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Role of water in the formation of granulite and amphibolite facies rocks Tobacco Root Mountains Montana

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THE ROLE OF WATER IN THE FORMATION OF GRANULITE AND AMPHIBOLITE FACIES ROCKS, TOBACCO ROOT MOUNTAINS, MONTANA

By

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Archaean granulite facies rocks in the Tobacco Root Mountains are restricted to mafic lithologies and intimately mixed with amphibolite facies rocks. Mineral assemblages in the granulites include hypersthene-plagioclase-hornblende, hypersthene-diopside-plagioclase-hornblende, and diopside-garnet-plagioclase-quartz±hornblende. Mafic amphibolite facies assemblages include hornblende-plagioclase and hornblende-diopside-plagioclase. Adjacent pelitic, quartzofeldspathic and calcic rocks lack the diagnostic minerals necessary to unequivocally place them in the granulite facies.

A low activity of water in the mafic rocks is responsible for this mixed pattern of metamorphic facies. The low activity of water may be due to internal buffering of melting reactions at a very local scale. Evidence of partial melting is present in both mafic and pelitic rocks. This transitional granulite facies event may have been initiated by magmatic heating of the lower crust triggered by the intrusion of abundant mafic dikes and plutons.

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1. INTRODUCTION

1.1 Introduction

Most granulite terrains occur in Precambrian shield areas where erosion has exposed the lower crust. In southern India workers have documented a transition zone from amphibolite to granulite facies where the metamorphic gradient is an unbroken prograde transition (Hansen and others, 1984). In South Africa granulite facies assemblages are restricted to particular lithologic horizons within a metasedimentary sequence (Waters and Whales, 1984). In New Zealand, retrograded granulite facies basement rocks and amphibolite facies cover rocks are separated by a major thrust fault (Oliver, 1980). In Greenland metadolerites exhibit a high degree of modal and paragenetic variation, consisting of amphibolite and granulite facies assemblages (Glassley and Sorensen, 1980).

Granulite facies metamorphism requires high temperature, moderate to high pressure, and low activity of water. There is widespread disagreement on the exact mechanism which produces this low activity of water. Powell (1983), Condie and others (1982), and Water and Whales (1984) all believe that granulites result as the refractory residual from partial melting. Newton and others (1980), Hansen and others (1984), and Holt and Wightman (1983) prefer pervasive "flooding" of CO2-rich fluids as the mechanism which lowers the activity of water. In this paper I hope to elucidate the mechanism responsible for granulite facies metamorphism in the southern Tobacco Root Mountains of southwestern Montana.

The Tobacco Root Mountains lie on the western edge of the Wyoming Archaean Province and are one of series of uplifted mountain ranges which are cored by quartzofeldspathic and amphibolitic gneisses (Figures 1 and 2). Original rock types include mafic sills and flows, ultramafic bodies, turbidites, calcareous shales, quartz-rich sandstones, argillaceous sandstone, and dolomitic sandstones with chert interbeds (Burger, 1966; Vitaliano et al, 1979), which were metamorphosed 2.75 Ga (Mueller and Cordua, 1976; James and Hedge, 1980). Based on the stratigraphic section Burger (1966) interpreted this sequence of meta-igneous and meta-sedimentary rocks as a passive margin-stable continental shelf. However, Hanley (1976) prefers a back-arc or marginal basin for the depositional setting of this metamorphic sequence.

More recently, Wilson and Hyndman (1988) have proposed a fore-arc basin setting. They believe that the metamorphic sequences in the Tobacco Root Mountains represent an accretionary wedge or sheet which formed in a collisional island-arc setting. Wilson and Hyndman consider the Franciscan complex of the California Coast Ranges a Mesozoic analog to the depositional and deformational sequences seen in the Tobacco Root Mountains. They also

