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Mesoproterozoic chronostratigraphy of the southeastern Llano uplift, central Texas

Joseph F. Reese*
Sharon Mosher†
James Connelly
Robert Roback§

Department of Geological Sciences, University of Texas, Austin, Texas 78712

ABSTRACT

The Llano uplift of central Texas exposes Mesoproterozoic crystalline rocks affected by a Grenvillian orogeny between 1.2 and 1.1 Ga. We report four new U-Pb zircon protolith ages of 1247 ± 4, 1257 ± 3, 1272 $^{+8}/_{-5}$, and 1366 ± 3 Ma for four quartzofeldspathic rocks from the regionally defined Packsaddle Schist and Valley Spring Gneiss in the southeastern part of the uplift. The 1366 ± 3 Ma gneiss also yields a metamorphic age of 1325 ± 5 Ma. These new U-Pb ages, in conjunction with previous U-Pb age data, demonstrate that several regionally defined map units contain constituents with widely disparate ages.

We have identified four age suites for protoliths of metamorphic rocks in the southeastern part of the Llano uplift that appear to represent rock packages of distinct tectonic origins: (1) the northern, 1366–1272 Ma felsic gneisses of volcanic, plutonic, and continentally derived sedimentary origin (Valley Spring Gneiss and an older gneiss component), (2) the geographically intermediate, ca. 1257–1247 Ma (and possibly older) basinal sequence that formed along a continental shelf and slope near an arc (Packsaddle Schist), (3) the southern, 1326–1275 Ma remnant of an exotic, ensimatic arc complex (Big Branch Gneiss and Coal Creek Serpentinite and plutonic complex), and (4) the 1239–1232 Ma tectonized felsic rocks that intruded the first two suites. The first three suites of rocks were structurally imbricated during Grenville orogenesis, and the fourth suite may either represent early synorogenic crustal melts or be related to the volcanic rocks in the Packsaddle Schist.

In addition, these new data show that, contrary to previous reports, *younger* Packsaddle Schist lies in structural contact above *older* components of the Valley Spring Gneiss. Moreover, one of the dated meta-igneous units is the oldest unit yet found in the uplift and records an early period of metamorphism prior to formation of most Llano uplift rocks. Its 1366 ± 3 Ma protolith age is coeval with rocks of the Western Granite-Rhyolite terrane. Age and geochemical similarities link this unit of unknown regional extent with the Western Granite-Rhyolite terrane of known Laurentian affinity. Thus, this component of the Llano uplift may be the basement on which the younger components of the Valley Spring Gneiss and Packsaddle Schist formed in a tectonic setting proximal to Laurentia and south of the Western Granite-Rhyolite terrane.

INTRODUCTION

The Llano uplift of central Texas exposes the largest tract (~9000 km^2) of Mesoproterozoic crystalline rocks in the south-central United States (Fig. 1). These rocks, as well as smaller exposures in west Texas and northern Mexico, comprise the western continuation of the Grenville orogenic belt of eastern North America (Mosher, 1993, 1998). Detailed structural, metamorphic, and geochronologic studies within the Llano uplift have shown that supracrustal and plutonic rocks were affected by a ca. 1.2–1.1 Ga orogenic event that involved polyphase, synmetamorphic ductile deformation (Nelis et al., 1989; Carter, 1989; Mosher, 1993, 1998; Reese, 1995) and transitional amphibolite-, granulite-, eclogite-facies dynamothermal metamorphism (Carlson and Nelis, 1986; Wilkerson et al., 1988; Carlson and Reese, 1994; Carlson and Schwarze, 1997; Carlson, 1998). Late syntectonic to posttectonic granitic plutons were emplaced at ca. 1.1 Ga synchronously with a low-pressure metamorphic event that overprinted the earlier, higher-pressure assemblages (Bebout and Carlson, 1986; Walker, 1992; Reed, 1995, 1999; Carlson, 1998). In the southeastern part of the uplift, the 1326–1275 Ma mafic plutonic rocks and a serpentinized harzburgite (the Coal Creek Serpentinite) form a distinct lithotectonic terrane (Coal Creek domain; Roback, 1996a) that is interpreted to represent an ensimatic arc that evolved separately from the rest of the Llano uplift and accreted to the southern margin of North America during Grenville orogenesis (Roback, 1996a; Mosher, 1998). Timing of accretion is bracketed between the age of the youngest protolith in the arc terrane and the age of the oldest stitching pluton—i.e., between 1275 $^{+2}/_{-1}$ Ma and 1119 $^{+6}/_{-3}$ Ma (Reed et al., 1995; Roback, 1996a; Mosher, 1998). Protolith ages of mylonitic rocks within the terrane-bounding shear zone suggest that accretion occurred after 1238 $^{+8}/_{-6}$ Ma (Walker, 1992), and metamorphic ages support accretion at ca. 1150–1120 Ma (Roback, 1996b; Roback and Carlson, 1996; Mosher, 1998).

The Mesoproterozoic tectonic history prior to collisional orogenesis is less well constrained. The penetrative deformational and metamorphic overprint makes identification of protoliths and lithotectonic relationships difficult, and previous attempts at defining the tectonic setting for protolith formation were hampered by the lack of absolute age constraints and structural control. Most early workers (e.g., Paige, 1912; McGehee, 1979) considered the contacts between metamorphic units across the uplift to be conformable and stratigraphic in nature. Thus, a stratigraphy for the major Precambrian metamorphic units in the Llano uplift was established on the basis of their relative structural level within open, regional-scale folds and regional correlation of grossly similar litholo-

*Present address: Department of Geology and Geography, Northwest Missouri State University, Maryville, Missouri 64468.
†Corresponding author; e-mail: mosher@mail.utexas.edu.
§Present address: Los Alamos National Laboratory, Los Alamos, New Mexico 87545.

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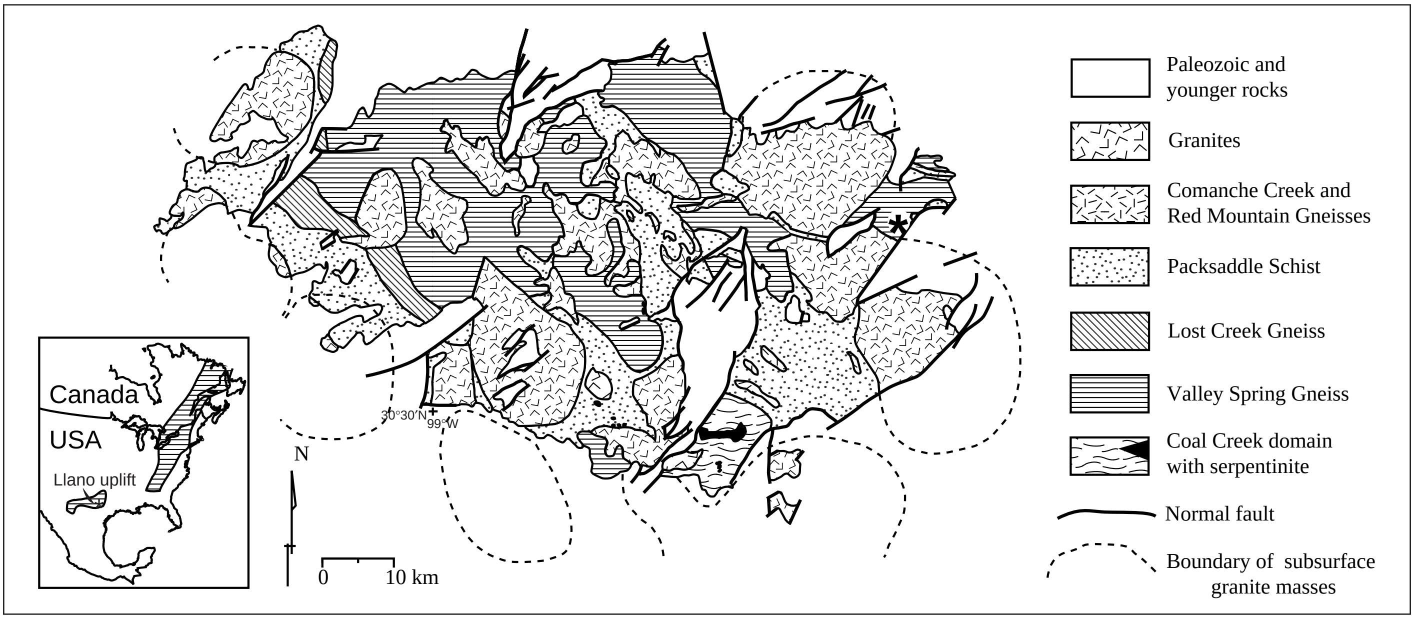


Figure 1. Generalized geologic map of the Llano uplift, central Texas (after Mosher, 1993). Asterisk designates the location of Inks Lake gneiss at Inks Lake State Park. Inset shows outlined locations of Grenville orogenic belts in North America.

gies (Fig. 2A) (see McGehee, 1979; Barnes, 1988; and references therein). The first application of modern U-Pb geochronology (Walker, 1992) suggested that this simple stratigraphic succession was in error and that regional map units were tectonically juxtaposed (Fig. 2B). Resolving this discrepancy is fundamental to determining the precollisional tectonic setting along the southern margin of Laurentia.

This paper presents U-Pb geochronology from four quartzofeldspathic units in the southeastern part of the Llano uplift (Fig. 3) from an area where the structure in the area has been mapped in detail (Reese, 1995). The samples were selected from key locations where contact relationships were carefully documented. The results establish the protolith ages for the major regional map units in the southeastern part of the uplift and—coupled with those of other geochronologic investigations (Walker, 1992; Reese, 1995; Roback, 1996a)—their age variability. In this paper, we reevaluate the previously defined stratigraphy, regional map units, and structural relationships and identify four age suites of metamorphic protoliths that appear to represent rock packages of distinct tectonic origins. Furthermore, we present data indicating that at least one gneissic unit is the age equivalent of rocks of the Western Granite-Rhyolite terrane, and we suggest a possible link between gneisses in the uplift and the North American craton immediately to the north. All of these relationships provide important temporal and spatial constraints on tectonic models for the Mesoproterozoic tectonic evolution of the southern margin of Laurentia.

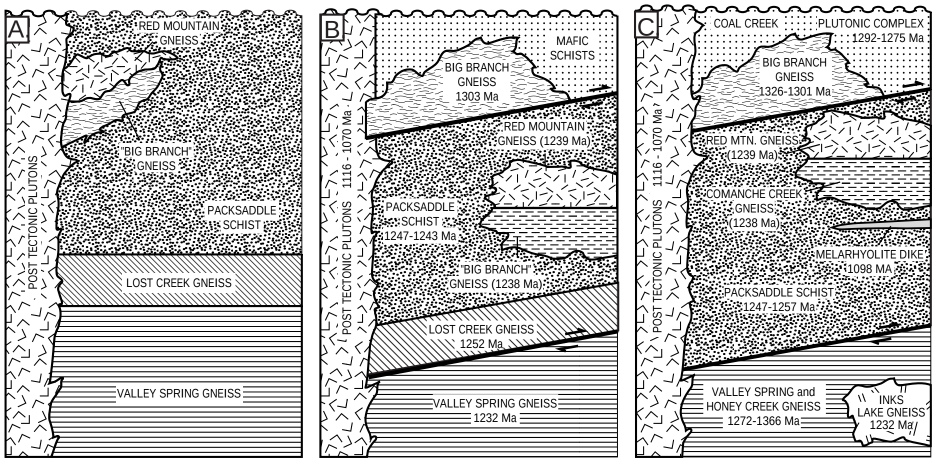


Figure 2. (A) Original stratigraphy (after McGehee, 1979). (B) Tectonostratigraphy of Walker (1992). (C) Revised chronostratigraphic and structural relationships in the southeastern part of the Llano uplift.

