American Mineralogist, Volume 70, pages 1151–1163, 1985

Petrology, geochemistry and origin of the Big Branch and Red Mountain gneisses, southeastern Llano Uplift, Texas

JAMES R. GARRISON, JR.[1]

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

Abstract

The 1.0–1.2 b.y. old rocks of the southeastern Llano Uplift, Texas include a 7-km-thick section of amphibolite-grade, stratified, mafic metasedimentary rocks with interlayers of more felsic composition (Packsaddle Schist). Prior to the end of maximum deformation, the sequence was intruded by syntectonic tonalite (Big Branch Gneiss). At 1167±12 m.y. ago, nearly contemporaneous with the emplacement of the tonalite, small sills of granite (Red Mountain Gneiss) were emplaced adjacent to the tonalite body. The Big Branch Gneiss is characterized by variable Al_2O_3 (14.90–18.14%), Sr (287–873 ppm), Rb (27–71 ppm), and Zr (108–348 ppm) and low Ni (7–25 ppm), Co (17–19 ppm), Cr (18–36 ppm), Sc (8–10 ppm) and K_2O/Na_2O (0.22–0.44); K/Rb ratios range from 274–394. The Big Branch Gneiss has initial $^{87}Sr/^{86}Sr = 0.7038 \pm 0.0002$. Two Big Branch Gneiss samples have La abundances 36–97 times chondritic and exhibit light REE enrichment with $|La/Sm|_N$ from 3.13–4.24 and $|La/Yb|_N$ from 12.40–29.34; neither sample exhibits a significant Eu anomaly. The Red Mountain Gneiss has a fairly uniform granitic composition but extremely variable Rb (127–286 ppm), Sr (17–69 ppm), Y (40–71 ppm), Zr (62–233 ppm), and K/Rb (138–348); Ni is uniform (10–15 ppm). The Red Mountain Gneiss has initial $^{87}Sr/^{86}Sr = 0.7057 \pm 0.0010$.

Major and trace element systematics are consistent with an island arc model in which the Big Branch Gneiss tonalite was generated by ~20% partial melting of basaltic portions of subducted oceanic crust at a depth greater than 55 km, leaving residual eclogite (±hornblende). The Big Branch Gneiss tonalite was emplaced into the island arc complex where it underwent in situ fractionation of plagioclase and minor hornblende. As the voluminous Big Branch Gneiss magma ascended through the lower portion of the island arc complex, it caused local partial melting of felsic portions of the volcanic and volcaniclastic materials to produce the granitic Red Mountain Gneiss magma, which was subsequently emplaced adjacent to the Big Branch Gneiss pluton. The Red Mountain Gneiss magma underwent a minor amount of in situ fractionation of biotite + quartz ± alkali feldspar ± magnetite.

Introduction

The Llano Uplift, Central Texas, is a gentle structural dome in which erosion has exposed 1.0–1.2 b.y. old Precambrian basement. The lower part of the exposed basement consists of a thickness of at least 3.8 km of metarhyolite and meta-arkose: the Valley Spring Gneiss (Mutis-Duplat, 1972; Droddy, 1978). The Valley Spring Gneiss is overlain by the much thinner (40–1000 m thick) Lost Creek Gneiss (Mutis-Duplat, 1972). These quartz-feldspar gneisses are overlain by at least 7 km of more mafic, stratified rocks, the Packsaddle Schist, which is intruded by a varied suite of syntectonic and late-kinematic igneous rocks ranging in composition from basalt to tonalite to granite (Garrison, 1979; 1981b). Both gneiss and schist are intruded by several large, unfoliated granite plutons, numerous small pegmatites, and basaltic to rhyolitic dikes (Goldich, 1941; Garrison et al., 1979).

The rocks of the eastern Llano Uplift underwent low-pressure metamorphism similar to the conditions described as andalusite-sillimanite type by Miyashiro (1961) and as cordierite-medium grade by Winkler (1979). Metamorphic mineral assemblages suggest that local metamorphic conditions may have reached a maximum of ~3.5 kbar and 650–710°C (Garrison, 1981a). Maximum regional dynamothermal metamorphism probably occurred about 1167 ± 12 m.y. ago and terminated about 1129±10 m.y. ago (Garrison et al., 1979). After regional uplift of some 6–7 km, the emplacement of the post-tectonic granite plutons about 1056±12 m.y. ago effected a widespread thermal overprint, as evidenced by regional averages of 1062±24 m.y. and 1037±13 m.y. for K–Ar ages of hornblendes and biotites, respectively.

In the southeastern part of the Llano Uplift, the Pack-

---

[1] Current mailing address: Core Laboratories, Inc., 1565 W. Mockingbird Lane, Suite 500, Dallas, Texas 75235.

0003–004X/85/1112–1151$02.00

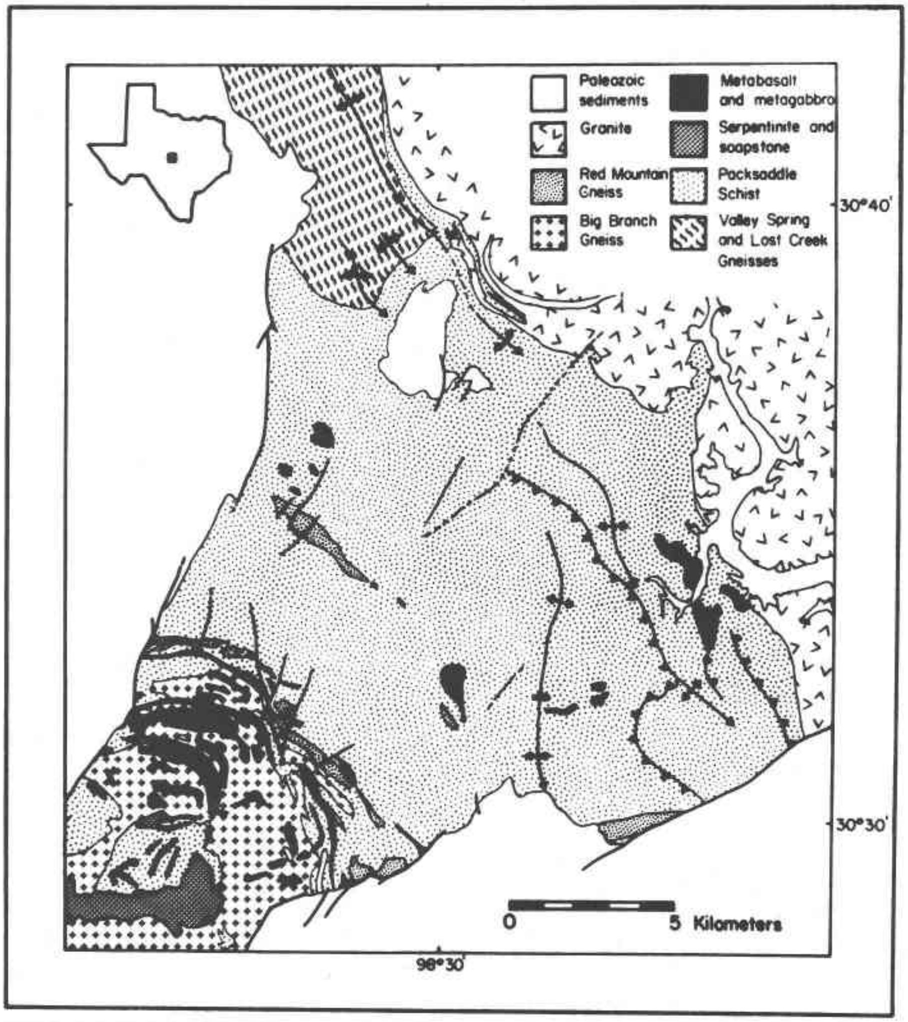

Fig. 1. Simplified geologic map of Precambrian rocks in the southeastern Llano Uplift, Central Texas. After McGehee (1963).

saddle Schist is more than 6.8 km thick and consists of two main rock types: hornblende schist (and amphibolite) and quartz-feldspar rocks that range from massive mica-poor varieties to micaceous schists (Burnitt, 1961; McGehee, 1963). The *lower* Packsaddle Schist, totaling 3 km, consists dominantly of graphitic schist with marble beds, intercalated with hornblende schist; quartz-feldspar rock is not uncommon. The *middle* Packsaddle Schist, a 1.6 km thick pelitic sequence, consists of thick interlayers of quartz-feldspar rock, muscovite schist, biotite-cordierite gneiss, cordierite schist, and quartz-feldspar-mica schist. The *upper* Packsaddle Schist, totaling 2.2 km, consists dominately of hornblende schist with interlayers of actinolite schist, quartz-feldspar rock, and mica schist. The upper 1.2 km of the *upper* Packsaddle Schist contains "melange" blocks of soapstone, talc rock, tremolite schist, and serpentinite, (all representing altered ultramafic material) and large olistostromal blocks of serpentinized peridotite and cumulate gabbro (Garrison, 1981a, 1981b). Large elongate blocks of metasedimentary and metavolcanic materials also occur within the melange. The protolith material of the Packsaddle Schist was probably an accumulation of shallow-water shelf and slope deposits rich in organic materials, intercalated with thick sections of mafic and felsic volcaniclastic materials. Olistostromal blocks of periodotite and gabbro were emplaced into the upper Packsaddle schist prior to major compressive orogeny and regional dynamothermal metamorphism and were probably derived from ophiolitic materials exposed adjacent to the island arc.

Located within the well-exposed Packsaddle Schist sequence of the southeastern Llano Uplift (Fig. 1) is a suite of syntectonic and late-kinematic intrusive rocks (McGehee, 1963; Garrison, 1979, 1981a, 1981b). These intrusives are generally confined to the *upper* and *middle* units of the Packsaddle Schist. The first major intrusive event was the near-synchronous syntectonic emplacement of the tonalitic Big Branch Gneiss and the granitic Red Mountain Gneiss. Prior to the end of maximum deformation, both the Packsaddle Schist and the Big Branch Gneiss were intruded by low- to middle-K_2O tholeiitic basalts (Garrison, 1981b).