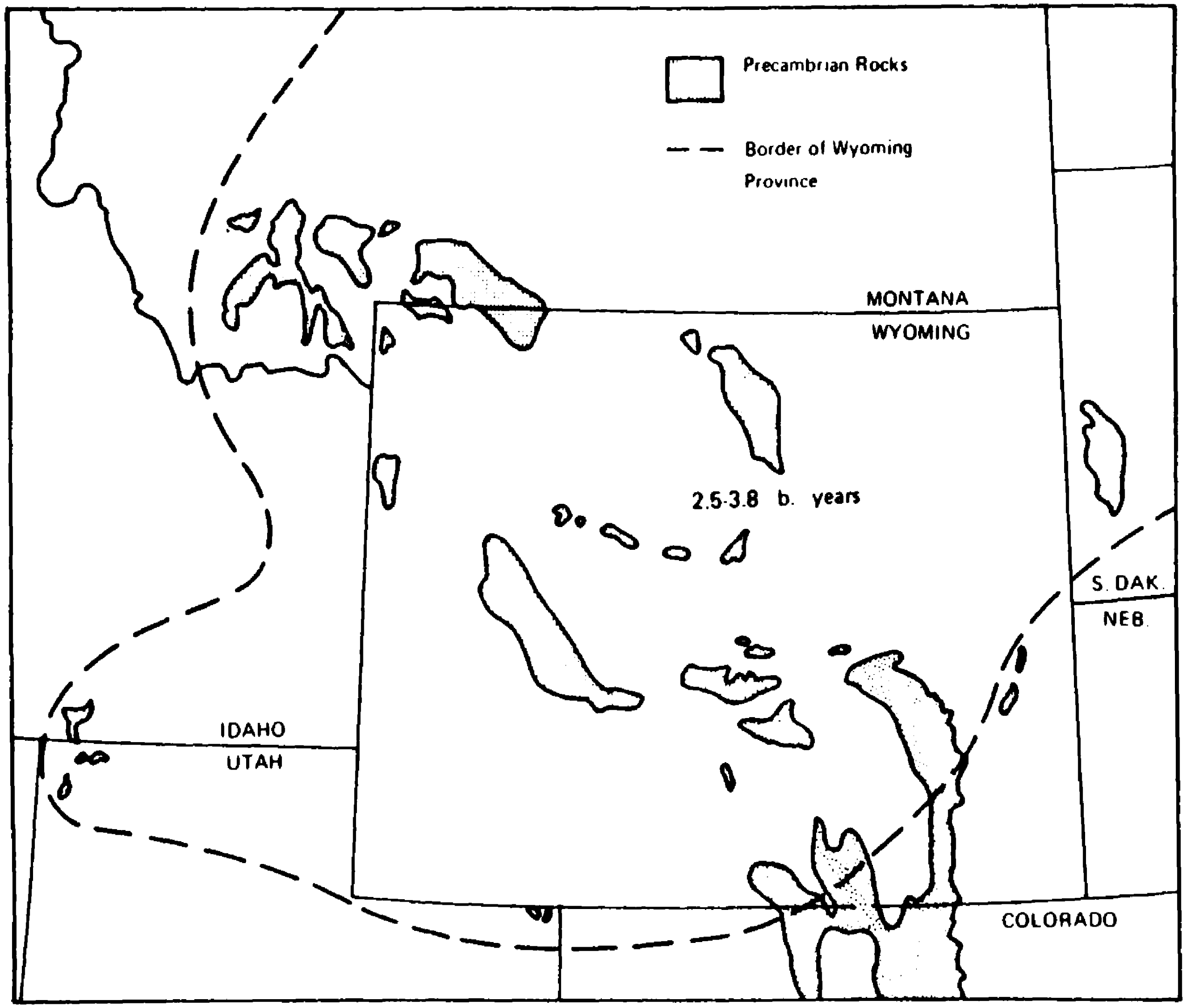


Figure 1. Outline of Wyoming Archean Province showing distribution of Archean rocks. From Condie (1982).

