Geology

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Geology 1981;9;225-230
doi: 10.1130/0091-7613(1981)9<225:CCSLUT>2.0.CO;2

Notes

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ABSTRACT

The Precambrian Coal Creek serpentinite, Llano Uplift, Texas, occurs within the upper part of the Packsaddle Schist, which appears to represent a thick sequence of shelf-edge volcaniclastic arc-flank metasediments. The serpentinite has a foliation defined by lizardite pseudomorphs after original foliated harzburgite tectonite, which deviates as much as 15° from the regional country-rock foliation. A few samples contain the relict assemblage olivine + orthopyroxene + anthophyllite reflecting re-equilibration to regional metamorphic conditions near 710 °C at ~3.5 kb. Oxygen and deuterium isotopic data indicate the lizardite could have formed in equilibrium with magmatic water at about 300 to 400 °C during regional uplift.

A likely petrogenetic model involves the olistostromal emplacement of a fragment of ophiolitic material, the Coal Creek ultramafic body, into the volcaniclastic arc-flank sediments. The island-arc model suggested for the Llano Uplift and the existence of ophiolitic material imply that brittle plate collisions were locally important 1,200 m.y. ago and that the orogenic event that affected the Llano terrane (that is, the Grenvillian orogeny) involved island-arc–continent interactions. The Llano Uplift contains the only exposed ophiolitic material along the entire "Grenvillian" orogenic belt.

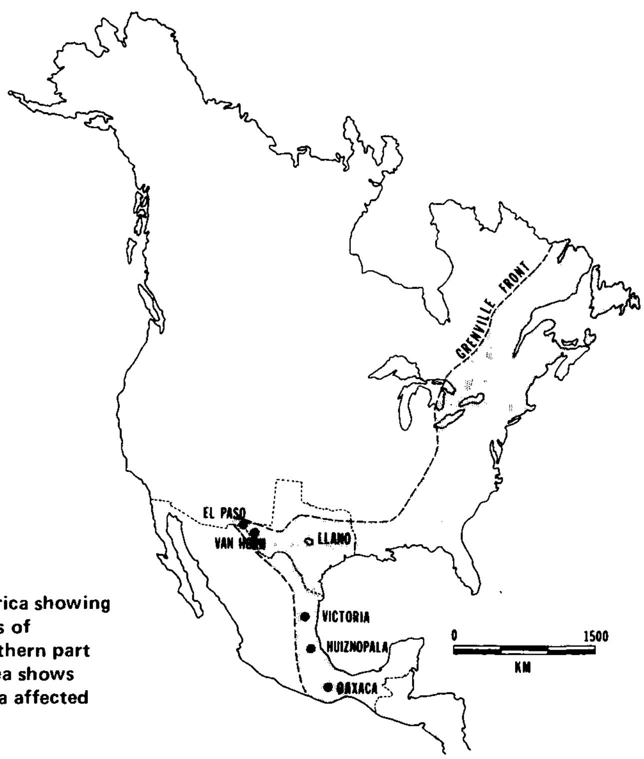

Figure 1. Map of North America showing location of principal outcrops of Grenville-age rocks along southern part of Grenville belt. Stippled area shows general area of North America affected by orogeny.

INTRODUCTION

Most geologists agree that peridotites and serpentinites commonly found in Paleozoic and younger orogenic belts are fragments of ophiolites allochthonously emplaced; most agree that brittle plate tectonics are implied. The types of tectonic processes operating during the Precambrian are much more controversial (see, for example, Wynne-Edwards, 1976; Dewey and Burke, 1973). This study evaluates the petrologic and tectonic history of the Coal Creek serpentinite from the 1.0- to 1.2-b.y.-old Llano orogenic terrane and suggests a petrogenetic model and a tectonic history for this terrane. Any model for these rocks has direct implications for the nature of tectono-metamorphic processes operating during the 1.0- to 1.2-b.y. orogeny.

Geologic Setting

The 1.0- to 1.2-b.y.-old rocks of the Llano Uplift, central Texas, form part of a discontinuous belt of "Grenvillian age" rocks (that is, rocks with K-Ar and Rb-Sr mineral ages of 750 to 1,150 m.y.) that extend from the Grenville province of Canada to the Oaxaca complex of southern Mexico (Fig. 1). The Llano Uplift is one of three areas of Grenvillian rocks exposed in Texas along the central part of the belt; these three exposures (Llano, Van Horn, and El Paso) form a distinct westward re-entrant along the present generally northeast-trending belt. North of the "Grenville front" in Texas are numerous subsurface occurrences of rhyolitic, granitic, and diabasic rocks (Muehlberger and others, 1967); these represent an older 1.2- to 1.3-b.y.-old, possibly anorogenic, complex.