Previous Stratigraphy

Previous workers (see McGehee, 1979; Barnes, 1988; and references therein) inferred a basic stratigraphic order for the major Precambrian metamorphic units in the Llano uplift, which was, from structurally lowest to highest (or what they considered oldest to youngest), Valley Spring Gneiss, Lost Creek Gneiss, and Packsaddle Schist (Fig. 2A) (McGehee, 1979; Barnes, 1981, 1988; also see Walker, 1992). In the southeastern part of the Llano uplift, the stratigraphy differed; the Lost Creek Gneiss is absent, and the Packsaddle Schist is structurally overlain by mafic rocks including the Coal Creek Serpentinite and Big Branch Gneiss (Barnes, 1978a, 1978b, 1978c; McGehee, 1979) (Figs. 1, 2, 3). The "stratigraphy" followed the original mapping of Paige (1912), who treated the Valley Spring Gneiss and Packsaddle Schist as sedimentary units with a gradational contact. Paige (1912) placed the contact between these two units at the base of a predominately gneissic sequence. McGehee (1979) introduced the term "Llano Supergroup" for these units and also considered them to be primarily of sedimentary origin with minor igneous components. On the basis

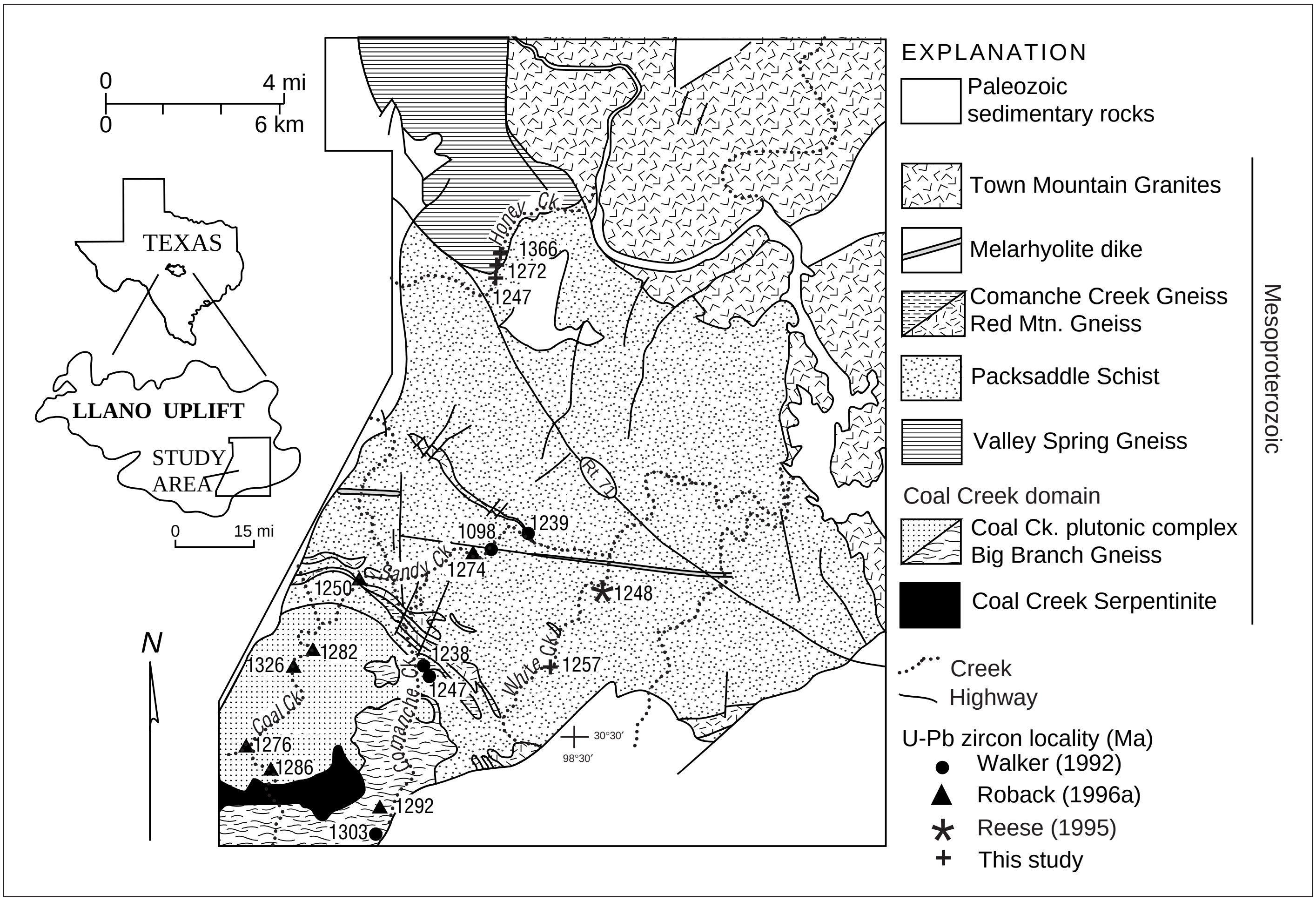


Figure 3. Geologic map of the southeastern part of the Llano uplift (modified from McGehee, 1979), showing U-Pb dates for the regional map units that have been dated. Areas of predominately Big Branch Gneiss or Coal Creek plutonic complex rocks are separated, although both units commonly occur together.

of gross lithologic similarities, McGehee (1979) subdivided the Packsaddle Schist in the southeastern part of the Llano uplift into, from structurally lowest to highest, the Honey, Sandy, Rough Ridge, and Click Formations (see McGehee, 1979, for detailed descriptions). Individual units within the Valley Spring Gneiss were also identified and mapped separately (Lidiak et al., 1961; Barnes, 1978c; McGehee, 1979). Early U-Pb, Rb-Sr, and K-Ar geochronologic studies (Tilton et al., 1957; Silver, 1963; Zartman, 1964, 1965; DeLong and Long, 1976; Garrison et al., 1979) established a Grenville age for both the metamorphism and late, crosscutting granitic plutons, providing a minimum age for the stratigraphic sequence.

Walker's (1992) study, which obtained protolith ages of 1303–1232 Ma for a suite of metamorphic units, demonstrated that regional map units contain rocks of greatly disparate age. He challenged the long-accepted stratigraphic order and suggested that these packages may have been tectonically juxtaposed to produce their present geometric configuration. It is notable that for the two regionally extensive map units in the uplift, Walker (1992) interpreted that *older* Packsaddle Schist structurally overlies *younger* Valley Spring Gneiss (Figs. 1, 2B) and suggested that the entire stratigraphy was inverted or tectonically imbricated.

Regional Map Unit Descriptions

The Valley Spring Gneiss is a regionally extensive map unit (Fig. 1) consisting primarily of quartzofeldspathic gneiss. The gneiss in the eastern part of the uplift has a bulk composition of a granite or arkose (Billings, 1962). Farther west, it has variable compositions more consistent with sedimentary (Mutis-Duplat, 1972; Droddy, 1978; Reed et al., 1996) or volcaniclastic protoliths and contains minor calc-silicate, marble, metagabbro, serpentinite, amphibolite, mafic and pelitic schist, and quartzite (Barnes, 1981, 1988). Paige (1912) originally defined the Valley Spring Gneiss as strictly sedimentary in origin, in part to distinguish it from younger, foliated intrusive rocks. In contrast, Stenzel (1935) considered most of the Valley Spring Gneiss, as mapped by Paige (1912), to be igneous in origin and redefined the gneiss to exclude all demonstrably sedimentary rocks. Subsequent workers (e.g., McGehee, 1979; Barnes, 1981), however, used Paige's (1912) map unit, but did not require a sedimentary origin. Barnes (1988) hypothesized that the gneiss represents a succession of felsic volcanic, pyroclastic, and volcaniclastic rocks intercalated with sedimentary units of varied rock type, whereas McGehee (1979) considered them sedimentary in origin. Although previous workers have speculated on the nature of the gneiss protolith, hypotheses on the tectonic setting in which the Valley Spring Gneiss formed are scant (cf. Mosher, 1998).

The Packsaddle Schist (Fig. 1) is a regionally extensive, lithologically heterogeneous map unit consisting of hornblende, graphite, biotite, muscovite, actinolite, and calcareous schists, quartzites and quartzofeldspathic rocks, amphibolites, and marbles. Rocks of the Packsaddle Schist have been interpreted as predominantly metasedimentary (Paige, 1912; McGehee, 1979; Garrison, 1981a, 1981b). McGehee (1979), however, suggested the possibility that it may represent a metamorphosed volcanogenic pile, with sedimentary and igneous precursors. Several workers (Billings, 1962; Patchett and Ruiz, 1989; Walker, 1992; Reese, 1995; Roback, 1996a) have identified units with igneous protoliths within the schist, including rare basaltic pillow lavas (Farmer, 1977) and sills (Roback, 1996a). The depositional environment for the Packsaddle Schist is interpreted to have been a continental-shelf-and-slope setting along the flank of an arc (Garrison, 1981a, 1981b, 1985; Mosher, 1998).

Much less extensive map units include the Big Branch and Red Mountain Gneisses in the southeastern part of the uplift (Fig. 3) and the Lost Creek Gneiss in the western part of the uplift (Fig. 1) (Barnes, 1981). The Big Branch Gneiss consists of 1326–1301 Ma (U-Pb zircon protolith ages) tonalitic gneisses adjacent to the Coal Creek Serpentinite (Fig. 3; see Roback, 1996a), whereas the Red Mountain Gneiss consists of a series of southwest-dipping granitic sills (0.1–1.5 km by 0.3–8 km) that intrude the structurally uppermost (and presumed "youngest") part of the Packsaddle Schist (Nelis et al., 1989) near the tectonic contact with the Coal Creek domain of Roback (1996a). One of these sills yielded a U-Pb zircon protolith age of $1239\ ^{+5}/_{-3}$ Ma (Walker, 1992). The Lost Creek Gneiss is a migmatitic granitic augen gneiss that yielded a zircon protolith age of 1252 ± 3 Ma in the northwestern part of the uplift (Walker, 1992).

