 1984, An assessment of the relative roles of a crust and mantle in magma genesis: An elemental approach: Royal Society of London Philosophical Transactions, ser. A, v. 310, p. 549–590.

Toomey, D. F., and Babcock, J. A., 1983, Stromatolites in the Precambrian Allamoore Formation, Millican Hills, west Texas, *in* Precambrian and Paleozoic algal carbonates, west Texas-southern New Mexico; 3rd International Symposium on Fossil Algae: Colorado School of Mines Professional Contributions no. 11, p. 329–345.

Torsvik, T. H., Smethurst, M. A., Meert, J. G., Van der Voo, R., McKerrow, W. S., Brasier, M. D., Sturt, B. A., and Walderhuaug, H. J., 1996, Continental break-up and collision in the Neoproterozoic and Paleozoic: A tale of Baltica and Laurentia: Earth Science Reviews, v. 40, p. 229–258.

Unrug, R., 1996, The assembly of Gondwanaland: Episodes, v. 19, p. 11–20.

Van Schmus, W. R., Bickford, M. E., and Turek, A., 1996, Proterozoic geology of the east-central mid-continent basement, *in* van der Pluijm, B. A., and Catacosinos, P. A., eds., Basement and basins of eastern North America: Geological Society of America Special Paper 308, p. 7–32.

Walker, N. W., 1992, Middle Proterozoic geologic evolution of the Llano Uplift, Texas: Evidence from U-Pb zircon geochronometry: Geological Society of America Bulletin, v. 104, p. 494–504.

Wasserburg, G. J., Wetherill, G. W., Silver, L. T., and Flawn, P. T., 1962, A study of the ages of the Precambrian of Texas: Journal of Geophysical Research, v. 67, p. 4021–4070.

Whitefield, C., 1997, A Sm-Nd isotopic study of the Coal creek domain and Sandy Creek shear zone [Master's thesis]: Austin, University of Texas at Austin, 159 p.

Wilkerson, A., Carlson, W. D., and Smith, D., 1988, High-pressure metamorphism during the Llano orogeny inferred from Proterozoic eclogitic remnants: Geology, v. 16, p. 391–394.

Wood, D. A., 1980, The application of a Th-Hf-Ta diagram to problems of tectomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province: Earth and Planetary Science Letters, v. 50, p. 11–30.

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