Several distinguishing characteristics are noted when rocks of the Llano Uplift are compared to other rocks along the Grenville belt (Garrison and Ramirez-Ramirez, 1978). The metamorphism of the Llano (and Van Horn) rocks was low pressure–high temperature as compared to the intermediate pressure–high temperature conditions along the majority of the northern

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and southern parts of the belt. The materials of the Llano terrane have a more mafic or "oceanic" character (amphibolites, hornblende schists, metabasalts, and *serpentinites*) as compared to the more silicic remobilized basement material (gray quartz-feldspar granulite gneisses) and overlying miogeosynclinal supracrustal material (marbles, quartzites, and aluminous paragneisses) of the Grenville province (Wynne-Edwards, 1976) and the Mexican part of the belt (Ortega-Gutiérrez, 1978; Ortega-Gutiérrez and others, 1977).

The Llano Uplift is an eroded structural dome in which igneous and metamorphic rocks of Grenvillian age are exposed. The lower part of the exposed metamorphic basement consists of >3.8 km of meta-rhyolite and meta-arkose, the Valley Spring Gneiss, the base of which is not exposed (Droddy, 1978). The Valley Spring Gneiss is overlain by the much thinner (40 to 1,000 m) meta-rhyolitic Lost Creek Gneiss (Mutis-Duplat, 1972). These gneisses are overlain by at least 7 km of more mafic stratified rocks, the Packsaddle Schist, which are intruded by a varied suite of syntectonic and late-kinematic igneous rocks (Garrison, 1978, 1979). This deformed metamorphic sequence was intruded by several large, circular, unfoliated granitic plutons (Goldich, 1941; Garrison and others, 1979), as well as by numerous small dikes of pegmatite, aplite, and rhyolite.

In the southeastern part of the Llano Uplift, the Packsaddle Schist consists of two main rock types: hornblende schist and quartz-feldspar rocks that range from massive mica-poor varieties to micaceous schists. The lower 2,500 m of the schist is dominantly graphitic schist with marble beds, intercalated with hornblende schist. The upper part of the sequence consists of thick sections of hornblende schist containing thick interlayers of quartz-feldspar rock, muscovite schist, cordierite schist, actinolite schist, and biotite-cordierite gneiss. The protolith of the Packsaddle Schist was probably an accumulation of shallow-water shelf and slope deposits rich in organic material, intercalated with thick sections of mafic and felsic volcaniclastics.

Located within the well-exposed southeastern Packsaddle Schist section is a varied suite of syntectonic and late-kinematic igneous rocks (Fig. 2). The first major intrusive event was the syntectonic emplacement of the tonalitic to granodioritic Big Branch Gneiss and the granitic Red Mountain Gneiss about 1,167 ± 12 m.y. ago (Garrison and others, 1979). Before the end of maximum deformation, a series of low- to medium-K_2O tholeiitic basalt sills intruded the schist and Big Branch Gneiss. After maximum deformation, another period of intrusion of low- to medium-K_2O tholeiitic basalt occurred. The syntectonic and late-kinematic metabasalts have major-element and trace-element affinities with both island-arc tholeiites and abyssal tholeiites (Garrison, 1978, 1979). This suite of metaigneous rocks, as well as the volcaniclastic protolith of the Packsaddle Schist, has been interpreted as a metamorphosed island-arc plutonic complex (Garrison, 1978, 1979).

The rocks of the southeastern Llano Uplift underwent low-pressure metamorphism; mineral assemblages suggest that local metamorphic conditions may have reached a maximum of 650 °C and ~3.5 kb. In the northwestern part of the uplift, conditions may have reached 650 to 700 °C at 5 to 6 kb. Maximum regional dynamothermal metamorphism probably occurred about 1,167 ± 12 m.y. ago and terminated about 1,129 ± 10 m.y. ago (Garrison and others, 1979). After regional uplift of some 6 to 7 km, the emplacement of the posttectonic granite plutons about 1,056 ± 12 m.y. ago effected a widespread thermal overprint (Garrison and others, 1979).

COAL CREEK SERPENTINITE

The most enigmatic and probably most significant metaigneous rock in the entire Llano Uplift, the Coal Creek serpentinite, occurs in the uppermost part of the Packsaddle Schist section at the southeastern edge of the Llano Uplift (Fig. 2). The Coal Creek serpentinite body is about 6 km long, east-west, and ranges in width from 0.5 to 2.3 km; large lobes on each end protrude northward. Along the central part of the body, the southern contact of the serpentinite dips about 60° to the south, shallowing to 40° at the western end. The outcrop pattern and dip suggest that the body is a thick, south-dipping sheet. The serpentinite body is intruded by hundreds of syntectonic and late-