U-PB ZIRCON GEOCHRONOMETRY

Data Collection and Analysis

Five samples of meta-igneous quartzofeldspathic units from the Packsaddle Schist and Valley Spring Gneiss in the southeastern part of the Llano uplift were collected for U-Pb analyses. All samples are from localities where field and petrologic characteristics (Figs. 4, 5, and 6) and structural relationships of the units are well known (Reese, 1995). We dated these units to test their stratigraphic and structural order and to check for temporal variability of regional map units. To resolve the geochronometric variability of the Packsaddle Schist, three units were sampled from different structural levels within the schist, two from the middle of the sequence and the other at its lower contact, adjacent to the Valley Spring Gneiss. To constrain the age relationships between the Packsaddle Schist and the Valley Spring Gneiss and to examine previously postulated structural relationships across this contact, we also collected two samples of Valley Spring Gneiss adjacent to the contact. Sample localities (Fig. 3; crosses) and analytical methods are given in Appendix 1. Isotopic data and calculated ages (2s) are presented in Table 1 and plotted in Figure 7. It should be noted that zircons dated in this study are from the same samples as those Reese (1995) dated by using bulk zircon fractions. One of the units previously yielded an age inconsistent with the field relationships, and another indicated complex zircon systematics. Considering the potential complexity of these rocks, four of the five dated by Reese (1995) have been reanalyzed by using significantly smaller size fractions of carefully hand-picked, high-quality zircons that were optically characterized by petrographic microscope and cathodoluminescence. A fifth sample from the middle of the Packsaddle Schist was not reanalyzed because the age determined by Reese (1995) is consistent with the redated Packsaddle Schist samples.

U-PB ZIRCON RESULTS

Packsaddle Schist—White Creek

Two felsic units from the middle part of the Packsaddle Schist (Rough Ridge Formation) exposed in White Creek were selected for dating (Reese, 1995; Fig. 3). The local preservation of primary features within the Packsaddle Schist allows identification of protoliths for some metasedimentary and metavolcanic rocks in spite of the generally strong penetrative strain. The units sampled are not intensely deformed and were chosen because field and petrographic characteristics (discussed below) indicate that they are

A

B

Figure 4. Packsaddle Schist metavolcanic unit; dated by Reese (1995) at 1248 ± 3 Ma. (A) Moderately foliated rhyolite or felsic tuff. The fine-grained quartzofeldspathic rock contains thin interlayers of micaceous quartzofeldspathic schist. (Arrow points to hammer for scale, center of photograph.) (B) Close-up of quartzofeldspathic rock in A showing color banding suggestive of compositional layering. Note that the banding is not due to differences in the degree of deformation, grain size, or mesoscopic composition. (Pencil for scale, bottom of photograph.)

volcanic in origin. Volcanic and volcaniclastic rocks in this area are interlayered with metasedimentary units. Much of the sequence consists of interlayered biotite and/or muscovite schist and micaceous quartzofeldspathic schist, quartzofeldspathic rock interlayered with muscovite schist, and biotite and/or muscovite schist. Interspersed with these units are amphibole and/or biotite schists and gneisses that locally are epidote rich. Crosscutting relationships indicate that some of the mafic units are intrusive (e.g., orthoamphibolites), but a volcanic origin for many is probable. Metasedimentary units include 0.2–5-m-thick quartzite interlayered with 0.1–2-m-thick muscovite schist, garnet-staurolite-sillimanite-biotite-muscovite schist, and microcline-andalusite-muscovite schist. The latter has been interpreted as a metabauxite deposit (Carlson and Reese, 1994). Volcanic and/or volcaniclastic rocks include variable ~10–30-cm-thick, fine-grained quartzofeldspathic rock interlayered with ~3–10-cm-thick micaceous quartzofeldspathic schist (Fig. 4). The quartzofeldspathic rock contains a color banding suggestive of a compositional layering, and no corresponding difference in mesoscopic composition, grain size, or degree of deformation is observed. Granitic orthogneisses also occur and may be equivalent to the Red Mountain Gneiss.

Packsaddle Schist—Sample 1 (PSRRV). This sample was collected from the structurally upper part of the Rough Ridge Formation of the Packsaddle Schist (Fig. 3). It is a poorly to moderately foliated, fine- to medium-grained, quartz-microcline-plagioclase rock with minor biotite, epidote, and Fe-Ti oxides. The sample contains equant <1 mm matrix grains and sporadic, isolated 1–2 mm quartz and feldspar porphyroclasts, which appear to be relict phenocrysts (Fig. 5B). Quartz porphyroclasts are rounded and consist of either single unstrained crystals (Fig. 5A) or aggregates of quartz grains. Many feldspar porphyroclasts contain inclusions of other feldspar, quartz, or biotite (Fig. 5C) or are aggregates (relict glomeroclasts) of smaller feldspar grains. The feldspar porphyroclasts are partially altered to sericite or calcite. The bimodal grain size is clearly part of the original texture and not the result of grain-size reduction of matrix grains by dynamic recrystallization. The rock shows no evidence of shear-related fabrics. In plane-polarized light, irregularly shaped aggregates of feldspar and quartz are surrounded by biotite (Fig. 6A), reminiscent of replaced and flattened lapilli. Minerals are inhomogeneously distributed across a single thin section, resulting in local compositional changes consistent with the unit being a volcanic tuff. The rock has the bulk mineral composition and texture of a slightly deformed and metamorphosed porphyritic dacite. Rock types of adjacent units are similar, some being slightly more micaceous and schistose and others being more quartzose and finer grained. All units trend northwest, dip southwest, are polydeformed, and have sharp to slightly gradational (on the centimeter scale) contacts that are folded. The unit sampled is currently ~10 m thick, whereas the package of quartzofeldspathic rocks in which the unit is contained is ~70 m thick. Original thicknesses have been modified by ductile deformation.

This sample yielded a single population of euhedral, clear, colorless to slightly cloudy zircons that typically lack visible inclusions or cores. These zircons vary from 25 to 75 μm in length, and their aspect ratios range from 2:1 to 4:1. Cathodoluminescence (CL) imaging shows straight internal growth zonation, typical of magmatic growth (Fig. 8A). The single morphological type and internal zonation collectively imply an igneous origin for this zircon population, either plutonic or volcanic. The lack of any other zircon type precludes a mixed detrital component, and the euhedral shapes require a very local source if the population is epiclastic.

Three fractions of the best euhedral zircon define a discordia line with intercepts at $1257^{+6}/_{-3}$ Ma and 507 ± 275 Ma (71% probability of fit); fraction Z1 is concordant and coincides with the upper intercept (Fig. 7A). The large error on the upper intercept is due to clustering near concordia and lies well outside the errors for the concordant point. We therefore prefer to assign an error commensurate with the concordant point to derive an age of 1257 ± 3 Ma. Because we interpret these zircons to be igneous in origin, this age is presumed to date the crystallization of the protolith.

Reese (1995) dated an additional unit near the base of the Rough Ridge Formation, (3 km north-northeast of the sample 1 (PSRRV) collection site (Fig. 3). He obtained an upper-concordia intercept of 1248 ± 3 Ma (with a lower intercept of ca. 0 Ma), which he interpreted as the igneous crystallization age of the volcanic protolith. Because this age is coeval with other ages for the rest of the Packsaddle Schist, this sample was not redated. This fine-grained quartzofeldspathic unit

TABLE 1. U-Pb DATA

Fraction	Mass (mg)	Concentration U (ppm)	Concentration Pb (ppm)	Measured Total common Pb (pg)	Measured $^{206}Pb/^{204}Pb$	Corrected atomic ratios* $^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	±	$^{207}P/^{235}U$	±	$^{207}Pb/^{206}Pb$	±	Ages (Ma) $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
SAMPLE 1 (PSRRV)															
Z1 10 sm clr euh prsm	0.008	104	23.3	4	3038	0.1263	0.21500	44	2.4439	60	0.08244	12	1255	1256	1256
Z2 6 sm clr clrls	0.002	131	29.7	3	1335	0.1480	0.21333	52	2.4212	70	0.08232	14	1247	1249	1253
Z3 13 sm clr euh prsm	0.010	124	27.7	2	8691	0.1397	0.21189	46	2.4023	56	0.08223	8	1239	1243	1251
SAMPLE 2 (PSBG)															
Z1 7 sub-euh w incl	0.006	82	18.6	1	6293	0.1540	0.21266	76	2.4071	86	0.08209	16	1243	1245	1248
Z2 8 sm cldy	0.011	112	25.4	22	788	0.1632	0.21253	62	2.4015	80	0.08195	18	1242	1243	1244
SAMPLE 3 (VSAG)															
Z1 2 med clr euh prsm	0.008	219	49.1	1	18203	0.1307	0.21452	56	2.4571	66	0.08307	8	1253	1260	1271
Z2 2 med clr clrls	0.003	221	48.9	2	5827	0.1296	0.21227	58	2.4299	66	0.08302	10	1241	1251	1270
Z3 2 med clr euh prsm	0.005	181	40.0	4	3213	0.1299	0.21219	52	2.4303	62	0.08307	12	1240	1252	1271
SAMPLE 4 (VSHEG)															
Z1 euh fract cldy incl	0.024	326	79.7	11	10546	0.1587	0.22841	58	2.7311	70	0.08672	10	1326	1337	1354
Z2 fract cldy	0.032	535	129.9	20	12271	0.1575	0.22673	56	2.7074	66	0.08660	10	1317	1330	1352
Z3 sub-euh cldy	0.020	506	122.8	12	12503	0.1715	0.22399	74	2.6636	86	0.08624	12	1303	1318	1344
Z4 cldy crack mag	0.019	782	167.1	40	4810	0.1164	0.20662	72	2.4191	82	0.08491	14	1211	1248	1314
Z5 sph v clr prsm	0.015	121	29.9	5	5626	0.1886	0.22526	80	2.6423	94	0.08508	18	1310	1313	1317
Z6 sph v clr prsm	0.016	110	27.4	3	7406	0.2029	0.22490	98	2.6389	112	0.08510	16	1308	1312	1318
Z7 clr sph mag	0.015	117	29.2	4	6376	0.2021	0.22483	84	2.6458	90	0.08535	20	1307	1313	1323

Note: Abbreviations: cldy—cloudy; clr—clear; clrls—colorless; euh—euhedral; fract—fractured; incl—inclusions; mag—magnetic (at 1° backslope, full magnetic field strength on Frantz separator); med—medium size (75–100 μm); prsm—prisms; sm—small size (50–75 μm); sph—spherical; sub—subhedral; w—with; v—very.

*Ratios corrected for fractionation, 1 pg laboratory Pb blank, initial common Pb calculated by using Pb isotopic compositions of Stacey and Kramers (1975) and 0.25 pg U laboratory blank. Two-sigma uncertainties on isotopic ratios, calculated with a modified unpublished error propagation program written by L. Heaman, are reported after the ratios and refer to the least significant digits. All fractions were well abraded.