Late-kinematic low-K_2O tholeiitic basalts were intruded as dikes into the folded rocks. The syntectonic and late-kinematic metabasalts and metagabbros have chemical compositions similar to island arc tholeiitic basalts (Garrison, 1981b). This suite of metaigneous rocks, as well as the volcaniclastic protolith materials of the Packsaddle Schist, have been interpreted as a metamorphosed island arc plutonic complex (Garrison, 1979, 1981a, 1981b).

The Big Branch Gneiss (Barnes, 1945) occurs as a large plutonic mass occupying most of the *upper* Packsaddle Schist in the southeastern Llano Uplift, with an outcrop diameter greater than 10 km (Fig. 1). The Big Branch Gneiss is a texturally and mineralogically complex body whose composition varies greatly, depending in part upon proximity to its contact with the Red Mountain Gneiss. Away from the contact, the Big Branch Gneiss is a poorly- to well-foliated gray rock consisting of quartz and plagioclase, with minor biotite, hornblende, and microcline. The Big Branch Gneiss commonly contains inclusions of the Packsaddle Schist. Within a few hundred meters of its contact with the Red Mountain Gneiss, porphyroblasts of pink microcline appear in the Big Branch Gneiss, increasing in size and abundance so that nearest the contact they make up nearly a quarter of the rock and may reach a diameter of several centimeters (Clabaugh and Boyer, 1961). These authors suggested that the Red Mountain magma was emplaced slightly later than the Big Branch Gneiss body while the latter was still warm, producing alkali metasomatism of the adjacent Big Branch Gneiss. Blaxland (1975) concluded that near the contact with the Red Mountain Gneiss a maximum alkali enrichment of 40% occurred relative to initial Na + K.

The Red Mountain Gneiss (Barnes et al., 1950) is a red granite gneiss that occurs as a series of sill-like bodies forming an arcuate trend consistent with the regional structure (Fig. 1). It contains xenoliths of schist, and local discordant contacts with the enclosing Packsaddle Schist attest to its igneous origin. Mineralogically, the Red Mountain Gneiss is a microcline granite containing minor biotite and muscovite.

The field work of Clabaugh and Boyer (1961) and the Rb–Sr isotopic work of Garrison et al. (1979) provide evidence for near isochronous intrusion of the Red Mountain and Big Branch magmas. Clabaugh and Boyer (1961) pointed out that the Red Mountain intrusive rock exhibits no evidence of chilling against the Big Branch Gneiss rocks, although it was chilled against the Packsaddle Schist country rock. Garrison et al. (1979) found that the Rb–Sr whole-rock isochron ages for the two bodies are identical within the calculated 2σ errors; in fact they represent two parallel isochrons with initial $^{87}Sr/^{86}Sr$ ratios of 0.7038 ± 0.0002 and 0.7057 ± 0.0010 for the Big Branch Gneiss and Red Mountain Gneiss, respectively. Garrison et al. (1979) calculated a preferred age of syntectonic emplacement of the two bodies of 1167 ± 12 m.y.

In this study, a suite of samples was collected from the Big Branch and Red Mountain Gneisses and analyzed for major and trace elements. By characterizing the major element, trace element, and Sr isotopic systematics of these two syntectonic intrusive rocks, a petrogenetic model and more complete geologic history for the Llano Uplift are developed. Any model for these rocks has direct implications for the nature of tectono-magmatic processes operating during this 1.0–1.2 b.y. orogenic event. The postulated "alkali metasomatism" of the Big Branch Gneiss where in contact with the Red Mountain Gneiss is reexamined in light of this new major and trace element chemical data.

Analytical methods

Five to ten kilogram samples of the Big Branch and Red Mountain Gneisses were crushed and sized to less than 160 mesh in a tungsten carbide shatter-box; five gram representative aliquots were split from this material for use in chemical isotopic analysis. Petrographic descriptions and sample locations for these rocks can be found in Garrison et al. (1979) and Garrison (1979).

More element analyses of whole rocks were performed by G. K. Hoops of the University of Texas at Austin using the standard analytical methods outlined by Shapiro and Brannock (1961) and Shapiro (1975).

Rb, Sr, Ni, Y, and Zr abundances in whole-rock samples were determined by X-ray fluorescence spectrometry (XRF) using the procedures outlined by Garrison (1981b). The precisions for Rb, Sr, Ni, Y, and Zr are 6%, 2%, 1%, 10%, and 6% (1σ), respectively. The accuracy of these analyses is estimated to be 1–5%. Rb and Sr in selected samples were determined by isotope dilution mass spectometry (Garrison et al., 1979); accuracy and precision for these Rb and Sr determinations are 0.5% (1σ).

Abundances of Sc, Cr, Co, Hf, Ta, and Th, and the rare earth elements (REE) La, Ce, Sm, Eu, Tb, and Yb in selected whole-rock samples were determined by instrumental neutron activation analysis (INAA). Procedures are outlined by Garrison (1981b) and the data reduction procedure is described by Tiezzi (1981). The precisions for Sc, Cr, Co, Hf, Ta, and Th are 0.7%, 0.8%, 0.8%, 10% and 10% (1σ), respectively. Precisions for the REEs La, Ce, Sm, Eu, Tb, and Yb are 0.3%, 13%, 1%, 3%, 5%, and 4% (1σ), respectively.

Petrography

The Red Mountain Gneiss is typically a fine- to medium-grained red granite gneiss composed of 50% perthitic microcline, 40% quartz, 4% plagioclase (oligoclase), 5% biotite, 1% magnetite with accessory amounts of muscovite, apatite, sphene, zircon, and allanite (Burnitt, 1961). In the interior of the main sill-like body, the rock becomes coarser and the microcline content increases as large porphyroblasts appear. When the gneiss occurs in small isolated bodies, the plagioclase content may approach 15% (Burnitt, 1961; McGehee, 1963).

Texturally the Red Mountain Gneiss is quite variable depending on distance from the margins of the sill-like bodies and the type of country rock present. The gneiss is finer-grained where in contact with Packsaddle Schist and exhibits textural evidence of chilling such as relict outlines of high-temperature quartz. The gneiss is much coarser where in content with the Big Branch Gneiss. The foliation of the Red Mountain Gneiss in the northern portions and near the contacts with the schist is defned by elongate microcline and quartz grains and thin streaks of biotite. These quartz grains have a preferred orientation of their c-axes (Clabaugh and Boyer, 1961). Towards the southeast, the Red

Mountain Gneiss becomes less foliated and slightly coarser. In the interior of the main sill-like body, the rock is unfoliated.

The Big Branch Gneiss is typically a medium- to fine-grained gray gneiss composed of 35–60% plagioclase ($An_{30.7}Ab_{68.6}Or_{0.7}$ to $An_{36.0}Ab_{63.3}Or_{0.7}$), 25–40% quartz, 10–20% biotite, and 5–10% magnesio-hornblende (Garrison, 1979). The mafic minerals occur in clusters and as minor disseminated groundmass constitutents. Microcline is usually present in minor amounts, rarely making up more than 2% of the rock. Accessory idiomorphic epidote (2%) is common, and in some rocks it occurs as an alteration of plagioclase and in granular aggregates making up as much as 13% of the rock (Burnitt, 1961; Richmann, 1977). Other accessory minerals are sphene, apatite, zircon, magnetite, and ilmenite.

Burnitt (1961) noted that the Big Branch Gneiss becomes more foliated, lighter in color, and more quartz-rich in the north and northeastern portions of the pluton. Burnitt (1961) noted that near the margins of the body, the gneiss is relatively fine-grained and more distinctly foliated, possibly representing a marginal phase of the pluton. As the contact of the Big Branch Gneiss with the Red Mountain Gneiss is approached, the Big Branch Gneiss becomes an augen gneiss with microcline prophyroblasts (augen) making up 20–30% of some samples (Burnitt, 1961; Clabaugh and Boyer, 1961). The augen have been cataclastically deformed and recrystallized to various degrees. The rock (here referred to as the *marginal phase*) is distinctly coarser and resembles a porphyritic quartz monzonite or granodiorite. In these samples, biotite becomes slightly more abundant; it appears that the plagioclase/quartz ratio decreases only slightly, while the (microline + plagioclase)/quartz ratio increases more dramatically.

Geochemistry

Major element geochemistry

Major element chemical analyses of seven samples of Big Branch Gneiss and four samples of Red Mountain Gneiss are presented, along with molecular norms, in Table 1. Molecular norms were calculated volatile-free with Fe_2O_3/FeO adjusted, where required, by the criteria of Irvine and Baragar (1971).

Red Mountain Gneiss. The four samples of Red Mountain Gneiss have a fairly uniform granitic composition (Table 1). These samples exhibit a correlation of decreasing MgO (0.20–0.02%), K_2O (5.62–4.34%), TiO_2 (0.18–0.01%), FeO* (i.e., all Fe calculated as FeO) (1.80–0.68%), and MgO/(MgO + FeO*) ratio (0.10–0.028) with increasing SiO_2 content (75.07–77.68%). The normative orthoclase/albite ratio (*or*/*ab*) (1.21–0.78) also decreases with increasing SiO_2; total alkalis remain approximately constant. Although the data base for the Red Mountain Gneiss is quite small, these chemical trends suggest that minor in situ differentiation may have occurred within these relatively thin sill-like bodies. The existence of relict outlines of high-temperature quartz in the chilled margins of the Red Mountain sills suggests that quartz was a near-liquidus phase and can be considered a possible fractionated phase.