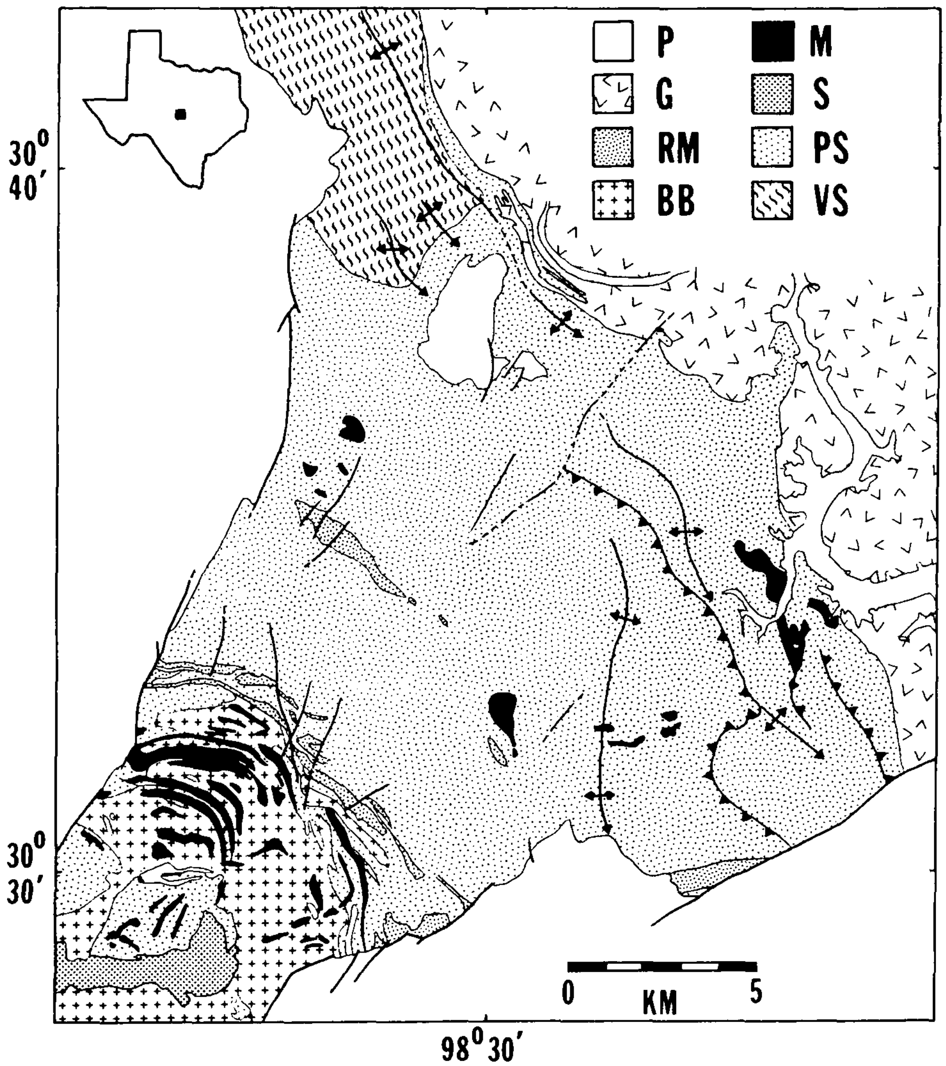

Figure 2. Simplified geologic map of southeastern Llano Uplift, Texas (after McGehee, 1963). VS = Valley Spring Gneiss; PS = Packsaddle Schist; S = Coal Creek serpentinite; M = metabasalts and metagabbros; BB = Big Branch Gneiss; RM = Red Mountain Gneiss; G = granite; P = Paleozoic sediments.

kinematic low-K_2O tholeiites similar in composition to the metabasalts within the schist.

Local Contact Features

The Coal Creek serpentinite is bordered on the south by the Big Branch Gneiss, except along Big Branch Creek where it is in contact with a small sliver of Packsaddle Schist (Fig. 2). Along the northern margin, the serpentinite is in contact with both Big Branch Gneiss and Packsaddle Schist (Barnes and others, 1950). In this area, the Packsaddle Schist is dominantly hornblende schist with minor amounts of intercalated quartz-feldspar rock, some of which grades into quartz-muscovite schist. Many small lenticular soapstone and talc bodies (up to 1,500 m long) are scattered throughout this schist sequence.