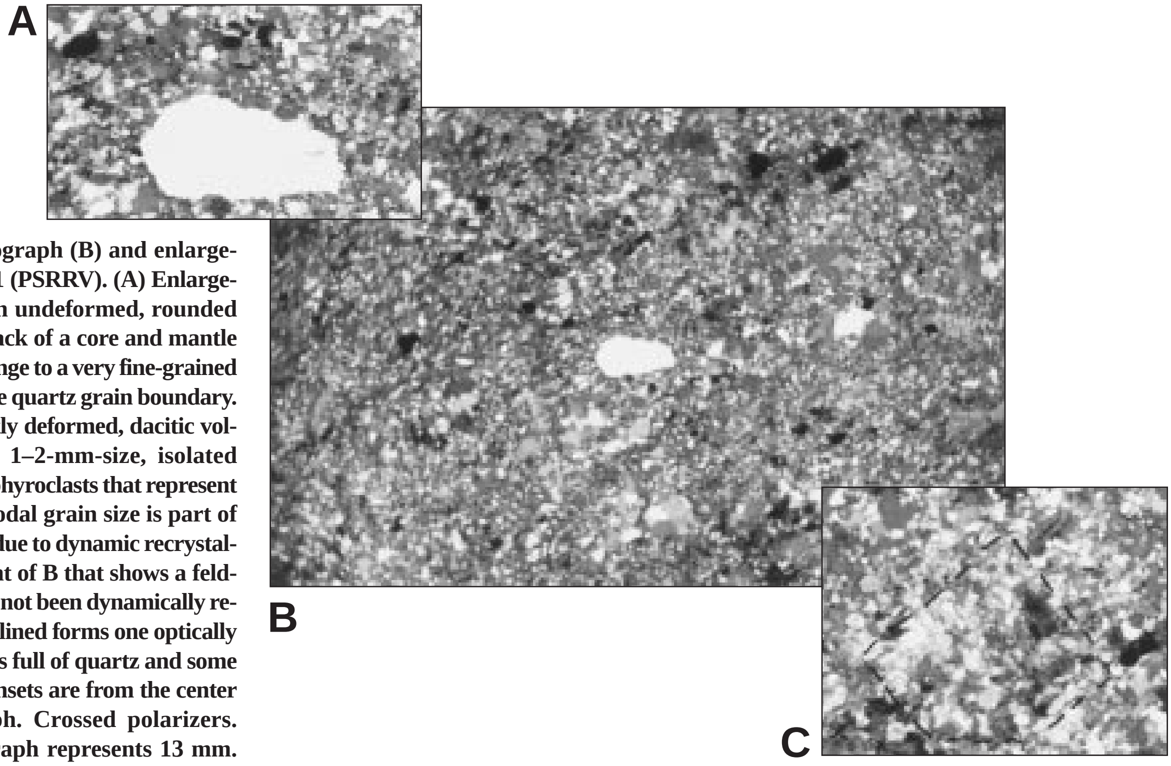


Figure 5. Photomicrograph (B) and enlargements (A, C) of sample 1 (PSRRV). (A) Enlargement of B that shows an undeformed, rounded quartz grain. Note the lack of a core and mantle structure; an abrupt change to a very fine-grained matrix occurs at the large quartz grain boundary. (B) Recrystallized, slightly deformed, dacitic volcanic rock, containing 1–2-mm-size, isolated quartz and feldspar porphyroclasts that represent relict phenocrysts. Bimodal grain size is part of original texture and not due to dynamic recrystallization. (C) Enlargement of B that shows a feldspar phenocryst that has not been dynamically recrystallized; the area outlined forms one optically continuous grain, but it is full of quartz and some biotite inclusions. Both insets are from the center of the photomicrograph. Crossed polarizers. Width of photomicrograph represents 13 mm.

is well foliated, lineated, and crenulated. Overall it has the same texture as sample 1 (PSRRV), but is more deformed (Fig. 6B). The composition and texture are consistent with those of a deformed and metamorphosed, thinly layered rhyolitic tuff (Fig. 4). It is part of a massive felsic schist and gneiss unit composed of quartz, microcline, and minor plagioclase, biotite, and muscovite. Microcline (partially altered to muscovite) occurs within the matrix and as submillimeter-sized porphyroclasts; rare grains are up to 3 mm in size. Foliation is defined by quartz-rich and feldspar-rich layers and aligned biotite, and no evidence exists for shear-related fabrics. The unit is in sharp contact at its base and top with poorly exposed amphibole schists; all units strike northwest and are polydeformed. The sampled rock layer is ~3 m thick, and the entire quartzofeldspathic rock package is ~50 m thick and extends for at least 6 km to the west-northwest (Barnes, 1978a, 1978b; Nelis et al., 1989).

Contact Between Packsaddle Schist and Valley Spring Gneiss

The contact between the Valley Spring Gneiss and the Packsaddle Schist along Honey Creek (Fig. 3) is an ~100-m-wide, southwest-dipping ductile shear zone. Both the Packsaddle Schist and the Valley Spring Gneiss have mylonitic fabrics with a top-to-the-northeast (thrust) shear sense (Reese, 1995). Three samples adjacent to the Valley Spring Gneiss–Packsaddle Schist contact were selected to establish the absolute ages of units in this contact zone. Samples of Packsaddle Schist and Valley Spring Gneiss from the shear zone and a second sample of Valley Spring Gneiss from a unit <100 m north of, and structurally beneath, the shear zone were dated.

At this locality, the Packsaddle Schist (Honey Formation) is predominantly a metasedimentary succession of marbles, calc-silicate, graphitic, and micaceous schists, and minor quartzofeldspathic rocks (McGehee, 1979) with amphibolitic layers of probable mafic volcanic origin (Billings, 1962). Immediately below the structural contact with the Packsaddle Schist, the Valley Spring Gneiss is composed of a laterally extensive, layered sequence of gneisses subdivided by McGehee (1963) and Barnes (1978c). Both units sampled are part of Barnes's (1978c) Valley Spring Gneiss layer C. The structurally uppermost part of the Valley Spring Gneiss (in contact with the Packsaddle Schist) is a 5-m-thick augen gneiss that extends laterally westward for as far as 32 km (McGehee, 1979), occupying the same structural position in the Little Llano River area (Lidiak et al., 1961). It also extends northeastward around the hinge of the Babyhead anticline (Barnes, 1978c).

Packsaddle Schist—Sample 2 (PSBG). The sampled Packsaddle Schist unit is a 5-m-thick, well-foliated, thinly layered (0.5–10 cm), fine-grained, biotite-rich quartzofeldspathic gneiss with 1–3 mm microcline porphyroclasts. The unit occurs at the structurally lowermost part of the Packsaddle Schist (Fig. 3) ~200 m south of, and above, the Valley Spring Gneiss–Packsaddle Schist contact. The unit strikes to the northwest and dips moderately to the southwest. The rock contains a mylonitic fabric with asymmetric, rotationally recrystallized feldspar tails on microcline porphyroclasts. Thin layers of aligned biotite parallel the foliation. Although some porphyroclasts are large microcline crystals, others are clast-shaped aggregates of smaller grains (relict glomeroclasts). These aggregates are generally composed of either (1) garnet and lesser amounts of quartz and plagioclase (highly altered to epidote, muscovite, and calcite) (Fig. 6C) or (2) equal amounts of microcline, plagioclase, and quartz. The unit has been folded by at least two later generations of folds (Reese, 1995). The unit sampled is concordant and in sharp contact with surrounding, thick amphibole and muscovite-biotite schists of the Honey Formation. The unit is interpreted to be volcanic on the basis of its field and thin-section characteristics. It is relatively isolated from other similar units within the Packsaddle Schist, but is interlayered with units interpreted to be mafic volcanic flows on the basis of geochemistry and nearby basaltic pillow lavas (Billings, 1962; Farmer, 1977).

Locally within the unit, very thin (<0.5 cm), variably deformed, quartzofeldspathic veins parallel the dominant metamorphic fabric. We pref-