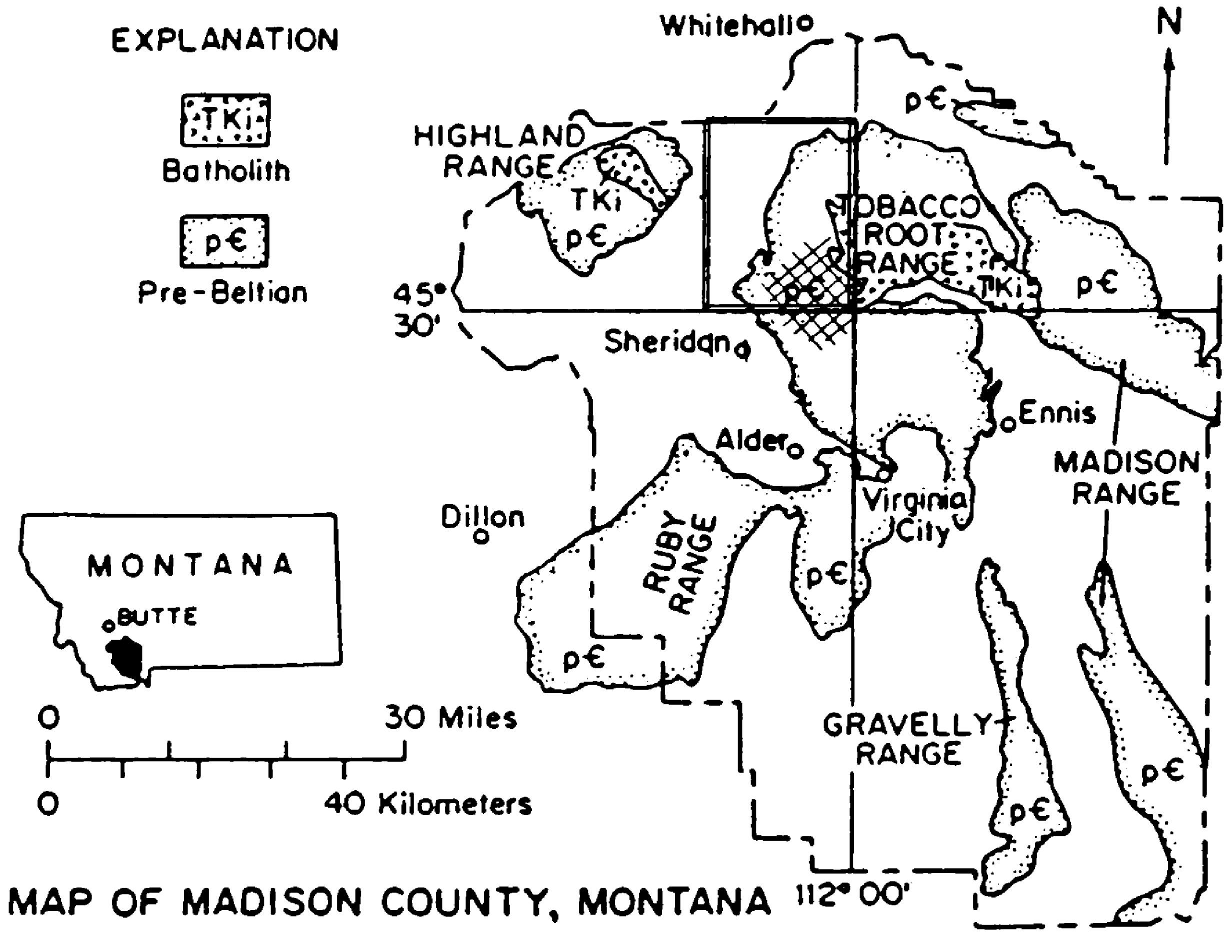


Figure 2. Location map showing study area. Waterloo 15' quadrangle is outlined. Area of Figure 3 is shown with crosshatching.

identify a Paleozoic analog in the western assemblage rocks present in the Roberts Mountains allochthon of Nevada based on similarities of lithology and structure.

1.2 Research Objectives and Methodology

Near Sheridan, in the southwestern part of the Tobacco Root Mountains, granulite facies mineral assemblages are intimately mixed with amphibolite facies mineral assemblages on the scale of the outcrop, hand specimen and thin section. These granulite and amphibolite facies assemblages occur in mafic rocks which most likely represent metamorphosed sills or flows. Recognition of granulite facies is based on the presence of hypersthene or the assemblage garnet-diopside-quartz. Hanley and Viataliano (1983) report mafic dikes of similar aspect north of Sheridan near Manhead Mountain. The purpose of this study is to determine why these granulite and amphibolite assemblages are so closely associated and why occurrences of hypersthene are restricted to the mafic rocks. In the rocks surrounding the metabasites, diagnostic granulite facies assemblages are absent. I conclude that the amount and presence of water in the mafic rocks plays a key role in the development of granulite facies mineralogy.