Near Big Branch Creek, where the serpentinite is in contact with a small sliver of schist, the extensively sheared outer 10 m of the serpentinite body consists of chlorite rock containing tremolite and magnetite. Slickensides generally parallel the contact with country rock. Talc-

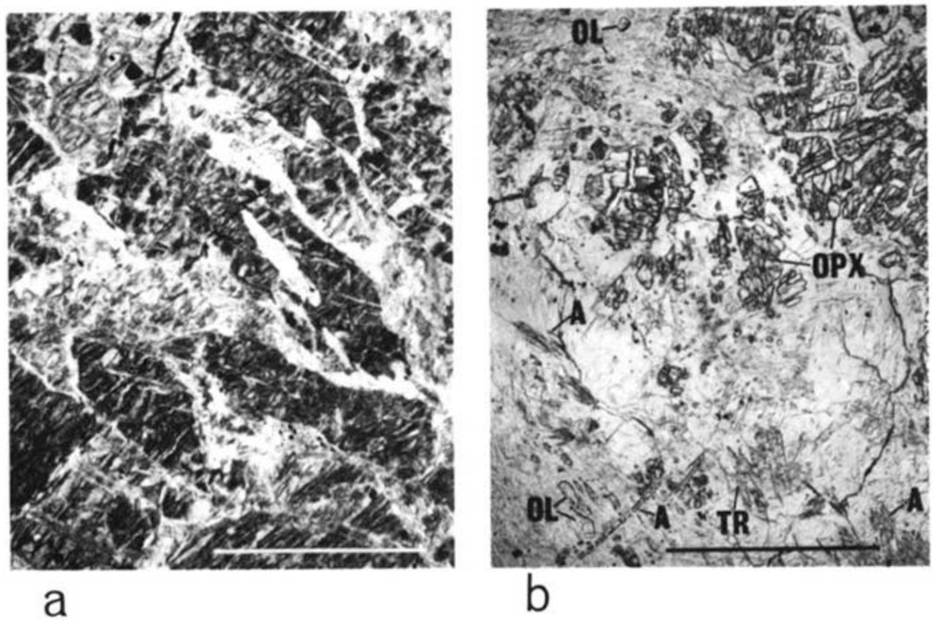

Figure 3. (a) Lizardite pseudomorphs after original elongate olivine grains. Crossed nicols; note uniform extinction. Scale bar = 1 mm. (b) Relict minerals in sample of serpentinite. A = anthophyllite; OL = olivine; TR = tremolite; OPX = orthopyroxene. Scale bar = 1 mm.