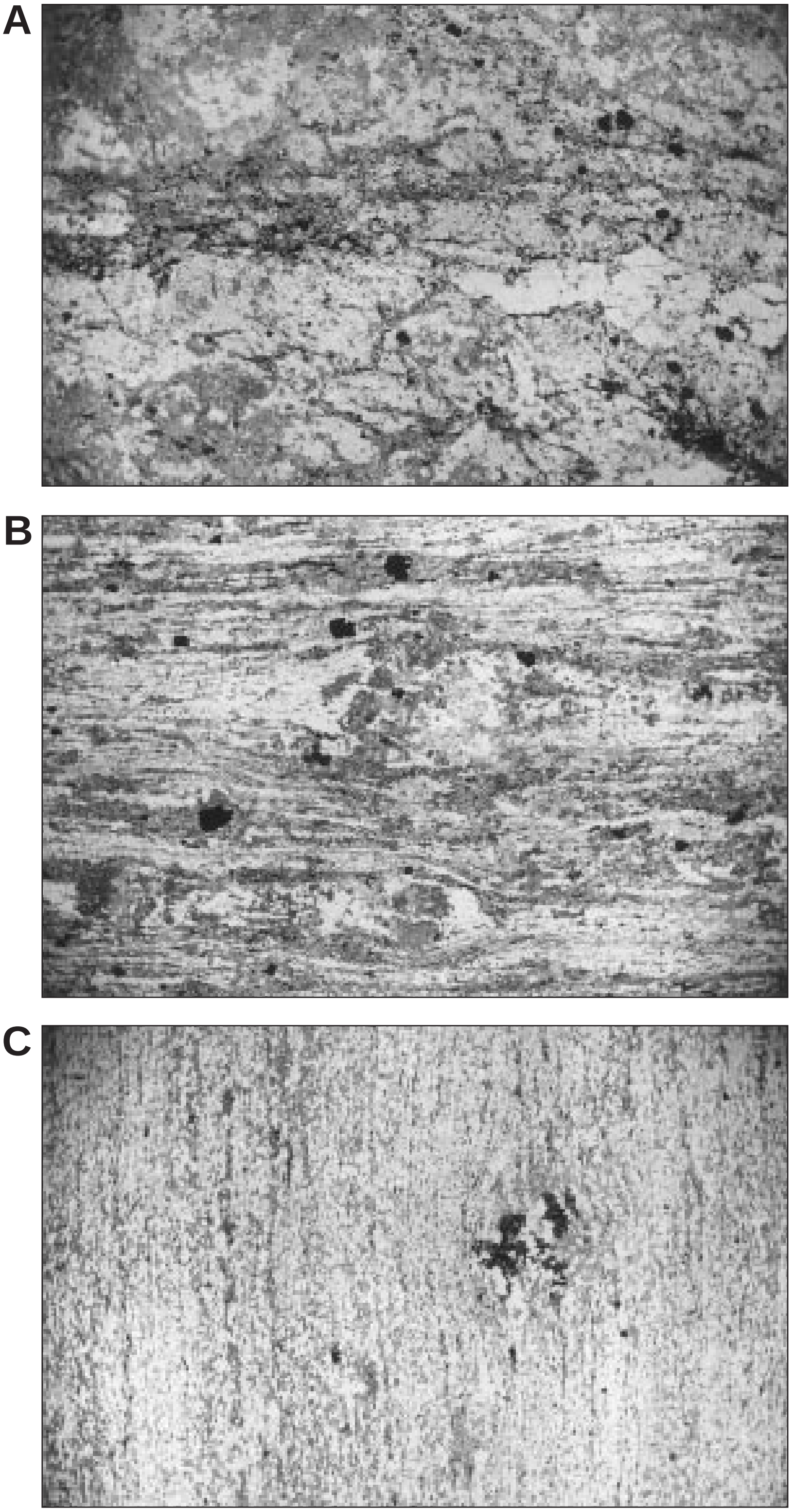


Figure 6. Photomicrographs of dated Packsaddle Schist samples. (A) Sample 1 (PSRRV): Irregularly shaped clusters of fine-grained, intermixed microcline, quartz, and plagioclase surrounded by biotite and opaques. Grains in clusters have distinctly different optical orientations and do not reflect dynamic recrystallization of a single larger grain. (Plane-polarized light; dark gray—plagioclase; light gray—microcline; clear—quartz; small, well-defined, dark gray blades—biotite; black—opaque grains.) Elongate clumps of biotite and opaque grains intermixed with lesser amounts of fine-grained plagioclase are interspersed. Rectangular shape in upper left is an optically continuous, twinned plagioclase grain. Rock is weakly foliated parallel to layering. The texture is consistent with that of a volcanic tuff; irregular clusters may be recrystallized and flattened lapilli. Different part of the same thin section in 5B, showing the variation in texture and mineral proportions between fine layers. Width of photomicrograph represents 13 mm. (B) Sample (PSRRB) dated by Reese (1995) from middle of Rough Ridge Formation (see Fig. 4 and text): Moderately foliated, layered rhyolite or felsic tuff. Composition varies across the slide. Large porphyroclast in upper center is an aggregate (glomeroclast) of fine-grained microcline (right side, light gray) and plagioclase (left side, dark gray, partly altered to calcite and muscovite) with interspersed biotite, opaque grains, quartz (clear), and amphibole. Rounded, dark gray porphyroclasts in lower left are single plagioclase crystals. Width of photomicrograph represents 13 mm. (C) Sample 2 (PSBG): Well-foliated, quartzofeldspathic rock (Packsaddle Schist) from near the contact between the Valley Spring Gneiss and the Packsaddle Schist. Large glomeroclast on right part of photomicrograph is composed of garnet and fine-grained plagioclase and quartz with minor microcline and biotite. (Plane-polarized light; colors represent same minerals as in A.) A second foliation is at ~50° to the main foliation (upper left to lower right). Width of photomicrograph represents 13 mm.

erentially collected material devoid of these veins to avoid possible zircon contamination. No physical or optical evidence of multiple populations of zircons was observed.

Zircons from sample 2 (PSBG) are nearly indistinguishable from those obtained from the other Packsaddle Schist (sample 1—PSRRV; including internal zonation; Fig. 8B), but have a slightly greater percentage of cloudy grains and grains that commonly exhibit pitted crystal faces. This single morphological type is also interpreted to be igneous in origin; minor resorption may have caused the pitted faces. Two fractions of euhedral zircons overlap concordia within error and yield an averaged $^{207}Pb/^{206}Pb$ age of 1247

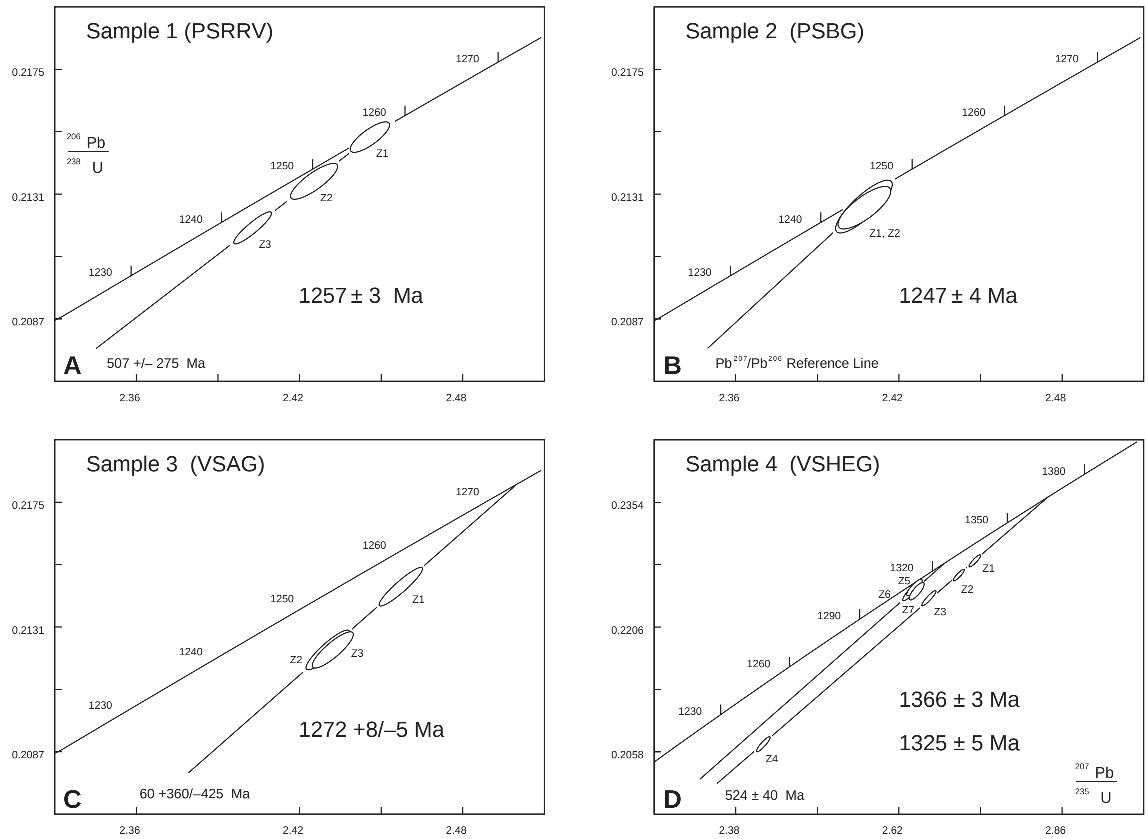


Figure 7. Concordia diagrams. (A, B) Packsaddle Schist samples 1 (PSRRV) and 2 (PSBG), respectively. (C, D) Valley Spring Gneiss samples 3 (VSAG) and 4 (VSHEG), respectively. Isotopic data are given in Table 1.

± 4 Ma, interpreted as the crystallization age for this rock (Fig. 7B).

Valley Spring Gneiss

Two samples from distinct, adjacent felsic gneiss units in the Valley Spring Gneiss were collected from directly north of, and structurally beneath, the southwest-dipping Valley Spring Gneiss–Packsaddle Schist contact along Honey Creek (Fig. 3). Both are part of the laterally extensive layered sequence of gneisses.

Valley Spring Gneiss—Sample 3 (VSAG). A sample was collected from a 5-m-thick augen gneiss 20 m north of the Valley Spring Gneiss–Packsaddle Schist contact (Fig. 3). The unit is concordant and in sharp contact with adjacent finer-grained felsic gneisses. It is well foliated and medium to coarse grained; it is composed of microcline, quartz, and plagioclase, with only minor biotite, apatite, iron oxides, and zircon. Microcline occurs within the matrix and as 3–20 mm, pink augen porphyroclasts with asymmetric recrystallized tails. The rock contains mylonitic fabrics defined by rotationally recrystallized elongate microcline, plagioclase, and quartz. No compositional segregation between minerals is observed.

Zircons from sample 3 (VSAG) are clear, colorless, and euhedral; their aspect ratios are between 2:1 and 5:1, and they range in size from 25 to 100 µm. Internal growth zonation is typically straight (Fig. 8C). The single morphological type, sharp terminations, internal zonation, and lack of abrasion on crystal surfaces are consistent with an igneous origin, either volcanic or intrusive.

Three fractions of clear euhedral zircon define a discordia line with 1272 $^{+8}/_{-5}$ Ma and 50 ± 425 Ma intercepts (57% probability of fit) (Fig. 7C). The large error on the upper intercept is due to clustering of data points near the concordia upper intercept. This age is interpreted to represent the crystallization age of the protolith. The lateral continuity of this thin (5 m) unit across more than 32 km suggests that it is a pyroclastic rhyolitic sheet, although the texture observed in thin section is compatible with it being a mylonitized plutonic rock.

Valley Spring Gneiss—Sample 4 (VSHEG). A second sample, collected from the upper part of the Valley Spring Gneiss, is a well-foliated, fine-grained, quartz-plagioclase-microcline gneiss with minor biotite, amphibole, and epidote. This unit occurs ~100 m north of the Valley Spring Gneiss–Packsaddle Schist contact along Honey Creek (Fig. 3) and is concordant with adjacent felsic gneiss units. It lies structurally beneath and in contact with the augen gneiss from which sample 3 (VSAG) was collected and does not have mylonitic textures. These units, including the augen gneiss, constitute Barnes's (1978c) Valley Spring Gneiss layer C. This unit shows a distinct compositional banding in the field with thin layers rich in epidote. In thin section, the banding is composed of alternating thin, nearly monomineralic layers of either plagioclase (partly altered to epidote), microcline, or amphibole; some layers contain a mixture of these minerals.

This sample contains two distinct zircon morphologic types. One type is elongate (3:1 to 4:1 aspect ratios) clear to cloudy, colorless, cracked zircons that are typically slightly rounded but contain straight internal zonation (Fig. 8D). Some, however, exhibit flat crystal faces and euhedral terminations. The second type is spherical to slightly elongate, is clear and colorless, and does not exhibit crystal faces. The shape and dominance of the elongate type are consistent with an igneous heritage, whereas the spherical grains could be either igneous or metamorphic. Overgrowths that truncate the regular zonation (observed in CL images as bright rims as in Fig. 8D) must be sec-

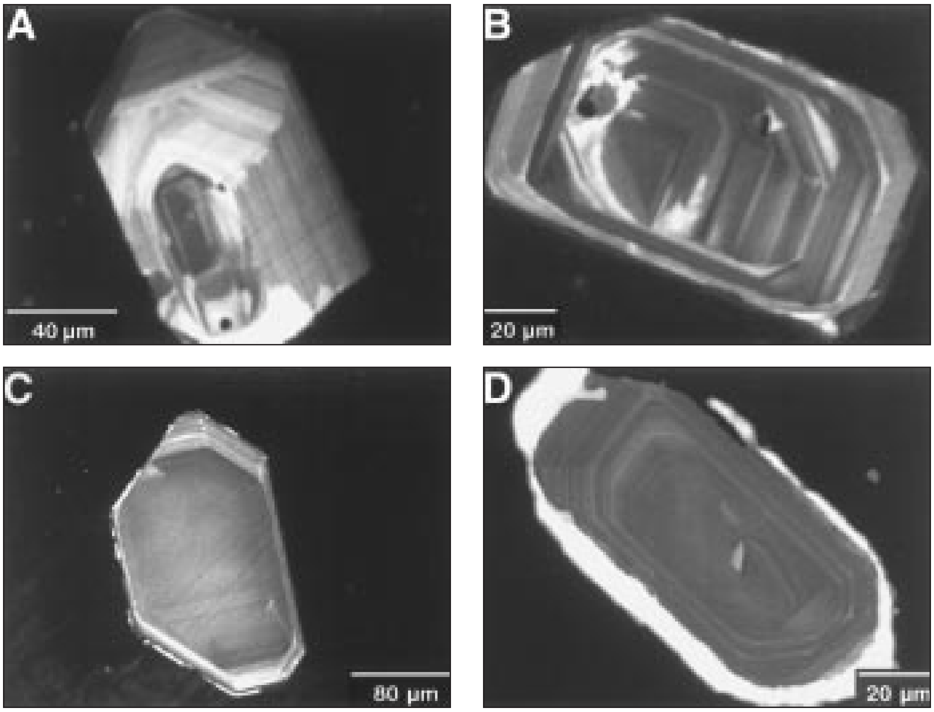


Figure 8. Cathodoluminescence images of typical zonation observed in zircons from each sample analyzed. (A) Sample 1—PSRRV. (B) Sample 2—PSBG. (C) Sample 3—VSAG. (D) Sample 4—VSHEG.

ondary zircon and may be related to the spherical zircons. The overgrowths were abraded prior to analyses of the elongate grains.