Specimens for a detailed investigation were collected along traverses through the area. These traverses were chosen for two purposes. The first was to determine the variety of rock types and their metamorphic facies. The second was to precisely locate the occurrences of granulite facies rocks and sample these outcrops more extensively. Figure 3 illustrates the generalized geology of the area and Figure 4 is an overlay showing sample locations.

Seventy-five thin sections were studied from various rock compositions to determine equilibrium mineral assemblages and record textural data which might have bearing on specific reactions. This data is summarized in Appendix A. Modal abundances of orthopyroxene, hornblende and plagioclase were point counted to determine the percent mafic minerals in the amphibolites and granulites.

Five samples were chemically analyzed in the commercial labs at Washington State University for major elements by XRF following the procedure described by Hooper and Johnson (1987). The results are listed in Table 1.

2. DATA

2.1 Field Relationships

In my area mafic sills/flows contain both amphibolite facies mineral assemblages and granulite facies mineral assemblages. Hornblende and plagioclase characterize the amphibolites whereas hypersthene and plagioclase, and diopside-garnet-quartz-plagioclase characterize the granulites. These mafic rocks have a foliation which parallels concordant contacts with surrounding lithologies.

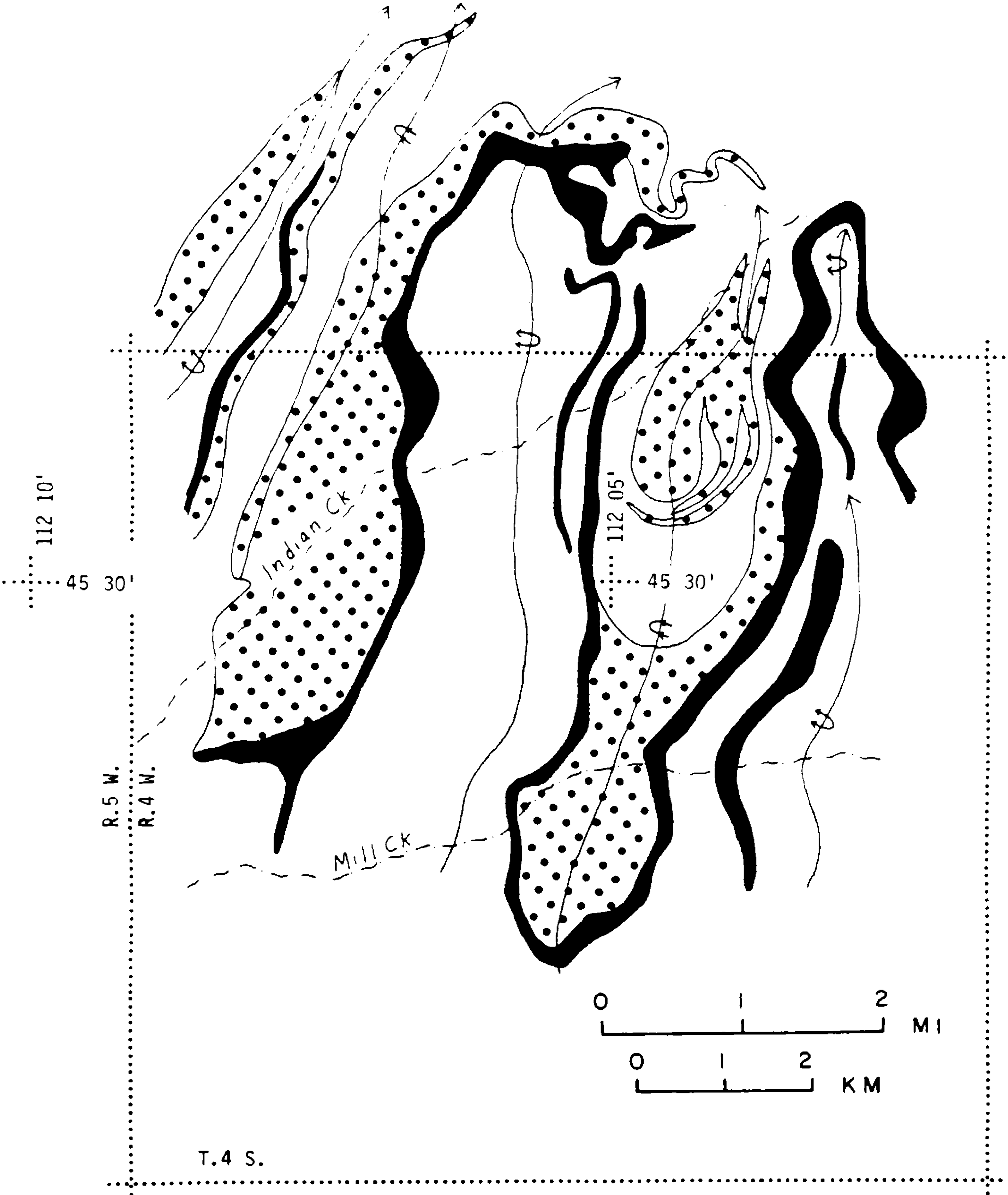


Figure 3. Generalized geologic map of part of the Waterloo 15' quadrangle, showing relationship between marble (solid), mafic rocks (stippled), and quartzofeldspathic gneiss (blank). From Vitaliano et al (1979).