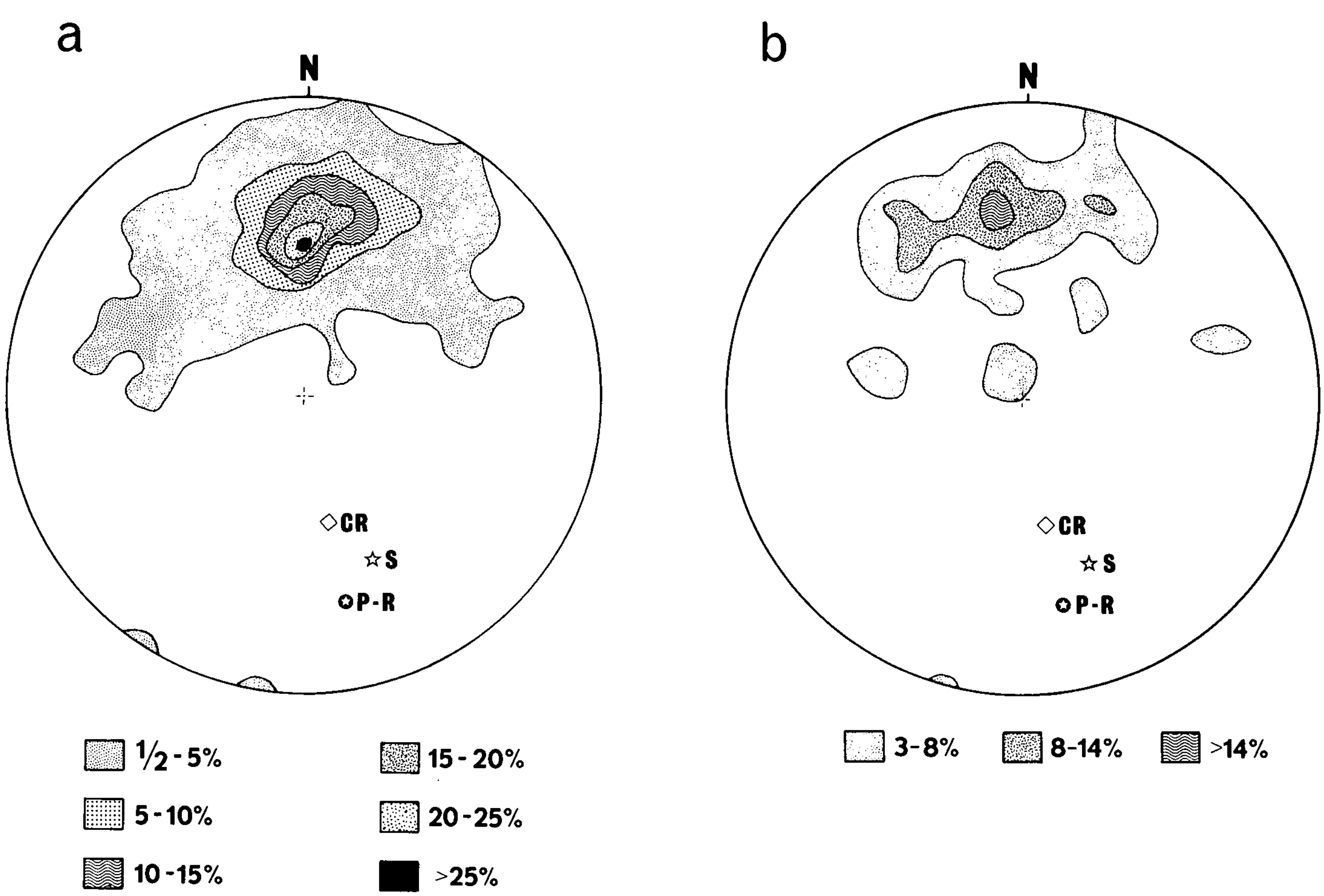

Figure 4. (a) π-diagram for poles to foliation in serpentinite (213 measurements). (b) π-diagram for poles to foliation in local country rock (36 measurements). CR = fold axis defined by country-rock foliation; S = fold axis defined by serpentinite foliation; P-R = fold axis defined by lineation in Packsaddle Schist and Red Mountain Gneiss which defines regional structure (Clabaugh and Boyer, 1961).

tremolite schist, with 5% to 20% chlorite, is common where the serpentinite is in contact with the hornblende schist country rock. Similar talc-tremolite rocks are associated with contact alteration (blackwall) zones of many ultramafic bodies (Chidester, 1969). Within the hornblende schist, some 10 m away from the contact of the serpentinite, an 0.8-m-wide lens of talc-tremolite schist occurs, bordered on both sides by chlorite-tremolite schist. This association is interpreted to represent the contact alteration of a small sliver of ultramafic rock, now talc-tremolite schist, separated from the amphibolitic country rock by chlorite-tremolite schist blackwall zones (Chidester, 1969). Many small pods of chlorite schist also occur proximally to the serpentinite contact.

These contact features make possible some inferences about the relative age and stratigraphic relations of the serpentinite and adjacent country rock. The now-altered fragments of ultramafic material discussed above could be either (1) small fragments of the main ultramafic mass, or (2) small protrusions of the irregular contact of the main mass into the country rock. The many isolated chlorite and talc bodies could represent fragments sheared off during tectonic emplacement, or breccia fragments broken off as the Coal Creek mass was emplaced as an olistostrome into a sedimentary basin (melange). However, the abundance of small ultramafic bodies in the schist, some distance from the Coal Creek mass, suggests that the many smaller bodies are blocks in an olistostrome. It follows that even the large Coal Creek serpentinite mass itself could have been emplaced as an olistostrome block, along with the smaller ultramafic bodies within the melange.

Structural Geology

The Coal Creek serpentinite is highly foliated, although locally massive varieties occur. The foliation generally strikes in an east-west direction along the length of the body and dips to the south. Metabasalt dikes are mostly concordant with the foliation, although some clearly crosscut it. Where dikes are numerous, the foliation may deviate by as much as 20° to 30° from east-west strike. It is not clear whether the foliation was deflected by the dikes or the dikes followed deflected foliation planes.

Foliation is defined by crude layering of lizardite pseudomorphs after metamorphic amphibole and by parallel alignment of elongate lizardite pseudomorphs after original olivine and pyroxene (Fig. 3a). The shape of these elongate pseudomorphs suggests that in the original peridotite, mineral grains had a strong preferred orientation, similar to the fabric of many metamorphic peridotite tectonites.

Figure 4 shows stereographic plots of poles to foliation planes within the serpentinite and poles to foliation planes within the surrounding country rock. The poles to serpentinite foliation (Fig. 4a) form a girdle suggesting a broad fold with an axis bearing S22°E and plunging south 40°. Poles to foliation in the local country rock (Fig. 4b) define a different girdle with a pole at S8°E, 54°S. Even with the