Four fractions of elongate, clear to cloudy, cracked zircons define a discordia line between 1366 ± 3 Ma and 524 ± 40 Ma (27% probability of fit); the upper intercept is interpreted to represent the crystallization of this igneous protolith (Fig. 7D). U-Pb data from three multigrain fractions of spherical zircons overlap and plot discordantly above this line, yielding an averaged ^{207}Pb/^{206}Pb age of 1322 Ma. We assumed that these zircons had been subjected to a Pb-loss history similar to that affecting the igneous grains; therefore, these three fractions were regressed with a conservative lower intercept of 524 ± 150 Ma to yield an upper intercept age of 1325 ± 5 Ma. Although not a rigorous regression, we think that this age provides a reasonable estimate for the timing of metamorphic zircon growth at this locality.

DISCUSSION

The U-Pb zircon geochronologic results of this study and those of Walker (1992), Reese (1995), and Roback (1996a) show that the regional map units (i.e., the Packsaddle Schist, Valley Spring Gneiss, and Big Branch Gneiss) each contain genetically and geochronometrically distinct, and thus unrelated, units. The age distribution of rocks across the uplift appears to be significantly more complex than previously envisioned. Thus, the regional map units as previously defined obscure lithotectonic and chronostratigraphic relationships among individual units. In addition, the polydeformed, metamorphic rocks consist of both plutonic and supracrustal rocks that in many areas have been transposed so much that the protoliths can no longer be identified. Consequently, we have not defined a new stratigraphy, although our results add to a developing chronostratigraphy for the uplift. In the discussion below, we reevaluate the regional map units and previously defined stratigraphic and structural relationships, explore possible connections to North America, and group the units into lithotectonic packages to facilitate the recognition of different tectonic settings.

Reevaluation of Regional Map Units and Previous Stratigraphy

Packsaddle Schist. The Packsaddle Schist, as originally defined, contains rocks ranging in age from 1292 to 1243 Ma that formed in separate tectonic environments (Walker, 1992; Reese, 1995; Roback, 1996a; this study). In the far southeastern part of the uplift near the Coal Creek Serpentinite (Figs. 1 and 3), rocks previously mapped as uppermost Packsaddle Schist (mafic part of the Click Formation, McGehee, 1979; older Packsaddle of Mosher, 1993) are 1292–1275 Ma foliated tonalites, gabbros, and granodiorites that form a plutonic complex (informally termed the Coal Creek plutonic complex by Mosher, 1996), which intrudes the 1326–1301 Ma Big Branch Gneiss (Roback, 1996a). These rocks, together with the Big Branch Gneiss and Coal Creek Serpentinite, are part of Roback's (1996a) Coal Creek domain; their isotopic and geochemical signatures are distinct from those of the rest of the uplift (Roback et al., 1995; Whitefield, 1996). Following the suggestion of Roback (1996a), these units should no longer be grouped with the Packsaddle Schist.

Mapping and isotopic work by Whitefield (1996) has shown that the tectonic boundary between the Coal Creek domain and the genetically unrelated supracrustal rocks to the north is located at the southern margin of the Sandy Creek shear zone, a zone of mylonitization, intense transposition, and polyphase ductile deformation (Carter, 1989; Nelis et al., 1989; Roback, 1996a; Whitefield, 1996). This major boundary lies within what was previously mapped as the Click Formation of the Packsaddle Schist. The rocks immediately north of the Coal Creek domain are a heterogeneous package of quartz-feldspar-muscovite, muscovite-cordierite, muscovite, hornblende, and actinolite schists and fine-grained quartzofeldspathic rock (Barnes, 1978a; Carter, 1989) and thus are lithologically, as well as geochemically and isotopically, distinct from the Coal Creek domain (Roback, 1996a; Whitefield, 1996). This remaining part of the Click Formation and the structurally underlying Rough Ridge, Sandy, and Honey Formations of the original Packsaddle Schist (McGehee, 1979) are an interlayered sequence of schistose and gneissic units of great lithologic diversity. We retain the term "Packsaddle Schist" for this sequence, which forms most of what was originally mapped as Packsaddle Schist in the southeastern part of the Llano uplift (Fig. 3). We abandon the previously designated formation names within the Packsaddle Schist, given that the Click and Rough Ridge Formations both contain genetically unrelated rocks of widely disparate ages (Roback, 1996a; this study).

In an attempt to establish the age of the Packsaddle Schist (as defined above), layers of presumed volcanic origin have been dated from the structurally lowest (1247 ± 4 Ma, this study), middle (1257 ± 3 Ma, this study; 1248 ± 3 Ma, Reese, 1995), and uppermost (1247 $^{+8}/_{-6}$ Ma, Walker, 1992) part of this sequence. The units dated in this study and in Reese (1995) have original textures and field characteristics of volcanic rocks and occur as thick, laterally extensive lithologic successions. No intrusive contacts are observed, and the sampled layers are not sufficiently deformed to obliterate such contacts, if present. It should be noted that even within the Sandy Creek shear zone, crosscutting intrusive relationships between the Red Mountain Gneiss and adjacent rocks are still locally well preserved despite intense ductile deformation of all units (Garrison, 1985; Nelis et al., 1989; Carter, 1989).

This interpretation is consistent with that of Walker (1992), who first interpreted the 1247 $^{+8}/_{-6}$ Ma quartzofeldspathic layer at the top of this section to be volcanic and representative of the approximate age of the Packsaddle Schist as a whole. Patchett and Ruiz (1989) also interpreted similar fine-grained quartzofeldspathic units from the middle part of the Packsaddle Schist as felsic volcanic layers. Roback (1996a), however, noted that the layer dated by Walker (1992) is located within the Sandy Creek shear zone and is in tectonic contact with the underlying schist and an overlying mylonitic sill. He questioned whether the layer dated by Walker (1992) represented the age of the Packsaddle Schist protoliths. The layer dated by Walker (1992) structurally overlies a sequence of interlayered muscovite-cordierite schist and thin quartzofeldspathic units that are interpreted as a metasedimentary sequence containing thin, probable metavolcanic layers. The dated sample comes from the thickest (~30 m) and structurally highest of the quartzofeldspathic layers. This layer is very similar in its composition, age, field characteristics, and relationship to metasedimentary units to the other layers within the adjacent schist sequence and to the Packsaddle Schist units dated in this study. The dated layer, therefore, is interpreted as a volcanic unit that was deposited conformably within this supracrustal sequence.

Thus, fine-grained quartzofeldspathic rocks, interpreted as volcanic in origin and found throughout the Packsaddle Schist, indicate that the interlayered sedimentary protoliths were deposited at ca. 1247–1257 Ma. A granitic sill within the structurally uppermost Packsaddle Schist dated by Roback (1996a) at 1250 $^{+4}/_{-2}$ Ma is most likely cogenetic with the volcanic units and intrusive into this volcanosedimentary sequence. The upper and lower time limits on deposition of the supracrustal sequence, however, remain unconstrained. The sequence, where exposed in the southeastern part of the uplift, is polydeformed, structurally imbricated internally along ductile thrust zones, and bounded on both sides by major shear zones (Reese, 1995). Thus, younger or older units could be included in the sequence, and the entire depositional record may no longer be preserved. A white, cordierite-bearing, quartz-plagioclase-muscovite-epidote gneiss, previously mapped as part of the Rough Ridge Formation, yields an older age (1274 ± 2 Ma; Roback, 1996a) compared to the units dated in this study. Roback (1996a) originally suggested that it was a tectonically interleaved part of the Coal Creek domain plutonic complex. More recent isotopic work (Roback, unpublished Sm-Nd data) suggests that this unit is more closely related to the Packsaddle Schist. This unit may be the basement of the Packsaddle Schist, a part of the Valley Spring Gneiss, or an even older component of the Packsaddle Schist. Further work is needed to distinguish these possibilities.

Valley Spring Gneiss. Results from this study show that in the eastern part of the uplift, the Valley Spring Gneiss also contains units of even more widely disparate ages. Two adjacent layers within what was previously mapped as Valley Spring Gneiss (Figs. 2, 3) yield igneous protolith ages of 1272 $^{+8}/_{-5}$ Ma (sample 3—VSAG) and 1366 ± 3 Ma (sample 4—VSHEG). The felsic gneiss from Inks Lake State Park dated by Walker (1992) yielded an igneous protolith age of 1232 ± 4 Ma. The age diversity indicates that these units represent separate, genetically unrelated, suites of rocks. The oldest (1366 ± 3 Ma) gneiss, because of its age and earlier metamorphic history, most likely represents basement to the other units.

The Valley Spring Gneiss, as previously mapped, is areally the most extensive unit in the uplift (Fig. 1). Ongoing research, including a systematic U-Pb geochronologic study, is characterizing the units comprising the Valley Spring Gneiss and will determine the regional significance of the three distinctly different ages identified in the present study. Until then, we retain the Valley Spring Gneiss as a regional map unit as previously defined, but suggest that two well-characterized, geochronometrically diverse components be given informal names as outlined below.

To avoid confusion with the undated and younger dated components of the Valley Spring Gneiss, we informally refer to the older (1366 ± 3 Ma) component of the gneiss as the Honey Creek gneiss. This gneiss has a metamorphic age (1325 ± 5 Ma) that predates the protolith ages of all other dated rocks within the uplift. Its unusually old age should not be assumed to reflect the typical age of what has been mapped as the Valley Spring Gneiss.