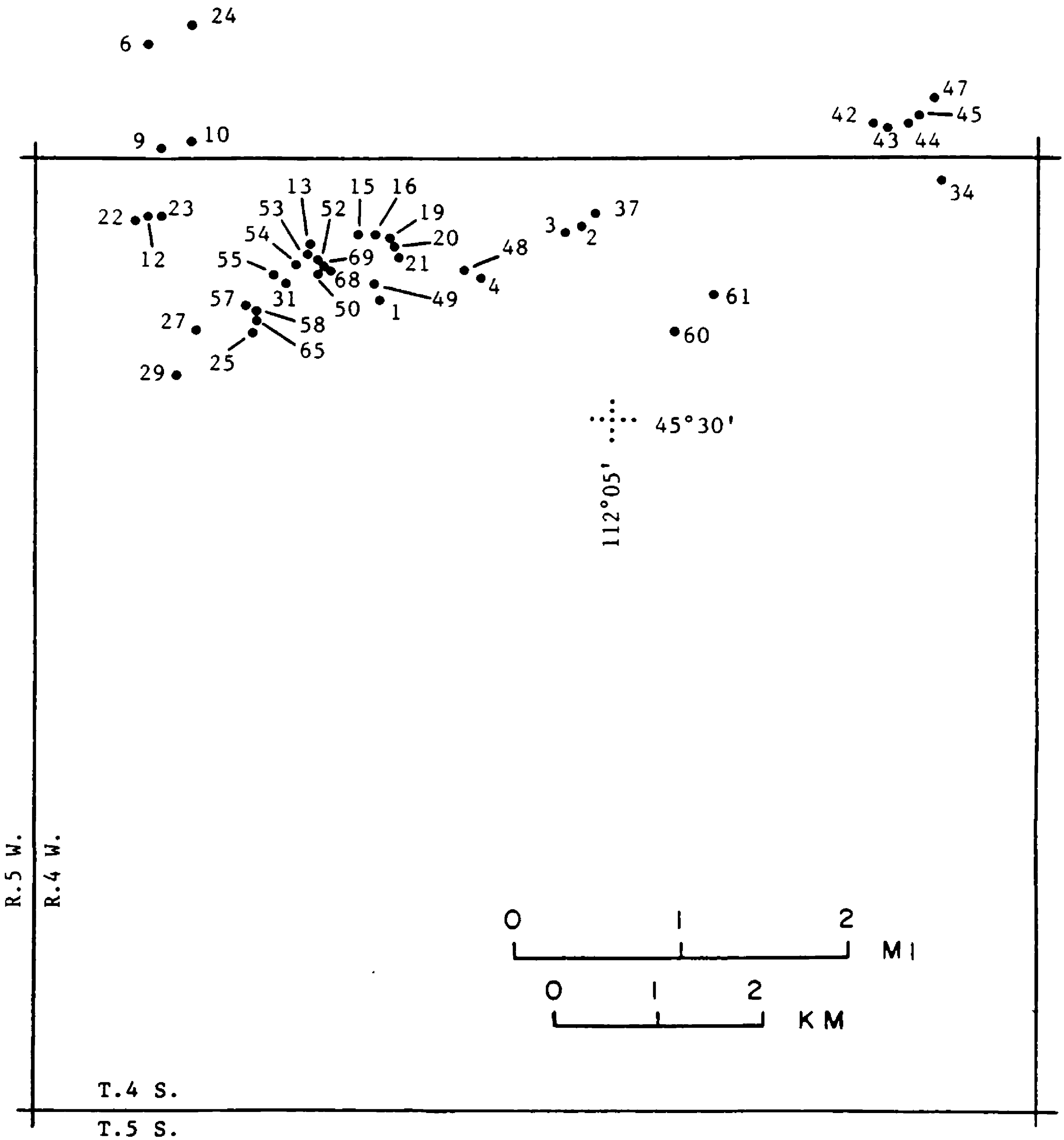


Figure 4. Sample location map.

Thickness of the mafic bodies exceeds 100 m. and may be as great as 900 m. (Vitaliano et al., 1979). The concordant nature of the contact and the lack of any pillow lava structures suggest that these mafic rocks originated as sills.

The presence of unambiguous granulite facies mineralogy is restricted to the mafic rocks. Pelitic and quartzofeldspathic rocks contain biotite, sillimanite, garnet and potassium feldspar. Muscovite is noticeably absent. The mineralogy in these rocks is considered uppermost amphibolite facies transitional into granulite facies. Carbonate rocks also lack diagnostic minerals (eg. scapolite), due to silica-deficiency (Burger, 1966).

Granulite- and amphibolite-facies rocks occur adjacent to each other in uneven patches in the mafic rocks. This mixing is most noticeable interior to the mafic bodies.

At locality 63, a mafic sill contacts the surrounding metasediments, and layering on the scale of 3 mm gives the rock a striped appearance (Figure 5). The layering consists of two distinct mineral assemblages: hypersthene + plagioclase ± hornblende and hornblende + plagioclase ± hypersthene. In addition to these thin layers, there are streaky layers and patches of felsic material ranging in thickness from 12 mm to 8 cm. The felsic layers and patches are overall coarser-grained and contain scattered grains of hornblende and orthopyroxene up to 1 cm across.