TABLE 1. REPRESENTATIVE AVERAGE MINERAL ANALYSES FROM COAL CREEK SERPENTINITE

	Olivine	Orthopyroxene	Anthophyllite	Tremolite	Mesh Serpentine	Bastite Serpentine	Chromite	Magnetite
SiO_2	41.4 (1)	58.0 (2)	59.1 (1)	57.5 (3)	40.2 (4)	43.4 (4)	n.a.	n.a.
TiO_2	n.a.	0.03(1)	0.03(1)	0.04(1)	n.a.	n.a.	0.38(1)	0.07(1)
Al_2O_3	n.d.	0.34(2)	0.21(3)	0.55(5)	0.06(1)	0.25(1)	1.41(1)	0.05(1)
Cr_2O_3	0.10(1)	0.06(2)	0.04(1)	n.d.	0.08(2)	0.08(2)	37.9 (2)	0.11(1)
Fe_2O_3*	---	---	---	---	---	---	29.1	69.4
FeO	6.19(15)	4.68(14)	4.80(29)	1.37(2)	3.58(10)	5.02(10)	25.1 (6)	28.1 (3)
MnO	0.24(1)	0.14(3)	0.29(4)	0.07(2)	0.15(2)	0.30(3)	0.72(3)	0.07(2)
MgO	52.5 (2)	36.8 (2)	31.6 (1)	24.3 (1)	41.6 (5)	37.4 (5)	3.69(2)	1.18(1)
NiO	0.59(3)	n.a.	n.a.	n.a.	0.50(5)	0.06(1)	0.60(5)	1.28(4)
CaO	n.a.	0.07(1)	0.25(3)	12.6 (1)	n.a.	n.a.	n.a.	n.a.
Na_2O	n.a.	n.d.	0.03(2)	0.14(4)	0.05(1)	0.03(1)	n.a.	n.a.
Σ	101.02	100.12	96.35	96.57	86.22	86.54	98.90	100.26
cation basis	4	6	23	23	13.625	13.625	4	4
Si	0.991	1.979	7.979	7.909	3.744	4.008	---	---
Al^{IV}	0.000	0.013	0.021	0.088	0.007	0.028	0.000	0.000
Al^{VI}	0.000	0.000	0.010	0.000	0.000	0.000	0.061	0.002
Ti	---	0.000	0.000	0.004	---	---	0.011	0.002
Cr	0.002	0.001	0.004	0.000	0.006	0.005	1.105	0.003
Fe^{3+}	---	---	---	---	---	---	0.806	1.992
Fe^{2+}	0.124	0.133	0.539	0.153	0.279	0.387	0.773	0.893
Mg	1.874	1.873	6.368	4.981	5.785	5.142	0.203	0.067
Mn	0.005	0.004	0.031	0.008	0.012	0.023	0.023	0.002
Ni	0.011	---	---	---	0.037	0.004	0.018	0.039
Ca	---	0.002	0.036	1.857	---	---	---	---
Na	---	0.000	0.004	0.036	0.008	0.005	---	---
Σ	3.007	4.005	14.992	15.036	9.878	9.602	3.000	3.000

Note: n.a. = not analyzed; n.d. = not detected, <0.03 wt.%. 1σ error of least units cited given in parentheses. Analyses reported in weight percent oxides.

* All Fe determined as Fe; oxides based on crystal chemistry.

small data base available, the fold axis defined by the local country-rock foliation is consistent with the regional structure as previously mapped. Barnes (1945) reported a steeply dipping lineation in the Big Branch Gneiss bearing S10°E. Clabaugh and Boyer (1961) made 119 measurements of the lineations within the Packsaddle Schist and 143 in the Red Mountain Gneiss near Red Mountain 10 km to the north; they defined a coincident maximum at S12°E, 30°S, which is approximately the bearing and plunge of the major synclinal axis in this area of the Llano Uplift.

The Coal Creek serpentinite foliation represents a fold axis with a 15° eastward deviation from the major synclinal axis and a plunge almost 15° less steep. There are four possible explanations for this deviation: (1) it is not real; the foliations are identical within the errors of measurement; (2) the foliation of the serpentinite has been severely deflected by the emplacement of swarms of metabasalt dikes; (3) the regional foliation has been refracted through the serpentinite; or (4) the foliation within the serpentinite mass is, in fact, different and represents a pre-emplacement tectonite fabric preserved by serpentine pseudomorphs. At the 3° error commonly associated with field measurements, the deviation is real at the 95° confidence level. It is unlikely that random emplacement of dikes could have produced such a uniform deviation. It is reasonable to assume that the dikes were emplaced along a pre-existing foliation. Explanation 4 above is supported by the occurrence of scattered chromite layers parallel to foliation and the preferential orientation of the elongate lizardite pseudomorphs.

Layered ultramafic rocks with chromite layers are common in the lower parts of ophiolite complexes. It is possible that the ultramafic protolith of the Coal Creek serpentinite is analogous to these layered ultramafic rocks—a harzburgite tectonite. If the Coal Creek body is a sedimentary block within a melange, it is likely that the general pattern of relict cumulate or tectonite layering could be subparallel to the layering in the metasedimentary rocks; because lithologic layering in the schist is parallel to regional foliation, the deviation in serpentinite and country-rock foliation may be expected.