The younger (1232 ± 4 Ma; Walker, 1992) component of the Valley Spring Gneiss is informally referred to as the Inks Lake gneiss (Reese, 1995), recognizing its similarity to other foliated granitic units of the same age that are not mapped as part of the Valley Spring Gneiss. This body is exposed on the eastern side of Inks Lake State Park and is of unknown regional extent. Where dated, it is a foliated, compositionally and texturally homogeneous granitic rock, markedly different in character from the polydeformed, interlayered felsic and mafic gneisses forming the Valley Spring Gneiss elsewhere in the park (Helper, 1996) and outside of the northeastern part of the uplift. The origins of foliated granites within the Valley Spring Gneiss and of meta-aplites within the Packsaddle Schist have long been a matter of speculation (Paige, 1912; Stenzel, 1935; McGehee, 1979; Barnes, 1988; Reese, 1995). Barnes (1988) noted that some of the Valley Spring Gneiss, during orogenesis, may have undergone partial melting or been intruded by granitic magma to produce migmatites. McGehee (1979, p. 25) proposed a possible genetic relationship among the Red Mountain intrusive rocks, metagranitic bodies distributed throughout the Valley Spring Gneiss, and meta-aplitic bodies in the far southeastern part of the uplift (Fig. 3). In fact, the Inks Lake gneiss shares a similar emplacement age (1232 ± 4 Ma) with the Red Mountain (1239 $^{+5}/_{-3}$ Ma) and Comanche Creek (1238 $^{+8}/_{-6}$ Ma) Gneisses. We speculate that the Inks Lake gneiss is related to these gneisses and that it represents a later granitic or possibly migmatitic body contained within the older components of the Valley Spring Gneiss and is not representative of Valley Spring Gneiss.

Big Branch Gneiss. The Big Branch Gneiss, as previously mapped (Barnes, 1978a; McGehee, 1979), also contains two temporally distinct units. The type Big Branch Gneiss is a gray tonalitic gneiss dated at 1326–1301 Ma (Walker, 1992; Roback, 1996a). The type locality of the body is located directly south of the Coal Creek Serpentinite (Fig. 3) in the far southeastern part of the uplift. North of the Coal Creek domain, a 1238 $^{+8}/_{-6}$ Ma (Walker, 1992) microcline augen gneiss, previously mapped as Big Branch Gneiss (Clabaugh and Boyer, 1961; McGehee, 1979; Barnes, 1988; Carter, 1989; marginal facies of Garrison, 1985), crops out in a west-northwest–trending belt (Fig. 3) parallel to and immediately south of the Red Mountain Gneiss. We differentiate this younger unit from the Big Branch Gneiss and rename it the Comanche Creek Gneiss, following Reese (1995). The Comanche Creek Gneiss is a thin, elongate (0.3 by 5.5 km) quartz monzonite body with microcline augen and is considered a sill on the basis of its homogeneous composition, relict igneous texture, and outcrop pattern. The type locality of the Comanche Creek Gneiss (Fig. 3) is located where the augen gneiss belt is exposed along Comanche Creek just south of Red Mountain. At this location, the structure of this unit has been mapped in detail by Carter (1989) and sampled for U-Pb zircon geochronology by Walker (1992). Clabaugh and Boyer (1961), McGehee (1979), Garrison (1985), and Carter (1989) provided detailed lithologic descriptions of this unit.

The Comanche Creek Gneiss and adjacent Red Mountain Gneiss bodies both intrude the Packsaddle Schist and appear to share a common geologic history (Carter, 1989). The Red Mountain

Gneiss has been dated at 1239 $^{+5}/_{-3}$ Ma (Walker, 1992) at a locale ~5 km north of Red Mountain proper. (The type Red Mountain Gneiss intrudes the ca. 1238 Ma Comanche Creek Gneiss.) The two units, however, are lithologically distinct. The Comanche Creek Gneiss is granodioritic to quartz monzonitic in composition and bears biotite and abundant, large, white microcline augen. In contrast, the Red Mountain Gneiss is variably foliated to massive, pink to red, and granitic in composition (Garrison, 1985). The units are readily distinguishable in the field and can be mapped as separate units.

Reevaluation of Structural Relationships

New age data (this study) combined with structural mapping (Reese, 1995) for the Packsaddle Schist and the Valley Spring Gneiss across their mutual contact in the Honey Creek area (Figs. 3 and 9) demonstrate that the temporal relationship postulated by Walker (1992) is incorrect. On the basis of his ages for units that were separated by ~25 km, he surmised that older (1243–1247 Ma) Packsaddle Schist lies structurally above younger (1232 ± 4 Ma) "Valley Spring Gneiss" (as previously defined) and that the contact is tectonic in nature with older rocks thrust over younger rocks. We have demonstrated that the Valley Spring Gneiss is 1272 $^{+8}/_{-5}$ to 1366 ± 3 Ma immediately beneath a Packsaddle Schist unit dated at 1247 ± 4 Ma; thus younger rocks are in fault contact above older rocks (Figs. 3 and 9).

It is important to note that no *stratigraphic* relationship can be inferred from the field relationships. The contact is a ductile shear zone with an unknown amount of displacement. Kinematic indicators show that the younger Packsaddle Schist has been translated northeastward over the older Valley Spring Gneiss (Reese, 1995) (Fig. 9). Thus, this contact is not a primary, gradational, depositional contact, as originally defined by Paige (1912) and McGehee (1979) and as interpreted elsewhere in the uplift (Billings, 1962; Lidiak et al., 1961).

Possible North America Connections

The felsic gneiss dated at 1366 ± 2 Ma (sample 4—VSHEG; Figs. 3 and 7; Honey Creek gneiss) is the oldest rock yet found in the Llano uplift. The age and compositional similarity of this unit to rocks of the Western Granite-Rhyolite terrane (Denison et al., 1984; Thomas et al., 1984) north of the Llano province (Fig. 10) raise the possibility of a genetic relationship. Reese et al. (1992) speculated that the Honey Creek gneiss may represent a part of the Western Granite-Rhyolite terrane along the southern margin of the North American craton reworked during the Grenville orogeny.

The age of this older gneiss provides another piece of evidence suggesting that the Llano province, of which the Llano uplift is but a small exposure, formed along the southern margin of Laurentia. On the basis of crustal-formation ages determined from Nd isotope data, Nelson and DePaolo (1985) and Patchett and Ruiz (1989) suggested that Llano province crust could have formed along the southern cratonal margin contemporaneously with 1300–1500 Ma Midcontinent Granite-Rhyolite terrane crust and could have been later reworked during Grenville orogenesis. Initial Pb isotope ratios from Llano uplift meta-igneous rocks are similar to those reported for the Western Granite-Rhyolite terrane (James and Walker, 1992), suggesting that these meta-igneous rocks may have been equivalent to, or had their source in, this terrane. The presence of the similar age Western Granite-Rhyolite terrane directly to the north suggests that the older gneissic component of the Valley Spring Gneiss (i.e., the Honey Creek gneiss) may represent the basement of the Packsaddle Schist and younger components of the Valley Spring Gneiss in a tectonic setting proximal to Laurentia.

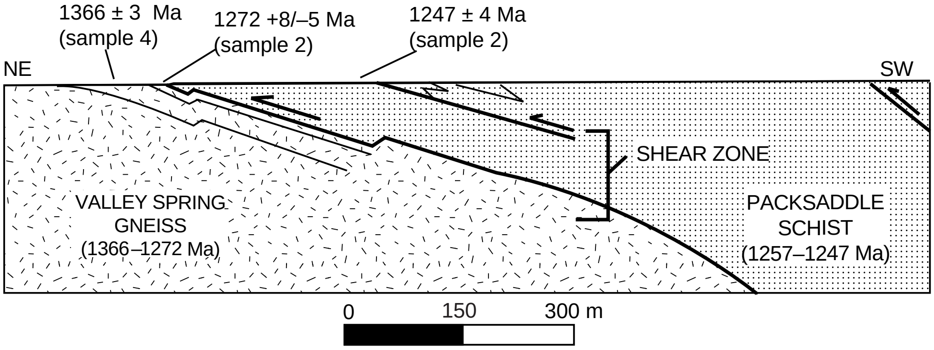


Figure 9. Generalized cross section through the Valley Spring Gneiss–Packsaddle Schist contact. Younger Packsaddle Schist lies structurally above older Valley Spring Gneiss. Units on both sides of the contact are mylonites with top-to-the-northeast shear sense, indicating that this contact is a ductile thrust zone. The mylonites have been folded by two later generations of folds.

Resolution of Age Suites

The regional distribution of geochronometric data from this study, coupled with the results of Walker (1992) and Roback (1996a), reveals a fundamental pattern of chronostratigraphic units in the southeastern part of the Llano uplift. Four age suites, incorporating metamorphic units that, in large part, are geographically segregated, can be resolved from the current data (Figs. 2 and 3). Relatively young Packsaddle Schist (ca. 1257–1247 Ma and possibly older) is structurally wedged between older (1366–1272 Ma) felsic gneisses to the north and older (1326–1275 Ma) mafic and tonalitic rocks to the south; younger (1239–1232 Ma), meta-intrusive rocks occur locally throughout the southeastern part of the Llano uplift.

The southernmost age suite consists of the Coal Creek domain of Roback (1996a), including the 1326–1301 Ma Big Branch Gneiss, the 1292–1275 Ma Coal Creek plutonic complex, and the Coal Creek Serpentinite. These rocks represent an allochthonous ensimatic arc terrane that was accreted during Grenville orogenesis (Roback, 1996a) (Fig. 11).

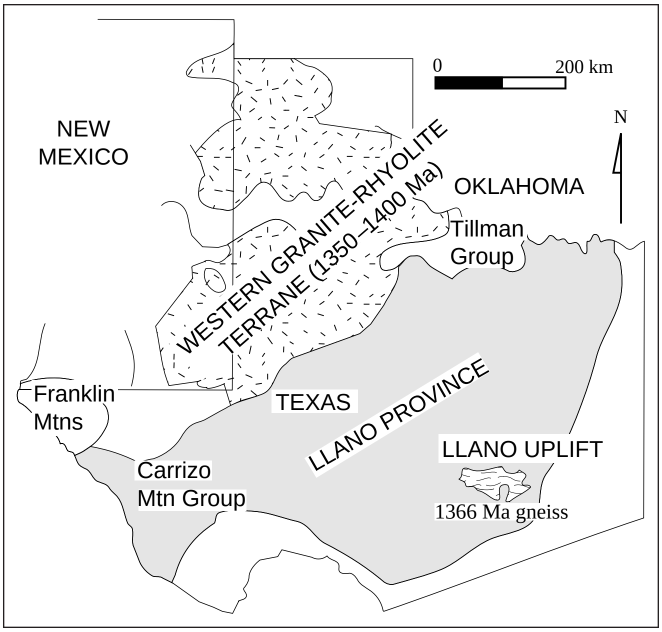
Structurally underlying the Coal Creek arc complex is the second age suite, the Packsaddle Schist. Dates for several Packsaddle Schist units from the highest to lowest structural levels within the sequence cluster around 1257–1243 Ma (this study; Walker, 1992). These dates are interpreted as protolith ages for felsic metavolcanic rocks and therefore date the interlayered metasedimentary rocks. If further work shows that these ages are representative of the entire Packsaddle Schist, then its protolith formed in a brief time span. The possibility of a longer history of deposition, however, is suggested by the white gneiss of questionable affinity dated at 1274 ± 2 Ma (Roback, 1996a). The Packsaddle Schist is interpreted as a basinal sequence formed along a continental shelf and slope that received mafic and felsic volcanic and volcaniclastic material from an active continental arc as well as terrigenous sediment from the continent (Garrison, 1981a, 1981b, 1985; Mosher, 1998).