The normative quartz (*q*), albite (*ab*), and orthoclase (*or*) contents of the four Red Mountain Gneiss samples are shown in Figure 2 plotted on the ternary Q–Ab–Or diagram; the cotectic line at $P_{H_2O} = 2$ kbar (heavy solid line) and the temperature minima for $P_{H_2O} = 0.5$, 3, 5, and 10 kbar (plus signs) in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O (Tuttle and Bowen, 1958, Luth et al., 1964) are also shown. The least fractionated Red Mountain Gneiss sample (i.e., with lowest SiO_2 and highest MgO/(MgO + FeO*) ratio), RM-1, with 2.29 mol% normative anorthite (*an*), plots near the cotectic line at $P_{H_2O} = 2$ kbar. The most fractionated sample, RM-5, with 1.39 mol% *an*, plots near the cotectic line at $P_{H_2O} \sim 0.5$ kbar. Since field relationships (Clabaugh and Boyer, 1961) and Rb–Sr isotopic systematics (Garrison et al., 1979) suggest that the Red Mountain granitic magma was intruded during peak dynamothermal metamorphism, at a pressure (P_{total}) near 3–4 kbar, it is likely that the Red Mountain magma was H_2O-undersaturated. The loci of the Red Mountain Gneiss data on the Q–Ab–Or ternary suggest: (1) that the Red Mountain magma may have frationated alkali feldspar and (2) that at the time of igneous differentiation, $P_{H_2O} \sim 0.5$ kbar. The experimental study of Whitney (1975) of the system "granite–H_2O" indicates that for quartz to be a near-liquidus phase, as suggested from petrographic data, at $P_{total} = 3$–4 kbar, the system must contain less than 4 wt.% H_2O. At $P_{total} = 3$–4 kbar, a granitic magma requires 8–9 wt.% H_2O to be H_2O-saturated (Whitney, 1975). A granitic magma containing ≤ 4 wt.% H_2O would have an effective $P_{H_2O} \leq 1.5$ kbar.

Experimental studies (Piwinskii, 1968; Gibbon and Wyllie, 1969; Whitney, 1975) indicate that a granite similar in composition to the Red Mountain Gneiss would have, as possible near-liquidus phases, biotite, alkali feldspar, plagioclase, quartz, and magnetite. The correlation of increasing Na_2O (3.05–3.83%) with increasing SiO_2 in the Red Mountain Gneiss suggests that plagioclase was not an important fractionating phase. On balance, the major element systematics of the Red Mountain Gneiss are best explained in terms of crystal-liquid fractionation involving the assemblage biotite + quartz ± alkali feldspar ± magnetite.

Big Branch Gneiss. Chemical analyses of six samples of "normal" Big Branch Gneiss (i.e., those samples containing only minor amounts of microcline) from the northern and southern portions of the pluton are presented in Table 1, along with one sample, BB-1, representing the microcline-rich *marginal phase* of the gneiss near the Red Mountain body (with 27% modal microcline). The "normal" Big Branch Gneiss samples are tonalitic in composition (64.37–68.55% SiO_2); *marginal phase* sample BB-1 is compositionally similar to granodiorite or quartz monzonite (70.47% SiO_2). When the normative *ab*, *an*, and *or* data for these samples are plotted on the normative Ab–An–Or classification diagram of O'Connor (1965), as modified by Barker (1979), five of the six "normal" Big Branch Gneiss samples plot within the tonalite field (Fig. 3). Sample BB-4 (67.23% SiO_2) plots within the trondhjemite field, although it has too high FeO* + MgO (5.35%) to be trondhjemite as strictly defined by Barker (1979). The microcline-rich *marginal phase* sample plots distinctly away from the other samples, along the boundary between the fields of granite and quartz monzonite.

Table 1. Chemical analyses and norms of Big Branch and Red Mountain Gneisses

	86T15D	BB-6X	BB-8	BB-3	BB-4	BB-6	BB-1	RM-1	RM-4	RM-3	RM-5
SiO_2	64.37	64.62	64.63	65.98	67.23	68.55	70.47	75.07	75.26	75.80	77.68
TiO_2	0.44	0.38	0.41	0.41	0.70	0.77	0.51	0.18	0.11	0.01	0.01
Al_2O_3	18.14	16.82	17.47	17.22	14.90	15.10	14.32	12.69	13.11	12.76	12.23
Fe_2O_3	1.05	1.19	1.17	0.98	2.47	3.00	1.08	1.42	1.32	0.90	0.57
FeO	2.49	2.83	2.41	2.40	1.67	2.35	2.95	0.52	0.30	0.08	0.17
MnO	0.04	0.06	0.04	0.06	0.11	0.08	0.06	0.02	0.01	0.01	0.01
MgO	1.90	2.32	1.69	1.77	1.46	0.83	0.73	0.20	0.16	0.04	0.02
CaO	5.65	5.12	4.89	4.87	2.66	3.37	1.88	0.53	0.50	0.46	0.30
Na_2O	4.54	4.14	4.49	4.58	5.31	4.20	3.15	3.05	3.53	3.83	3.66
K_2O	1.00	1.47	1.05	1.27	2.34	1.69	3.89	5.62	4.90	4.74	4.34
H_2O^+	0.40	0.48	0.54	0.54	0.24	0.20	0.18	0.12	0.22	0.21	0.13
H_2O^-	0.02	0.08	0.18	0.08	0.09	0.04	0.08	0.16	0.12	0.11	0.11
CO_2	0.02	0.04	0.05	0.01	0.08	0.01	0.10	0.01	0.00	0.13	0.00
P_2O_5	0.13	0.20	0.16	0.15	0.23	0.33	0.23	0.06	0.02	0.01	0.02
	100.19	99.75	99.18	100.32	99.49	100.52	99.63	99.65	99.56	99.09	99.25
q	17.02	18.32	19.41	19.06	18.86	27.18	29.47	32.70	32.78	32.53	37.06
c	0.00	0.00	0.49	0.00	0.00	1.13	2.31	0.86	1.27	0.58	1.13
or	5.90	8.76	6.30	7.51	13.93	10.11	23.54	33.92	29.50	28.62	26.19
ab	40.74	37.50	40.92	41.17	48.05	38.20	28.98	27.98	32.31	35.15	33.58
an	26.15	23.18	23.57	22.71	9.99	14.75	8.02	2.29	2.40	2.27	1.39
di	0.81	0.91	0.00	0.40	1.44	0.00	0.00	0.00	0.00	0.00	0.00
wo	0.41	0.45	0.00	0.20	0.72	0.00	0.00	0.00	0.00	0.00	0.00
en	0.27	0.30	0.00	0.13	0.62	0.00	0.00	0.00	0.00	0.00	0.00
fs	0.13	0.15	0.00	0.07	0.10	0.00	0.00	0.00	0.00	0.00	0.00
hy	7.41	9.16	7.18	7.25	3.98	4.48	5.34	0.56	0.45	0.11	0.06
en	4.97	6.16	4.74	4.76	3.44	2.32	2.06	0.56	0.45	0.11	0.06
fs	2.44	3.00	2.45	2.49	0.54	2.16	3.28	0.00	0.00	0.00	0.00
mt	1.10	1.26	1.24	1.03	2.32	2.40	1.16	0.90	0.50	0.19	0.41
il	0.61	0.53	0.58	0.57	0.98	1.09	0.73	0.26	0.16	0.01	0.01
hm	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.41	0.60	0.51	0.14
ap	0.25	0.40	0.32	0.29	0.45	0.66	0.46	0.12	0.04	0.02	0.04

[1] molecular norms calculated volatile free and with Fe_2O_3/FeO adjusted according to the criteria of Irvine and Baragar (1971); all analyses by G.K. Hoops of the University of Texas at Austin except 86T15D by Barnes et al. (1942).

The "normal" Big Branch Gneiss samples are characterized by very low K_2O/Na_2O ratios (0.22–0.44), low K_2O (1.00–2.34%), high Al_2O_3 (14.90–18.14%), especially in the less silicic samples, and high MgO + FeO* (5.05–6.22%); microcline-rich *marginal phase* sample BB-1 has substantially higher K_2O/Na_2O (1.23) reflecting the higher K_2O content (3.89%) and the high modal abundance of microcline in the sample. The "normal" Big Branch Gneiss samples show a general decrease in Al_2O_3 (18.14–14.90%), CaO (5.65–2.66%), MgO (2.32–0.83%), and MgO/(MgO + FeO*) (0.37–0.14) and a slight increase in K_2O (1.00–2.34%) (Fig. 4) and TiO_2 (0.38–0.77%) with increasing SiO_2 (64.37–68.55%) and Thornton and Tuttle (1960) differentiation index (i.e., *q* + *ab* + *or*) (62.9–79.7); MgO + FeO* (6.22–5.05) remains fairly constant. These general chemical trends suggest fractionation of a Al_2O_3- and CaO-rich phase, such as plagioclase, and a ferromagnesian phase or phases.

When the Big Branch Gneiss samples are plotted on the Alkali–FeO*–MgO diagram (Fig. 5), the five most magnesian samples outline a trend subparallel to the A–M side of the triangle that is very similar to the trend of the calc-alkaline plutonic rocks of the Cascades province, northwestern U.S. (Carmichael et al., 1974). Fe-rich sample BB-6 (68.55% SiO_2 and 5.05% FeO*) lies significantly above the other samples.

When the Big Branch Gneiss data are plotted on the ternary Q–Ab–Or diagram (Fig. 2), the "normal" Big Branch Gneiss samples are clearly separated from the K-rich marginal zone sample BB-1. Since these samples contain substantial normative *an* (8.02–26.15 mol%), they cannot be adequately represented in the system

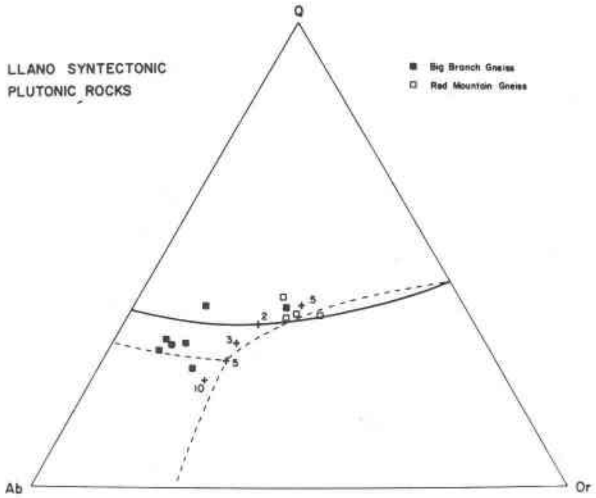

Fig. 2. Ternary Q–Ab–Or diagram on which are plotted the normative quartz, albite, and orthoclase data for the Big Branch Gneiss (*solid squares*) and the Red Mountain Gneiss (*open squares*). Weight percent used for plot. The *solid line* outlines the cotectic curve at $P_{H_2O} = 2$ kbar in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O: temperature minima for $P_{H_2O} = 0.5$, 3, 5, and 10 kbar are denoted by *plus signs* (+) (Tuttle and Bowen, 1958; Luth et al., 1964). The *dashed lines* represent the projection of the 5 kbar isobaric cotectic curves in the system $CaAl_2Si_2O_8$–$NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O, onto the Q–Ab–Or plane of the An–Ab–Or–Q tetrahedron (Carmichael, 1963).