Mineralogy and Petrology

The Coal Creek serpentinite consists of Al-poor lizardite with accessory amounts of magnetite. Generally, the serpentinite lacks relict minerals; metamorphic tremolite, talc, and chlorite are common but form less than 5% of the rock. Locally, podiform concentrations of tremolite occur in which radiating splays (up to 10 cm in diameter) form as much as 20% to 30% of the rock. Relict chromite occurs as scattered subhedral (up to 1 mm) grains and locally as thin (up to 1 cm thick) discontinuous layers that are commonly tightly folded. A few samples contain the relict assemblage olivine + orthopyroxene + anthophyllite + tremolite + chromite with minor amounts of magnetite and retrograde talc and chlorite (Fig. 3b).

Representative average analyses (6 to 10 analyses per grain) of minerals from the Coal Creek serpentinite are presented in Table 1. The olivines [Mg/(Mg + Fe) = 0.94] and orthopyroxenes [Mg/(Mg + Fe) = 0.93 and 0.34% Al_2O_3] have compositions slightly more magnesian than similar phases in metamorphic peridotites (Coleman, 1977). The Fe-Mg equilibrium between co-existing olivine and chromite [Cr/(Cr + Al) = 0.95 and Mg/(Mg + Fe) = 0.21; Fabries, 1979] suggests equilibration at 655 °C, which indicates that the olivine + spinel assemblage re-equilibrated to regional metamorphic temperatures.

The compositional data suggest that the harzburgite assemblage olivine + orthopyroxene + chromite re-equilibrated to metamorphic conditions; this assemblage is probably in equilibrium with the metamorphic assemblage anthophyllite + tremolite. The assemblage olivine + orthopyroxene + anthophyllite has a very restricted stability field controlled by the reaction anthophyllite + forsterite $\rightleftharpoons$ 9 enstatite + H_2O. In the system $MgO\text{-}FeO\text{-}SiO_2\text{-}H_2O$, the above assemblage exists in a very restricted divariant field. Under conditions of $P_{H_2O} = P_{total}$ = 4 kb, this reaction will occur at about 710 ± 30 °C (Day and Halbach, 1979). These conditions are consistent with the occurrence of tremolite in Ca-rich subsystems and the olivine-spinel Fe-Mg equilibria.

OXYGEN AND DEUTERIUM ISOTOPIC STUDIES

Five samples of Coal Creek serpentinite have relatively uniform δO^{18} (+5.22 to +6.85) and δD (−76 to −81). The δO^{18} and δD values for the Coal Creek serpentinite samples are similar to values of continental lizardite-chrysotile serpentinites, but they generally have 10‰ heavier δD than lizardite-chrysotile serpentinites from ophiolites (Fig. 5; Wenner and Taylor, 1973).

Most lizardites are believed to have formed near 85 to 130 °C, on the basis of oxygen isotope geothermometry (Wenner and Taylor, 1971). Assuming that the Coal Creek serpentinite formed at 100 °C with a very large water/rock ratio, the lizardite formed in equilibrium with water with δO^{18} = −1.29‰ to +0.33‰ and δD = −108‰ to −113‰. Since the δD values of serpentinites generally reflect equilibration with local meteoric waters, the above situation can be realized if the lizardite formed in equilibrium with sea water ($\delta O^{18} = \delta D = 0.0$) and the δD reflects further isotopic exchange with local meteoric water. Because the meteoric waters in this area have $\delta D \sim -30$, it is clear that the lizardite could not have undergone such a D/H exchange with present-day meteoric water.

The calculations of Sakai and Tsutsumi (1978) reveal that the lizardite could have formed in equilibrium with magmatic water (δO^{18} = +7.0 and δD = −70) at 300 to 400 °C with a water/rock ratio of about 5. This is consistent with the formation of Al-free lizardite which has a maximum stability of about 400 °C (Chernosky, 1975), as well as the formation of the metasomatic blackwall reaction zones. Because the intrusion of the post-tectonic granites raised the temperature of

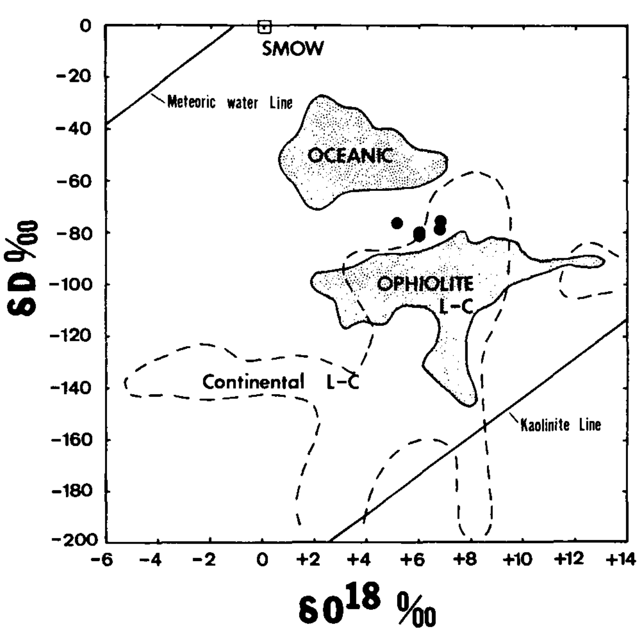

Figure 5. Oxygen and deuterium data for Coal Creek serpentinite (solid circles) plotted on the δD-δO18 diagram. Ranges of ophiolite, oceanic, and continental serpentinites from Wenner and Taylor (1973). L-C = lizardite-crysotile.