Structurally underlying and directly north of the Packsaddle Schist is the third age suite. It consists of the Valley Spring Gneiss, including the 1272 $^{+8}/_{-5}$ Ma augen gneiss and a sequence of gneisses with preliminary U-Pb ages of 1288–1275 Ma (Roback, reported in Mosher, 1996), and the substantially older 1366 ± 3 Ma Honey Creek gneiss (Figs. 2 and 3). The Valley Spring

Gneiss is interpreted to represent plutonic, felsic volcanic, volcaniclastic, and sedimentary rocks that either formed along an extended passive margin (Reese, 1995) or as part of a continental-margin arc and forearc basin (Mosher, 1998). The extent and probable protolith of the Honey Creek gneiss are currently unknown. It provides a link to the Western Granite-Rhyolite terrane, however, and thus ties the Llano uplift to the southern margin of Laurentia.

The fourth suite consists of felsic plutonic rocks that intrude the Packsaddle Schist and Valley Spring Gneiss. Within the Packsaddle Schist, adjacent to the boundary with the Coal Creek arc terrane, is a belt of younger felsic sills, including the 1239–1238 Ma Comanche Creek and Red Mountain Gneisses (Figs. 2 and 3). Of similar age and bulk mineral content, but geographically removed, is the 1232 ± 4 Ma Inks Lake gneiss. Numerous other foliated fine-grained granitic sills (undated) are found within the Valley Spring Gneiss. Recognition of metaplutonic units with protolith ages clustering around 1239–1232 Ma raises the possibility that a regionally pervasive igneous event may have occurred at this time in the uplift. This event may have been a period of crustal melting marking the onset of Grenville continental collision, orogenic thickening, and contractional deformation (Reese, 1995). Alternatively, it may have been a continuation of the earlier magmatism recorded in the Packsaddle Schist. If so, the entire suite may be part of a continental margin arc that formed as a result of subduction under the southern North American margin prior to continental collision (Mosher, 1998).

Figure 10. Generalized geologic map showing the Llano province and the Western Granite-Rhyolite terrane. A gneissic unit (Honey Creek gneiss) within the Valley Spring Gneiss in the southeastern part of the Llano uplift is consistent in age (1366 ± 3 Ma) with rocks of the Granite-Rhyolite terrane, suggesting a possible tectonic link between the two provinces (after Denison et al., 1984, and Thomas et al., 1984).



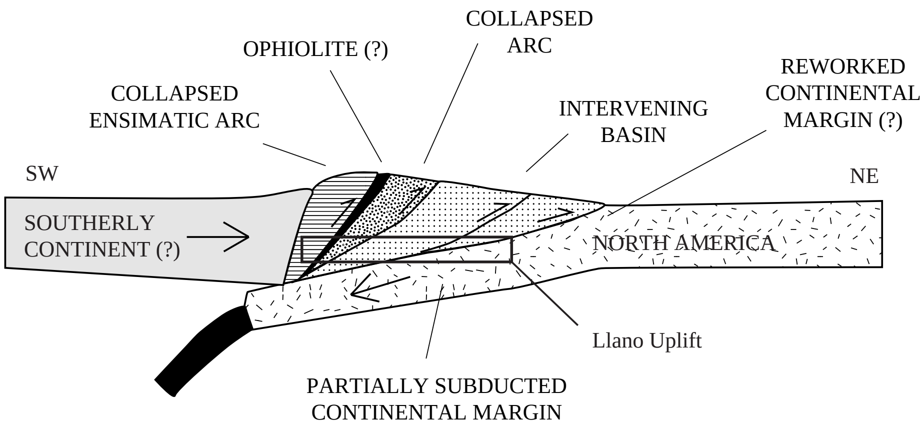


Figure 11. Schematic cross section showing post–1232 Ma, pre–1098 Ma Grenville collisional margin in the southeastern part of the Llano uplift, assuming south-dipping subduction (after Reese, 1995). Several different tectonic assemblages were telescoped and transported onto the southern North American continental margin. They include from southwest to northeast (in descending tectonic order): older plutonic arc rocks (1326–1301 Ma Big Branch Gneiss; horizontal ruling), possible fragmented ophiolite (Coal Creek Serpentinite; black), and slightly younger arc rocks (1292–1275 Ma Coal Creek plutonic complex; coarse dot pattern); a younger intervening basinal sequence (ca. 1257–1247 Ma and possibly older, Packsaddle Schist; fine dot pattern); and older, felsic plutonic and supracrustal rocks including the possibly tectonically reworked Mesoproterozoic southern margin of North America (1366–1272 Ma Valley Spring Gneiss; random dashes). Boxed area shows present Llano uplift exposure.

CONCLUSIONS

Integration of new and existing U-Pb age data shows that previously defined regional metamorphic map units in the southeastern part of the Llano uplift, central Texas, contain geochronometrically disparate and genetically unrelated components. On the basis of lithologic and age contrasts, we have modified two and informally subdivided one of the regionally extensive map units for the southeastern part of the uplift.

This study has shown that, where in contact, *younger* Packsaddle Schist is in tectonic contact above *older* Valley Spring Gneiss, contrary to the opposite relationship proposed by Walker (1992).

The oldest unit dated thus far in the uplift is a felsic gneiss with an igneous protolith age of 1366 ± 3 Ma and a metamorphic age of 1325 ± 5 Ma. This gneiss may represent the basement on which the Packsaddle Schist and younger components of the Valley Spring Gneiss were deposited. The similarity in age to rocks of the Western Granite-Rhyolite terrane directly north of the Llano province suggests a genetic link with this terrane. This older crustal component likely formed as part of the southern margin of Laurentia and was later tectonized during Grenville orogenesis.

With new U-Pb age data, four southwest-dipping, lithotectonically distinct packages of metamorphic rocks are recognized in this part of the uplift. These age packages of rocks apparently formed in different tectonic settings and were later juxtaposed during Grenville orogenesis. Packsaddle Schist—an arc-flank, continental-shelf-and-slope sequence with protolith ages of ca. 1257–1247 Ma (and possibly older)—occupies a structural position below the 1326–1275 Ma Coal Creek ensimatic arc to the south and above the 1366–1272 Ma Valley Spring Gneiss (with an older gneiss component) to the north. Younger meta-intrusive rocks—including the 1239 Ma Red Mountain and 1238 Ma Comanche Creek orthogneisses and, tentatively, the 1232 Ma Inks Lake gneiss—occur locally throughout the eastern Llano uplift. These intrusive rocks may represent early orogenic melts related to crustal thickening or arc-related rocks associated with the 1257–1247 Ma volcanic rocks within the Packsaddle Schist.

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APPENDIX 1. DESCRIPTIONS OF SAMPLE LOCALITIES AND METHODS

Sample Localities

1. Packsaddle Schist—Sample 1 (PSRRV). Collected on Lesikar property, Llano County, on west side of White Creek where ranch road crosses creek, 0.3 km north-northeast of White Creek ford on Click Quadrangle Map No. 43 (Barnes, 1978a). UTM coordinates 14RNJ47807603.

2. Packsaddle Schist sample (PSRRB) of Reese (1995). Taken from basal quartzofeldspathic gneiss of the Rough Ridge Formation, as defined by McGehee (1979), on Franklin property, Llano County, along south bank of White Creek. Locality is 0.5 km southeast of Franklin ranch house on Dunman Mountain Quadrangle Map No. 44 (Barnes, 1978b). UTM coordinates 14RNJ49127860.

3. Packsaddle Schist—Sample 2 (PSBG). Collected on Moursund property, Llano County, from low ledge over which Honey Creek flows and directly south of prominent amphibole schist exposures on the west bank of the creek. Locality is 0.9 km north-northeast of Highway 71 on Cap Mountain Quadrangle Map No. 45 (Barnes, 1978c). UTM coordinates 14RNJ45498917.

4. Valley Spring Gneiss—Sample 3 (VSAG). Sampled on Moursund property, Llano County, from augen gneiss unit exposed on west bank of Honey Creek 1.1 km north-northeast of Highway 71 and only meters north of the Valley Spring Gneiss–Packsaddle Schist contact on Cap Mountain Quadrangle Map No. 45 (Barnes, 1978c). UTM coordinates 14RNJ45558942.

5. Valley Spring Gneiss—Sample 4 (VSHEG). Collected on Moursund property, Llano County, from quartzofeldspathic gneiss ledge cropping out on east side of Honey Creek stream bed, 1.2 km north-northeast of Highway 71. Sample is part of Valley Spring Gneiss unit C of Barnes (1978c) on Cap Mountain Quadrangle Map No. 45. UTM coordinates 14NRJ45598948.

Methods

Rock samples were crushed to mineral size under clean conditions by using a jaw crusher and disc pulverizer, and minerals were separated by using a Wilfley table, disposable sieves, heavy liquids, and a Frantz magnetic separator at the University of Texas at Austin. Zircons were characterized through the use of a binocular reflected-light microscope, transmitted-light petrographic microscope (with condenser lens inserted to minimize edge refraction), and a scanning cathodoluminescence (CL) imaging system on a JEOL 730 scanning electron microscope.

Multiple or single grains of each population were selected for analysis on the basis of optical and magnetic properties to ensure that only the highest-quality grains were analyzed. All mineral fractions analyzed were strongly abraded (Krogh, 1982), subsequently reevaluated optically, and then washed successively in distilled 4*N* nitric acid, water, and acetone. They were loaded dry into Teflon capsules with a mixed $^{205}Pb/^{235}U$ tracer solution and dissolved with HF and HNO_3. Chemical separation of U and Pb from zircon through the use of 0.055 mL columns (after Krogh, 1973) resulted in a total Pb procedural blank of ~1 pg over the period of analyses. The U procedural blank is estimated to be 0.25 pg. Pb and U were loaded together with silica gel and phosphoric acid onto an outgassed filament of zone-refined rhenium ribbon and analyzed on a multicollector MAT 261 thermal-ionization mass spectrometer, either operating in static mode (with ^{204}Pb measured in the axial secondary-electron multiplier [SEM] ion-counting system) or in dynamic mode in which all masses were measured sequentially by the SEM ion-counting system. Ages were calculated by using the decay constants of Jaffey et al. (1971). Errors on isotopic ratios were calculated by propagating uncertainties in measurement of isotopic ratios, fractionation, and amount of blank. Results are reported in Table 1 with 2σ errors. Linear regressions were performed by using the procedure of Davis (1982). The goodness of fit of a regressed line is represented as a probability of fit, where 10% or better is considered acceptable and corresponds to a mean square of weighted deviates (MSWD) of 2 or less.

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