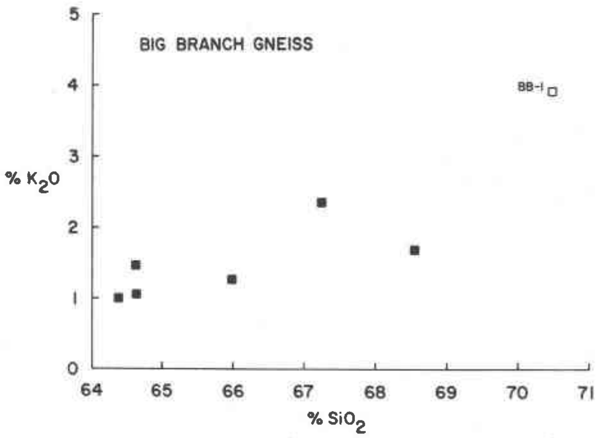

Fig. 4. Plot of weight percent K_2O versus weight percent SiO_2 for the "normal" Big Branch Gneiss samples (*solid squares*) and the microcline-rich *marginal phase* sample BB-1 (*open square*).

$NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O. They can be represented in the system $CaAl_2Si_2O_8$–$NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O (i.e, in the An–Ab–Or–Q tetrahedron). The dashed line in Figure 2 represents the projection of the 5 kbar isobaric cotectic curve, defined by the intersection of the cotectic surfaces plagioclase + quartz + liquid + vapor, plagioclase + alkali feldspar + liquid + vapor, and quartz + alkaki feldspar + liquid + vapor in the system $CaAl_2Si_2O_8$–$NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O, onto the Q–Ab–Or base of the An–Ab–Or–Q tetrahedron (Carmichael, 1963). In this system, sample BB-1 plots very close to 5 kbar isobaric cotectic curve on the plagioclase + quartz + liquid + vapor surface. The "normal" Big Branch Gneiss samples lie distinctly above the base of the tetrahedron within the plagioclase + liquid + vapor volume. The loci of the "normal" Big Branch Gneiss samples within this volume suggest that the "normal" samples cannot be related simply by fractionation of plagioclase, within this simple five component

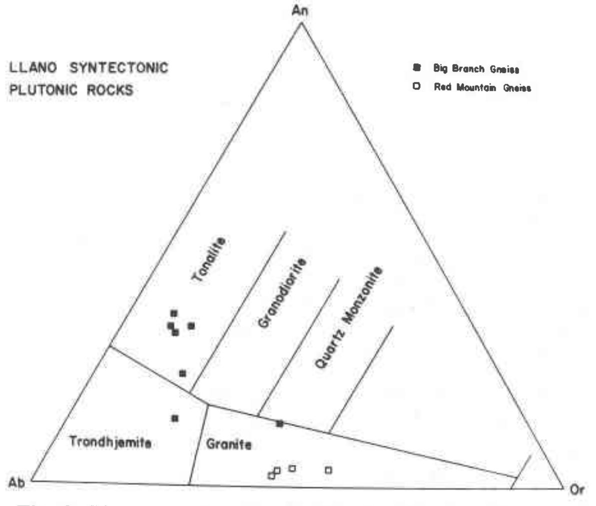

Fig. 3. The normative An–Ab–Or classification diagram for siliceous igneous rocks of O'Connor (1965), as modified by Barker (1979). The data for the Big Branch Gneiss samples are shown by *solid squares*; the Red Mountain Gneiss samples are shown by *open squares*.

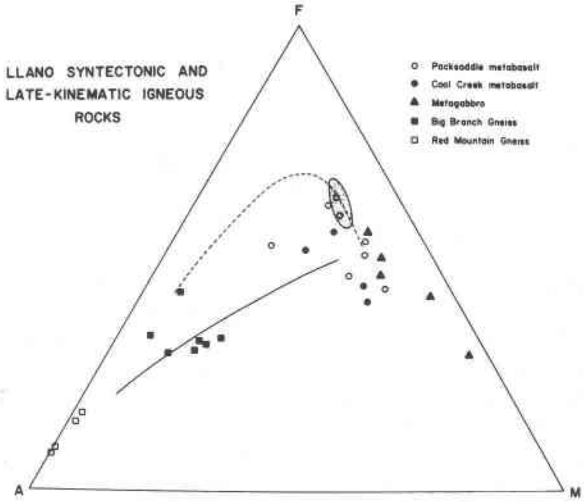

Fig. 5. Alkali–FeO*–MgO (AFM) diagram for the syntectonic and late-kinematic metaigneous rock suite of the Llano Uplift, Texas. *Solid line* outlines the trend for the Cascades province, northwestern U.S. (Carmichael et al., 1974). *Dashed line* outlines general trend for the island arc suite from Tonga (Ringwood, 1975). Strippled area is Packsaddle Schist amphibolites (Garrison, 1981b). Weight percent oxides used for plot.

Table 2. Trace element analyses of samples of Big Branch and Red Mountain Gneisses (ppm)

	BB-3	BB-6X	BB-6	BB-4	BB-1	BB-8	RM-1	RM-3	RM-4	RM-5
Sc	8	10	--	--	--	--	--	--	--	--
Cr	18	36	--	--	--	--	--	--	--	--
Co	17	19	--	--	--	--	--	--	--	--
Ni	13	25	7	15	16	13	10	15	15	13
Rb	33	31	41*	71*	150*	27	134*	286*	210*	127*
Sr	649	873	426*	287*	122*	692	69*	17*	30*	30*
Y	<15	<15	--	--	--	--	40	71	--	--
Zr	108	110	297	348	293	118	233	62	167	87
Hf	2.76	2.93	--	--	--	--	--	--	--	--
Ta	2.39	3.38	--	--	--	--	--	--	--	--
Th	3.28	6.60	--	--	--	--	--	--	--	--
La	11.82	32.04	--	--	--	--	--	--	--	--
Ce	24.32	63.20	--	--	--	--	--	--	--	--
Sm	2.07	4.15	--	--	--	--	--	--	--	--
Eu	0.64	1.08	--	--	--	--	--	--	--	--
Tb	0.20	0.32	--	--	--	--	--	--	--	--
Yb	0.58	0.66	--	--	--	--	--	--	--	--
$\|La/Sm\|_N$	3.13	4.24	--	--	--	--	--	--	--	--
$\|La/Yb\|_N$	12.40	29.34	--	--	--	--	--	--	--	--
Rb/Sr	0.051	0.036	0.096	0.247	1.230	0.039	1.942	17.00	7.00	4.233
K/Rb	319.5	393.7	342.2	273.6	215.3	322.9	348.2	137.6	193.7	283.7

* analyses by isotope dilution mass spectrometry (Garrison et al., 1979).

system; another phase, probably ferromagnesian, must also be involved. Since the least fractionated Big Branch Gneiss samples lie well within the plagioclase + liquid + vapor volume, quite a distance from the cotectic surfaces near the plagioclase-quartz side of the tetrahedron, it is unlikely that liquids of their compositions could have crystallized a significant amount of alkali feldspar. Furthermore, it is also unlikely that microcline-rich *marginal phase* samples such as BB-1 are related to the "normal" Big Branch Gneiss by simple crystal-liquid fractionation.

The Big Branch Gneiss samples have bulk compositions and K_2O/Na_2O ratios similar to those of the tonalites described from the Precambrian tonalite-trondhjemite terranes of Colorado and New Mexico (Barker et al., 1976), northeastern Minnesota (Arth and Hanson, 1975; Goldich et al., 1972), the Superior Province of Manitoba (Ermanovics et al., 1979), Scotland and eastern Greenland (Tarney et al., 1979), and Labrador (Collerson and Bridgwater, 1979). The silicic Big Branch Gneiss samples are actually quite similar in composition to the calcic trondhjemites (Barker, 1979) of these complexes, although they are somewhat too mafic (i.e., MgO + FeO* = 5.05–6.22%) to be classified as trondhjemites sensu stricto.

Trace element geochemistry

The abundances of Sc, Cr, Co, Ni, Rb, Sr, Y, Zr, Hf, Ta, and Th and the REES La, Ce, Sm, Eu, Tb, and Yb for selected samples of the Big Branch and Red Mountain Gneisses are presented in Table 2.

Red Mountain Gneiss. The Red Mountain Gneiss samples are characterized by variable Rb (127–286 ppm), Sr (17–69 ppm), Y (40–71 ppm), Zr (62–233 ppm), and K/Rb ratios (138–348); Ni (10–15 ppm) is relatively uniform. These variations do not correlate with any index of igneous differentiation such as SiO_2 or Thornton–Tuttle Index. These limited trace element data *do not necessarily* invalidate or confirm the suggestion that the Red Mountain magma underwent a minor amount of crustal-level fractionation of biotite + quartz ± alkali feldspar ± magnetite.