the country rock to about 650 °C (Garrison and others, 1979), serpentinization and metasomatism must have occurred after their intrusion 1,056 ± 12 m.y. ago. It is possible that during regional uplift, late magmatic water associated with these large granitic plutons was responsible for serpentinization and metasomatism of the Coal Creek ultramafic body.

OPHIOLITES AND GRENVILLIAN OROGENIC STYLE

The Coal Creek serpentinite appears to represent the tectonite part of an ophiolite sequence. Nearby large hornblendite bodies could represent fragments of cumulate parts (Fig. 2). An olistostromal mode of emplacement for the Coal Creek mass is suggested by the field and structural data. The occurrence of ophiolitic fragments within the arc-flank (melange?) metasedimentary rocks of the Packsaddle Schist is consistent with any number of "plate-tectonics" origins for ophiolites.

Several tectonic models have been proposed to explain the geologic history of the northern Grenville belt, but little attention has been given to the central and southern parts of the belt. Dewey and Burke (1973) proposed a *brittle* plate-tectonics model in which huge thickening of the continental crust produced by a continent-continent collision along a subduction zone (a Tibetan-type continental collision) explains the reworking of older basement, the anorthosite massifs, and the widespread occurrence of high-grade granulite metamorphic conditions. They had no direct evidence for the existence of the indicative ophiolitic or eugeosynclinal materials for a suture zone. Wynne-Edwards (1976), opposed to this idea because of the lack of any well-defined suture zones, proposed a model in which the Grenville orogenic belt was created by sequential deformation of *ductile*, unruptured continental crust over a spreading center. He suggested that the occurrence of only granitic gneisses and platform-type metasedimentary rocks attests to the ensialic and ductile nature of Proterozoic orogenesis.

The island-arc model developed for the Llano Uplift implies that brittle plate tectonics was at least locally important 1,200 m.y. ago. On the North American craton, only features such as the Coronation geosyncline, the Circum-Ungave geosyncline, and the Mid-Continent Geophysical Anomaly suggest that pre-Phanerozoic brittle tectonics was operative (rifting events). There is a curious absence of ophiolitic material and low-pressure metamorphic rocks in the 1,000- to 2,000-m.y.-old Precambrian orogenic belts. This lack of exposed suture zones, ophiolites, and alpine-type ultramafics in these orogenic belts is probably a simple consequence of the level of erosion. Isostatic uplift has caused most of these diagnostic materials to be eroded away.

By virtue of its location along a re-entrant in the Grenville belt, the Llano Uplift escaped the intense metamorphism, crustal thickening, and uplift that accompanied the postulated continent-continent collision along the eastern margin of the North American craton nearly 1,100 m.y. ago. The present level of erosion along the main Grenville belt in Canada and Mexico represents the removal of at least 20 km of material, whereas in the Llano terrane only 12 to 15 km of material have been removed. The shallower level of erosion allowed the preservation of the eugeosynclinal metasedimentary rocks, island-arc plutonic rocks, and fragments of ophiolitic material that occur in the southeastern Llano Uplift of Texas. The Llano Uplift contains the only exposed ophiolitic material along the entire "Grenvillian" orogenic belt.

Thus, from the model and arguments presented here, it seems likely that brittle plate-tectonics processes operated at least 1,200 m.y. ago. The orogenic event that affected the Llano terrane (Grenville orogeny) involved island-arc–continent interactions. This allows comparison of igneous and tectono-metamorphic processes that operated in 1,200-m.y.-old orogenic belts in the Precambrian and processes occurring in present-day regimes.

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ACKNOWLEDGMENTS

Reviewed by J. C. Maxwell and D. Roeder. I thank D. Smith, J. C. Maxwell, and S. E. Clabaugh for discussions and criticism. L. S. Land kindly performed the oxygen and deuterium isotopic analyses. Microprobe facilities were provided by University of Texas at Austin and University of Tennessee.

MANUSCRIPT RECEIVED SEPT. 5, 1980

REVISED MANUSCRIPT RECEIVED FEB. 12, 1981

MANUSCRIPT ACCEPTED FEB. 25, 1981