Trace element heterogeneity within the Red Mountain Gneiss was also observed by Garrison, et al. (1979), Rb–Sr systematics of eight samples from their study show excess scatter which they consider to be geological in origin; the Rb–Sr isotopic data scatter badly about a best-fit isochron which yields an age of 1167 ± 12 m.y. and initial $^{87}Sr/^{86}Sr$ ratio of 0.7057 ± 0.0010. They suggested that the Red Mountain Gneiss magma probably consisted of subsystems, with differing Rb and Sr (and probably Ni, Y, and Zr) concentrations, that failed to equilibrate during intrusion. They further suggested that these heterogeneous isotopic and trace element abundances may have been inherited from a heterogeneous "crustal" source. This is consistent with the initial $^{87}Sr/^{86}Sr$ ratio of 0.7057, the highest initial $^{87}Sr/^{86}Sr$ ratio of any of the syntectonic or late-kinematic metaigneous rocks in the southeastern Llano Uplift. The nearly isochronous Big Branch Gneiss has initial $^{87}Sr/^{86}Sr$ ratio = 0.7038 ± 0.002. This more mafic Big Branch Gneiss magma may have provided the heat to initiate the partial melting event that gave rise to the Red Mountain magma.

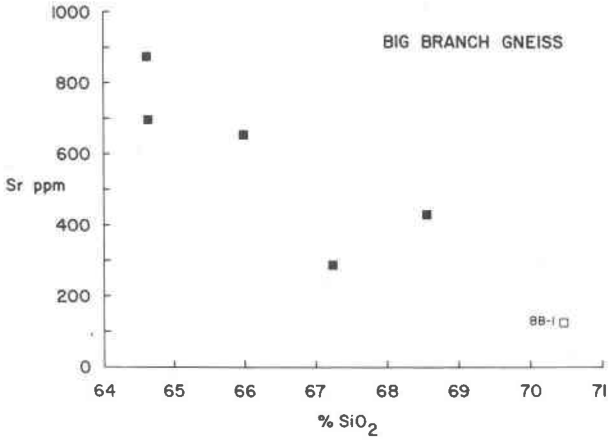

Fig. 6. Plot of ppm Sr versus weight percent SiO_2 for the "normal" Big Branch Gneiss samples (*solid squares*) and the microcline-rich *marginal phase* sample BB-1 (*open square*).

Big Branch Gneiss. The "normal" Big Branch Gneiss samples are characterized by high and variable Sr (287–873 ppm), Zr (108–348 ppm), and Rb (27–71 pm) and low Ni (7–25 ppm), Co (17–19 ppm), Cr (18–36 ppm), and Sc (8–10 ppm). These samples show a *general* decrease in Sr with increasing SiO_2 (i.e., differentiation) (Fig. 6); there is a *general* increase in Rb (Fig. 7), Zr, and Ti with increasing SiO_2. The K/Rb ratios (274–394) are relatively uniform through the entire range of SiO_2 contents. Microcline-rich *marginal phase* sample BB-1 has substantially higher Rb (150 ppm) and lower Sr (122 ppm) and K/Rb (215) than the "normal" Big Branch Gneiss samples.

The REE abundances in the Big Branch Gneiss samples BB-6X (64.62% SiO_2) and BB-2 (65.98% SiO_2), normalized to chondrites (Haskin et al., 1968), are presented in Figure 8. La abundances are 97 times chondritic in BB-6X and 36 times chondritic in BB-3. Both samples are enriched in light REEs with $|La/Sm|_N = 4.24$ and 3.13 and $|La/Yb|_N =$ 29.34 and 12.40 for BB-6X and BB-3, respectively. Neither sample exhibits a significant Eu anomaly.

Major element systematics require the fractionation of plagioclase and a ferromagnesian phase or phases. In the system "tonalite-granodiorite" at 3 kbar in the presence of excess H_2O, near liquidus phases are hornblende, plagioclase, and magnetite (Robertson and Wyllie, 1971; Gibbon and Wyllie, 1968; Piwinskii, 1968); at lower temperatures (i.e., less than 60% melt) biotite will begin to crystallize. In the absence of H_2O, clinopyroxene becomes stable on the liquidus and hornblende and biotite disappear (Robertson and Wyllie, 1971). There are several possible combinations of fractionating near-liquidus phases, each very sensitive to bulk composition, f_{O_2}, f_{H_2O}, temperature, and pressure. Since primary igneous phases are absent and the composition of the undifferentiated parent magma is not known, models for the crystal-liquid fractionation within the Big Branch magma can only be qualitatively evaluated. *Liquid line of descent* calculations and *quantitative* trace element modeling can only be considered illustrative at best. A qualitative inspection of the partition coefficients for the possible fractionating phases suggests that the major element and trace element systematics can best be explained by the fractionation of plagioclase and minor hornblende. The fractionation of substantial biotite would have the effect of decreasing K and Rb. Model *liquid line of descent* calculations, utilizing a hornblende composition most likely to be in equilibrium with a tonalitic liquid such as the Big Branch Gneiss (i.e., the hornblende in Table 40, number 27 of Deer et al., 1963), indicate that the fractionation of 25% plagioclase and minor hornblende can account for the observed major element variation of the "normal" Big Branch Gneiss samples. The absence of significant Eu anomalies in samples BB-6X and BB-3 would suggest that these samples are relatively undifferentiated and have not undergone substantial fractionation of plagioclase. These mafic Big Branch Gneiss samples may actually have compositions that approach that of the pres-

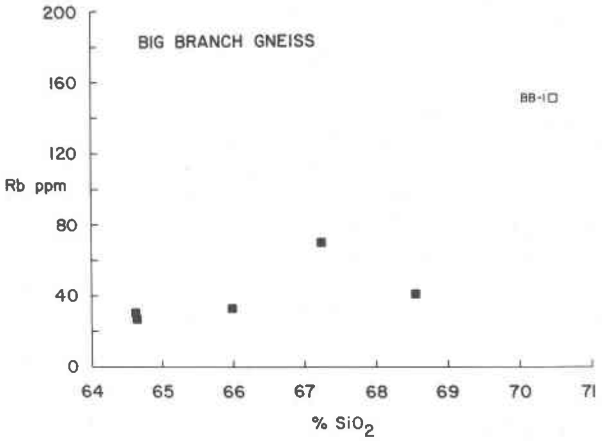

Fig. 7. Plot of ppm Rb versus weight percent SiO_2 for the "normal" Big Branch Gneiss samples (*solid squares*) and the microcline-rich *marginal phase* sample BB-1 (*open square*).

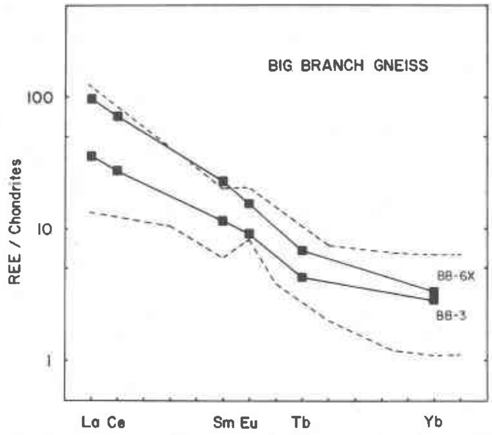

Fig. 8. Plot of chondrite-normalized REE abundances for two samples of Big Branch Gneiss. Dashed lines outline the range of tonalites and trondhjemites from Finland and Norway (Arth and Barker, 1976).

ent magma. At best, the major element and trace element data are *not inconsistent* with minor in situ "crustal-level" fractionation of plagioclase and minor hornblende.

The Big Branch Gneiss samples have Rb, Sr, Zr, Ni, and Cr abundances and K/Rb ratios similar to those of the tonalites from the Precambrian tonalite-trondhjemite terranes (i.e., Barker et al., 1976; Ermanovics et al., 1979; and Collerson and Bridgwater, 1979). The REE patterns of the two Big Branch Gneiss samples are similar to the fractionated REE patterns, with low heavy REE content and small or no Eu anomalies, of "high-Al_2O_3" trondhjemites such as the Kroenke Granodiorite and the Pitts Meadow Granodiorite of Colorado (Barker, et al., 1976) (Fig. 8).

Discussion

Origin of the Big Branch Gneiss

Hypotheses to explain the origin of "high-Al_2O_3" tonalite–trondhjemite suites (Barker, 1979), similar to the Big Branch Gneiss, have been constrained by trace element systematics, particularly the heavy REE-depleted chondrite–normalized REE patterns (Arth, 1979). These heavy REE-depleted patterns require that garnet and/or hornblende be a residual phase during partial melting or crystallization (i.e., Arth and Barker, 1976). This REE pattern was first observed for the Saganaga Tonalite by Haskin et al., (1968). A variety of models for the genesis of "high-Al_2O_3" tonalite–trondhjemite suites have been proposed: (1) fractional crystallization of tonalite from gabbroic liquid involving hornblende as a fractionating phase (Arth et al., 1978), (2) partial melting of amphibolite at less than 60 km depth leaving a hornblende-rich residuum (Arth and Barker, 1976; Barker and Arth, 1976), (3) partial melting of amphibolite or eclogite at depths greater than 70 km leaving a clinopyroxene + garnet (i.e., eclogite) residuum (Hanson and Goldich, 1972; Arth and Hanson, 1972; Barker et al., 1976), and (4) partial melting of amphibolitic "crustal" material (i.e., hornblende–plagioclase–biotite–quartz gneiss) at 20–25 km depth leaving a hornblende-rich residuum (i.e., Lappin and Hollister, 1980).

A fractional crystallization model was proposed by Arth, et al., (1978) and Hietanen (1943) to explain the origin of the tonalites and trondhjemites of the Uusikaupunki-Kalanti area, southwest Finland. They suggested that the tonalites were derived by fractionation of hornblende from a gabbroic liquid and that the more silicic trondhjemites could be derived by further fractionation of biotite and plagioclase, as well as hornblende. Such a fractional crystallization model cannot be supported for the Big Branch Gneiss tonalite because: (1) no compositions between gabbro and tonalite are represented within the Llano Uplift at the present level of exposure, (2) metabasalts and metagabbros within the study areas appear to have undergone only minor amounts of crustal level fractionation (Garrison, 1981b), and (3) the Big Branch Gneiss tonalite has a distinctly higher initial $^{87}Sr/^{86}Sr$ ratio than the metabasalt–metagabbro suite exposed within the Llano Uplift (Garrison, 1981b; Garrison, et al., 1979).

The Rb–Sr isotopic systematics of the Big Branch Gneiss tonalite clearly indicate that the Big Branch Gneiss tonalite could not have been derived by fractional crystallization from a gabbroic parent similar to those presently exposed within the Llano Uplift. Garrison (1981b) found that the metabasalt-metagabbro suite plotted along an Rb–Sr isochron that yielded an age of 1176 ± 77 m.y. with initial $^{87}Sr/^{86}Sr = 0.7029 \pm 0.0001$. Garrison (1981b) further suggested that metabasalts and metagabbros were derived by partial melting of undepleted mantle material with $^{87}Sr/^{86}Sr = 0.7029$ and $Rb/Sr = 0.029$. Although the 1167 ± 12 m.y. Rb–Sr isochron age for the Big Branch Gneiss is similar to that obtained for the metabasalt–metagabbro suite, the initial $^{87}Sr/^{86}Sr$ ratio of the Big Branch Gneiss (0.7038 ± 0.0002) is distinctly different from the metabasalt-metagabbro suite, at the 95% confidence level. Therefore, it follows that the Big Branch Gneiss tonalite could not have been derived by fractionation from a parent magma derived by simple partial melting of sub-Llano mantle material. Peterman (1979) found that tonalite-trondhjemite suites have low initial $^{87}Sr/^{86}Sr$ ratios that indicate either direct or indirect mantle derivation; the initial $^{87}Sr/^{86}Sr$ ratios define a single-stage mantle growth curve with $Rb/Sr = 0.025$, quite similar to the values postulated by Garrison (1981b) for the sub-Llano mantle. The Rb–Sr isotopic systematics of the Big Branch Gneiss would require a mantle source to have followed a growth curve with $Rb/Sr = 0.035$, a value well outside the Peterman (1979) growth curve, at the 99% confidence level. In this respect, the Big Branch Gneiss is unlike the tonalites from the Precambrian tonalite–trondhjemite suites. A fractional crystallization model for the derivation of the Big Branch Gneiss tonalite, similar to that proposed by Arth et al., (1978) for the southwest Finland suite, can still be considered a possibility if it is assumed that a ^{87}Sr-enriched parent magma did exist but is not exposed at the present level of erosion in the Llano Uplift. It also follows that, since the Sr evolution curve for the Big Branch Gneiss departs from the mantle growth curve (i.e., a multi-stage evolution), that the Big Branch Gneiss magma inherited some crustal-level Sr, either from oceanic or continental crustal material.

Many workers have invoked models in which 10–35% partial melting of basaltic material, of either amphibolitic, gabbroic, or eclogitic mineralogy to produce "high-Al_2O_3" tonalite–trondhjemite melts, leaving residua consisting of clinopyroxene, garnet and/or hornblende (Barker, et al., 1976; Arth and Hanson, 1972; Hanson and Goldich, 1972; Arth and Hanson, 1972; Rollinson and Windley, 1980; Tarney et al., 1979). The high Sr contents and lack of Eu anomalies in these "high-Al_2O_3" tonalite–trondhjemite suites make it necessary that plagioclase was not a residual phase. Experimental work by Stern and Wyllie (1978) has documented that 20% partial melting at 30 kbar (5% H_2O) of a quartz eclogite of abyssal tholeitte composition will produce a tonalitic liquid (62.3% SiO_2, $K_2O/Na_2O = 0.19$, 22.7% Al_2O_3, and ($FeO^* + MgO$) = 2.5%) leaving kyanite eclogite. Experimental studies of Wyllie (1971,

1979) and Lambert and Wyllie (1974) have shown that hornblende is stable in tonalitic liquids only up to pressures of about 22 kbar. Thus, whether the residuum is eclogitic or amphibolitic is a function of depth of magma geneiss. The high Al_2O_3 and Sr contents and the lack of a significant Eu anomaly in the Big Branch Gneiss samples indicate that plagioclase was not a residual phase; the heavy REE depletion requires the residuum to contain substantial garnet and/or hornblende. The high Co abundances and K/Rb ratios in the two Big Branch samples analyzed, both of which appear to be relatively unfractionated, argue that hornblende was, if present at all in the residuum, only a minor phase.

Lappin and Hollister (1980) suggested the tonalitic plutons within the Coast Plutonic Complex of British Columbia could be produced by crustal-level partial melting, at pressures of 6–8 kbar, of amphibolitic gneiss. They described a melt-producing reaction in which a hornblende–plagioclase–biotite–quartz gneiss would produce a tonalitic melt (57.47% SiO_2, 22.75% Al_2O_3, $(FeO^* + MgO) = 4.37\%$, and $K_2O/Na_2O = 0.19$) and a residuum of quartz + hornblende + plagioclase. This melt has a major element chemical composition quite different from the tonalites from the tonalite–trondhjemite suites and the Big Branch Gneiss. Since trace element data are lacking for the tonalite described by Lappin and Hollister (1980), trace element comparisons cannot be made, although it is clear that the melt would exhibit a Eu anomaly and probably low Sr and high Rb contents, in contrast to the trace element systematics exhibited by most "high-Al_2O_3" tonalite–trondhjemite suites and the Big Branch Gneiss.

On balance, the major and trace element systematics of the Big Branch Gneiss is best explained by a model in which the Big Branch Gneiss magma was produced by about 20% partial melting of a basaltic parent, either hornblende eclogite or quartz eclogite, at mantle depths, leaving a residuum of clinopyroxene + garnet ± hornblende. It is not possible to evaluate this model quantitatively and trace element models can only be considered illustrative at best because: (1) the exact nature and modal composition of the residuum is not known, (2) garnet/liquid partition coefficients are not well known (i.e., Irving and Frey, 1978), (3) the degree of late-stage modification of the trace element systematics of the most primitive Big Branch Gneiss samples by crustal-level crystal fractionation is not known, and (4) the nature and degree of contamination and hybridization by seawater, oceanic sediments, and crustal materials are not known (e.g., Kay, 1980). Simple qualitative model calculations suggest that the basaltic parental source material probably had REE abundances (15–40 times chondritic) and lithophile element abundances similar to basalts from ocean basins (e.g., Kay, 1977; Kay and Hubbard, 1978; Gill, 1976) and ophiolite complexes (e.g., Garrison, 1981b).

Depth and nature of partial melting. The major element and trace element systematics discussed above indicate that the Big Branch Gneiss magma was probably produced by about 20% partial melting of hornblende eclogite or quartz eclogite leaving the residual assemblage clinopyroxene + garnet ± hornblende; plagioclase was not a residual phase. Based on this information and the experimental work of Wyllie and co-workers (Wyllie, 1971, 1977, 1979; Stern, et al., 1975; Stern and Wyllie 1978; Lambert and Wyllie, 1974), it is possible to place some constraints on the depth of the partial melting event. If we assume that plagioclase was not stable in the tonalitic liquid at the depth of partial melting, the upper limit of plagioclase stability constrains the minimum depth of magma generation to be about 55 km, corresponding to a pressure of about 16 kbar. If hornblende is indeed a stable phase of the residual assemblage, the maximum stability of hornblende in tonalitic liquid constrains the maximum depth of the partial melting event to be less than 70 km, corresponding to a pressure of about 22 kbar. If the residual assemblage contains only clinopyroxene and garnet, the partial melting event occurred at depths greater than about 70 km.

Barker et al. (1976) suggested that the 1.7 b.y. old "high-Al_2O_3" Kroenke Granodiorite of the New Mexico–Colorado tonalite–trondhjemite terrane is chemically similar to Jurassic trondhjemite of the Klamath Mountains, California, and that the New Mexico–Colorado terrane may have formed in a similar tectonic environment—a continental margin subduction zone. Since many of the features and rock associations indicative of modern convergent plate margins were absent from the Colorado–New Mexico terrane, Barker et al. (1976) abandoned this model in favor of a model, similar to that proposed by Arth and Hanson (1972) for Archaen tonalites and trondhjemites of northwestern Minnesota, in which tectonics are dominated by *vertical* motion and partial melting of amphibolite and eclogite at the bases of foundering basaltic volcanic piles.

Since Garrison (1981a, 1981b) has provided evidence that the Precambrian orogenic event that affected the Llano rocks was coupled to brittle plate-tectonic processes, it follows that the production of the Big Branch Gneiss magma can be related to a plate tectono-magmatic process such as subduction and island arc development. Any model developed to explain the nature of the partial melting process must consider the following deductions: (1) chemically the source material had 15–40 times chondritic REE abundances and trace element abundances similar to ocean basin basalts (3) the magma had initial $^{87}Sr/^{86}Sr = 0.7038$, a value significantly higher than the 0.7029 ratio of sub-Llano mantle, and (4) the partial melting event occurred at a depth greater than 55 km, probably between 55 km and 70 km.

In a subduction model, the tonalitic Big Branch Gneiss magma could be generated by partial melting of (1) eclogitic portions of mantle material in the wedge above the subducted oceanic slab, or (2) basaltic portions of subducted oceanic crust. Model 2 is favored over model 1 because: (1) hornblende eclogite and quartz eclogite are extremely rare mantle materials (Ringwood, 1975; Mathias et al., 1970), (2) the trace element systematics indicate source material quite unlike normal mantle materials, and (3) the Big Branch Gneiss magma had initial $^{87}Sr/^{86}Sr$ ratio higher than sub-Llano mantle, although minor crustal contamination could also have augmented this ratio.

A magma generated by partial melting of subducted oceanic crust can either ascend to the surface in its original state (Ringwood, 1977) or it may react with overlying mantle peridotite to produce a hybrid pyroxenite zone that subsequently undergoes partial melting (i.e., Nicholls and Ringwood, 1973; Ringwood, 1974, 1975, 1977; Kay, 1977, 1980). Sekine and Wyllie (1982) modeled the hybridization between siliceous magmas and peridotite within the mantle wedge above the subducted slab and found that magmas produced by partial melting of the hybrid pyroxenite zone would leave residua of phlogopite–pyroxenite or phlogopite–garnet–websterite. Since the Big Branch Gneiss has trace element systematics suggesting an eclogitic residuum, it is likely that the Big Branch Gneiss tonalite magma ascended through the mantle wedge above the Benioff zone without significant hybridization.

Origin of the microcline-rich phase of the Big Branch Gneiss. The high alkali content of the microcline-rich *marginal phase* of the Big Branch Gneiss (e.g., sample BB-1) could be the result of: (1) mixing of the Big Branch Gneiss and Red Mountain Gneiss magmas as they ascended through the geosynclinal pile, (2) assimilation of felsic material along this particular margin of the Big Branch Gneiss pluton, or (3) alkali metasomatism effected by the adjacent Red Mountain Gneiss magmas as proposed by Clabaugh and Boyer (1961). As discussed earlier, it is unlikely that the microcline-rich *marginal phase* rocks are related to the "normal" Big Branch Gneiss by simple crystal-liquid fractionation. Blaxland (1975) concluded that a maximum alkali enrichment of 40% occurred near the contact of the Big Branch Gneiss with the Red Mountain Gneiss. Model least-square *liquid line of descent* calculations indicate that a microcline-rich sample such as BB-1 may have experienced as high as 75–100% K_2O-enrichment.

To account for the observed major element composition of *marginal phase* sample BB-1 by mixing of relatively undifferentiated Big Branch Gneiss magma (e.g., BB-6X) with Red Mountain Gneiss magma (e.g., RM-3) requires that the Big Branch Gneiss magma and Red Mountain Gneiss magma mix in proportions of 1.9 to 1, respectively. Mass-balance calculations for Rb and Sr reveal that the observed Rb and Sr abundances in *marginal phase* sample BB-1 cannot be explained by this simple magma mixing model; the observed Sr abundance is lower by a factor of two than that produced by magma mixing. Even mixing of differentiated Big Branch Gneiss magma (i.e., BB-6) with Red Mountain Gneiss magma fails to explain the observed trace element abundances.

Assimilation of felsic material by the Big Branch Gneiss magma to produce the hybrid microcline-rich *marginal phase* cannot be ruled out, since quartz feldspar rocks are widespread in the *lower* and *middle* Packsaddle Schist. Because of the lack of quantitative major and trace element data for these quartz-feldspar rocks, it is only possible to examine this model qualitatively. To explain the composition of the *marginal phase* rocks by assimilation of quartz-feldspar rocks, as in the case of magma mixing, requires that the Big Branch Gneiss magma mix with large amounts of quartz-feldspar rock. Assimilation of such large amounts of country rock would probably lead to major element, trace element, and Sr-isotopic characteristics other than those observed in the hybrid *marginal phase* rocks. Garrison et al., (1979) found that the Sr isotopic system of the Big Branch Gneiss appears to have been undisturbed; the Sr isotopic data permit a gain of Rb and loss of Sr from the system, but not the addition of Sr as might be expected from hybridization by magma mixing or assimilation.

The major element, trace element, and Sr isotopic data for samples of microcline-rich *marginal phase* Big Branch Gneiss (Garrison, 1979; Garrison et al., 1979; Blaxland, 1975) are probably on balance, best explained by a metasomatic process coupled to the near isochronous emplacement of the Big Branch Gneiss and Red Mountain Gneiss magmas.

Summary and geologic model

Models previously developed for rocks in the southeastern Llano Uplift, Texas have implied that brittle plate tectonics processes were operative during the 1.0–1.2 b.y. orogenic event that affected the Llano terrane (Garrison, 1981a, 1981b, 1982). Garrison (1981b) suggested that the Packsaddle Schist sequence, which includes the Big Branch and Red Mountain Gneiss, represents a thick sequence of island arc-flank metasediments and that the uppermost portion of these metasediments represents melange containing large olistostromal blocks, including serpentinized peridotite and ophiolitic debris derived from ophiolitic material exposed proximal to the island arc. The syntectonic and late-kinematic metabasalts and metagabbros that occur within the metasediments represent moderately Fe-rich, low- to medium-K_2O tholeiitic basalts, similar in composition to present-day island arc tholeiitic basalts, generated by partial melting of undepleted mantle material above the Benioff zone. Compositions of hornblende schists within the Packsaddle Schist sequence suggest that the protolith materials were basaltic volcaniclastic materials with strong tholeiitic affinities. The geologic model developed for these rocks is an island arc/subduction model in which events from early island arc development to final late-kinematic intrusion were dominated by tholeiitic volcanism and intrusion.

The occurrence of the syntectonic Big Branch and Red Mountain Gneisses within the volcaniclastic metasediments of the Packsaddle Schist coupled with the geochemical data discussed above indicate that the Big Branch Gneiss and Red Mountain Gneiss magmas were generated in response to island arc magmatic processes related to brittle plate subduction. The Big Branch Gneiss magma was generated by about 20% partial melting of basaltic portions of subducted oceanic crust at a depth greater than 55 km, leaving residual eclogite. The Big Branch Gneiss magma was emplaced into the lower portions of the island arc complex about 1167 ± 12 m.y. ago, and upon emplacement to depths of 12–15 km, underwent in situ fractionation of plagioclase and minor hornblende, possibly aided by tectonic filterpressing. As the voluminous Big Branch Gneiss magma ascended through the lower portion of the island arc complex, it caused local partial melting of felsic portions of the volcanic and volcaniclastic materials to produce the granitic Red Mountain Gneiss magma, which was emplaced as sill-like bodies only slightly later than the Big Branch Gneiss magma. Upon emplacement proximal to the Big Branch Gneiss pluton, the Red Mountain Gneiss magma underwent a minor amount of in situ fractionation of biotite + quartz ± alkali feldspar ± magnetite.

Acknowledgments

Suggestions and criticisms of D. Smith, S. E. Clabaugh, J. C. Maxwell, D. S. Barker, and L. E. Long are gratefully acknowledged. G. K. Hoops of The University of Texas at Austin kindly performed the major element whole-rock chemical analyses. L. Tiezzi performed INAA data reduction. Financial support for this project was provided by the Geology Foundation of the University of Texas at Austin and by Geological Society of America Research Grant 2191-77. D. S. Barker and F. W. McDowell reviewed an earlier version of this manuscript.

References

Arth, J. G. (1979) Some trace elements in trondhjemites—their implications to magma genesis and paleotectonic setting. In F. Barker, Ed., Trondhjemites, Dacites, and Related Rocks, p. 123–132. Elsevier, New York.

Arth, J. G. and Barker, F. (1976) Rare-earth partitioning between hornblende and dacitic liquid and implications for the genesis of trondhjemitic–tonalitic magmas. Geology, 4, 534–536.

Arth, J. G. and Hanson, G. N. (1972) Quartz diorites derived by partial melting of eclogite or amphibolite at mantle depths. Contributions to Mineralogy and Petrology, 37, 161–174.

Arth, J. G. and Hanson, G. N. (1975) Geochemistry and origin of the early Precambrian crust of northeastern Minnesota. Geochimica et Cosmochima Acta, 39, 325–363.

Arth, J. G., Barker, F., Peterman, Z. E., and Friedman, I. (1978) Geochemistry of the gabbro–tonalite–trondhjemite suite of southwest Finland and its implications for the origin of tonalitic and trondhjemitic magmas. Journal of Petrology, 19, 289–316.

Barker, F. (1979) Trondhjemites: definition, environment and hypotheses or origin. In F. Barker, Ed., Trondhjemites, Dacites, and Related Rocks, p. 1–12. Elsevier, New York.

Barker, F. and Arth, J. G. (1976) Generation of trondhjemitic–tonalitic liquids and Archean biomodal trondhjemite–basalt suites. Geology, 4, 596–600.

Barker, F., Arth, J. G., Peterman, Z. E. and Friedman, I. (1976) The 1.7- to 1.8-b.y.-old trondhjemites of southwestern Colorado and northern New Mexico: geochemistry and depths of genesis. Geological Society of America Bulletin, 87, 189–198.

Barnes, V. E. (1945) Soapstone and serpentine in the Central Mineral region of Texas, University of Texas Publication, 4301, 55–91.

Barnes, V. E., Dawson, R. F., and Parkinson, G. A. (1942) Building stones of central Texas. University of Texas Publication, 4246, 1–198.

Barnes, V. E., Schock, D. A., and Cunningham, W. A. (1950) Utilization of Texas serpentine. University of Texas Publication, 5020, 1–52.

Blaxland, A. B. (1975) Metasomatism of the Big Branch Gneiss by the Red Mountain Gneiss, Llano Country, Texas. Texas Journal of Science, 26, 391–399.

Burnitt, S. C. (1961) Geology of the Red Mountain area, Llano, Gillespie, and Blanco Counties, Texas. M.A. Thesis, The University of Texas, Austin.

Carmichael, I. S. E. (1963) The crystallization of feldspar in volcanic acid liquids. Quarterly Journal of the Geological Society of London, 119, 95–131.

Carmichael, I. S. E., Turner, F. J., and Verhoogen, J. (1974) Igneous Petrology. McGraw-Hill, New York.

Clabaugh, S. E. and Boyer, R. E. (1961) Origin and structure of the Red Mountain Gneiss, Llano County, Texas. Texas Journal of Science, 13, 7–16.

Collerson, K. D. and Bridgwater, D. (1979) Metamorphic development of Early Archean tonalitic and trondhjemitic gneisses: Saglek Area, Labrador. In F. Barker, Ed., Trondhjemites, Dacites, and Related Rocks. p. 205–273. Elsevier, New York.

Deer, W. A., Howie, R. A., and Zussman, J. (1963) Rock-Forming Minerals, Vol. 2, Chain Silicates. Longman, London.

Droddy, M. J. (1978) Metamorphic rocks of the Fly Gap Quadrangle, Mason County, Texas, Ph.D. Dissertation, The University of Texas, Austin.

Ermanovics, I. F., Ritchie, W. D., and Houston, W. N. (1979) Petrochemistry and tectonic setting of plutonic rocks of the Superior Province in Manitoba. In F. Barker, Ed., Trondhjemites, Decites, and Related Rocks, p. 323–362. Elsevier, New York.

Garrison, J. R., Jr. (1979) Petrology and geochemistry of the Precambrian Coal Creek serpentinite mass and associated metamorphosed basaltic and intermediate rocks, Llano Uplift, Texas. Ph.D. Dissertation, The University of Texas, Austin.

Garrison, J. R., Jr. (1981a) Coal Creek serpentinite Llano Uplift, Texas: A fragment of an incomplete Precambrian ophiolite. Geology, 9, 225–230.

Garrison, J. R., Jr. (1981b) Metabasalts and metagabbros from the Llano Uplift, Texas: petrologic and geochemical characterization with emphasis on tectonic settng. Contributions to Mineralogy and Petrology, 78, 459–475.

Garrison, J. R., Jr. (1982) Comment and reply on "Coal Creek serpentinite, Llano Uplift, Texas: a fragment of an incomplete precambrian ophiolite": Reply. Geology, 10, 441–442.

Garrison, J. R., Jr., Long, L. E., and Richmann, D. L. (1979) Rb–Sr and K–Ar geochronologic and isotopic studies, Llano Uplift, Texas. Contributions to Mineralogy and Petrology, 69, 361–374.

Gibbon, D. L. and Wyllie, P. J. (1969) Experimental studies of igneous rock series: the Farrington Complex, North Carolina, and the Star Mountain Rhyolite, Texas. Journal of Geology, 77, 221–239.

Gill, J. G. (1976) Composition and age of Lau Basin and Ridge volcanic rocks: implications for evolution of an interarc basin and remnant arc. Geological Society of America Bulletin, 87, 1384–1395.

Goldich, S. S. (1941) Evolution of the central Texas granites. Journal of Geology, 49, 697–720.

Goldich, S. S., Hanson, G. N., Hallford, C. R., and Mudrey, M. G., Jr. (1972) Early Precambrian rocks in the Saganaga Lake-Northern Light Lake area, Minnesota-Ontario Part I. Petrology and structure. In B. R. Doe and D. K. Smith, Eds., Studies in Mineralogy and Precambrian Geology, p. 151–177. Geological Society of America Memoir 135.

Hanson, G. N. and Goldich, S. S. (1972) Early Precambrian rocks in the Saganaga Lake-Northern Light Lake Area, Minnesota-Ontario Part II. Petrogenesis. In B. R. Doe and D. K. Smith, Eds., Studies in Mineralogy and Precambrian Geology, p. 179–192. Geological Society of America Memoir 135.

Haskin, L. A., Hasin, M. A., Frey, F. A., and Wildeman, T. R.

(1968) Relative and absolute terrestrial abundances of the rare earths. In L. H. Ahrens, Ed., Origin and Distribution of the Elements, p. 889–912. Pergamon, New York.

Hietanen, A. (1943) Uber das Grundgebirge des Kalantigebietes im sudwestlichen Finnland. Bulletin de la Commission Géologíque de Finlande, 130.

Irvine, T. N. and Baragar, W. R. A. (1971) A guide to the chemical classification of the common volcanic rocks. Canadian Journal of Earth Science, 8, 523–548.

Irving, A. J. and Frey, F. A. (1978) Distribution of trace elements between garnet megacrysts and host volcanic liquids of kimberlitic to rhyolitic composition. In M. J. Drake and J. R. Holloway, Eds., Experimental Trace and Element Geochemistry, p. 771–787. Geochimica et Cosmochimica Acta, 42.

Kay, R. W. (1977) Geochemical constraints on the origin of Aleutian magmas. In M. Talwani and W. C. Pitman III, Eds., Island Arcs Deep Sea Trenches and Back-Arc Basins, p. 229–242. American Geophysical Union, Washington, D. C.

Kay, R. W. (1980) Volcanic arc magmas: implications of a melting-mixing model for element recycling in the crust-upper mantle system. Journal of Geology, 88, 497–522.

Kay, R. W. and Hubbard, N. J. (1978) Trace elements in ocean ridge basalts. Earth and Planetary Science Letters, 38, 95–116.

Lambert, I. B. and Wyllie, P. J. (1974) Melting of tonalite and crystalization of andesite liquid with excess H_2O to 30 kilobars. Journal of Geology 82, 88–97.

Lappin, A. R. and Hollister, L. S. (1980) Partial melting in the Central Gneiss Complex near Prince Rupert, British Columbia. American Journal of Science, 280, 518–545.

Luth, W. C., Jahns, R. H., and Tuttle, O. F. (1964) The granite system at pressures of 4 to 10 kilobars. Journals of Geophysical Research, 69, 759–773.

Mathias, M. J., Siebert, J., and Rickwood, P. (1970) Some aspects of the mineralogy and petrology of ultramafic xenoliths in kimberlite. Contributions to Mineralogy and Petrology, 26, 75–123.

McGehee, R. V. (1963) Precambrian geology of the southeastern Llano Uplift, Texas. Ph.D Dissertation, The University of Texas, Austin.

Miyashiro, A. (1961) Evolution of metamorphic belts. Journal of Petrology, 2, 277–311.

Mutis-Duplat, E. (1972) Stratigraphic sequences and structure of Precambrian metamorphic rocks in Purdy Hill Quadrangle, Mason County, Texas. Ph.D. Dissertation, the University of Texas, Austin.

Nicholls, I. A. and Ringwood, A. E. (1973) Effect of water on olivine stability in tholeiites and the production of silica-saturated magmas in the island arc environment. Journal of Geology, 81, 285–300.

O'Connor, J. T. (1965) A classification of quartz-rich igneous rocks based on feldspar ratios. U.S. Geological Survey Professional Paper, 525-B, 79–84.

Peterman, Z. E. (1979) Strontium isotope geochemistry of Late Archean to Late Cretaceous tonalites and trondhjemites. In F. Barker, Ed., Trondhjemites, Dacites, and Related Rocks, p. 133–147. Elsevier, New York.

Piwinskii, A. J. (1968) Experimental studies of igneous rock series, central Sierra Nevada batholith, California, Journal of Geology, 76, 548–570.

Piwinskii, A. J. and Wyllie, P. J. (1968) Experimental studies of igneous rock series; a zoned pluton in the Wallowa batholith, Oregon. Journal of Geology, 76, 205–234.

Richmann, D. L. (1977) Rb–Sr ages of the Red Mountain and Big Branch Gneisses, Llano Uplift, Central Texas. M.A. Thesis, The University of Texas, Austin.

Ringwood, A. E. (1974) The petrological evolution of island arc systems. Journal of the Geological Society of London, 130, 183–294.

Ringwood, A. E. (1975) Composition and Petrology of the Earth's Mantle. McGraw-Hill, New York.

Ringwood, A. E. (1977) Petrogenesis in island arc systems. In M. Talwani and W. C. Pitman III, Eds., Island Arcs Deep Sea Trenches and Back-Arc Basins, p. 311–324. American Geophysical Union, Washington, D.C.

Robertson, J. K. and Wyllie, P. J. (1971) Experimental studies on rocks from the Deboullie Stock, Northern Maine, including melting relations in the water deficient environment. Journal of Geology, 79, 549–571.

Rollinson, H. R. and Windley, B. B. (1980) An Archean granulite-grade tonalite–trondhjemite–granite suite from Scourie, N.W. Scotland: Geochemistry and Origin. Contributions to Mineralogy and Petrology, 72, 265–281.

Sekine, R. and Wyllie, P. J. (1982) Synthetic systems for modeling hybridization between hydrous siliceous magmas and periodotite in subduction zones. Journal of Geology, 90, 734–741.

Shapiro, L. (1975) Rapid analysis of silicate, carbonate and phosphate rocks, revised edition. U.S. Geological Survey Bulletin, 1401, 1–76.

Shapiro, L. and Brannock, W. (1962) Rapid analysis of silicate, carbonate, and phosphate rocks. U.S. Geological Survey Bulletin, 1144-A, 1–56.

Stern, C. R. and Wyllie, P. J. (1978) Phase compositions through crystallization intervals in basalt–andesite–H_2O at 30 kbar with implications for subduction zone magmas. American Mineralogist, 63, 641–663.

Stern, C. R., W. L. Huang, and Wyllie, P. J. (1975) Basalt–andesite–rhyolite–H_2O: crystallization intervals with excess H_2O and H_2O-undersaturated liquids surfaces to 35 kilobars with implications for magma genesis. Earth and Planetary Science Letters, 28, 189–196.

Tarney, J., Weaver, B., and Drury, A. A. (1979) Geochemistry of Archean trondhjemitic and tonalitic gneisses from Scotland and East Greenland. In F. Barker, Ed., Trondhjemites, Decites, and Related Rocks, p. 275–299. Elsevier, New York.

Thornton, C. P. and Tuttle, O. F. (1960) Chemistry of igneous rocks. I. Differentiation index. American Journal of Science, 258, 664–684.

Tiezzi, L. J. (1981) Petrogenesis of basalts from the Mid-Atlantic Ridge 26°N. Ph.D. Dissertation, Texas A & M University, College Station.

Tuttle, O. F. and Bowen, N. L. (1958) Origin of granite in the light of experimental studies in the system $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O. Geological Society of America Memoir 74, 1–53.

Whitney, J. A. (1975) Phase assemblages in four synthetic rock compositions. Journal of Geology, 83, 1–31.

Winkler, H. G. F. (1979) Petrogenesis of Metamorphic Rocks (4th Edition). Springer-Verlag, New York.

Wyllie, P. J. (1971) Experimental limits for melting in the earth's crust and upper mantle. In The Structure and Physical Properties of the Earth's Crust. American Geophysical Union Monograph, 14, 279–301.

Wyllie, P. J. (1977) Crustal Anatexis: an experimental review. Tectonophysics, 43, 41–71.

Wyllie, P. J. (1979) Magmas and volatile components. American Mineralogist, 64, 469–500.

Manuscript received, January 29, 1982;
accepted for publication, July 2, 1985.