Figure 5. Photograph showing compositional layering in mafic granulite. Dark and light laminae are approximately 3mm wide. Sample 63.

It is possible that these felsic layers and patches may represent small-scale, in situ partial melting; the composition of these felsic areas is quartz diorite to tonalite. The contact between the felsic streaks and the layered rock is sharp at the scale of a few grains. This contrasts with the more wispy appearance of the 3 mm layers. At the base of this particular outcrop is a sharply bounded layer of amphibolite at least 12 cm thick. Thicker layering is also visible away from the contact but has a more diffuse character and is not always discernible. In a few blocks of rubblecrop, diffuse layering defines small-scale isoclinal folds (Figure 6).

Layers with abundant orthopyroxene are conspicuously paler in color than the layers with abundant hornblende. This difference in color is due to the mafic content of the rock. Rocks containing more hornblende are more mafic-rich than the rocks with more orthopyroxene (see Table 2 and Figure 13).

Pockets of hornblendite are scattered throughout the mafic rocks. These pockets are generally no more than a decimeter across; some surfaces are as large as a meter, but in these the third dimension is not exposed. The hornblende is much coarser-grained than in surrounding rock types; average grain size is 1 cm with some hornblende crystals reaching 2 cm.

In addition to the hypersthene-bearing granulites, rocks

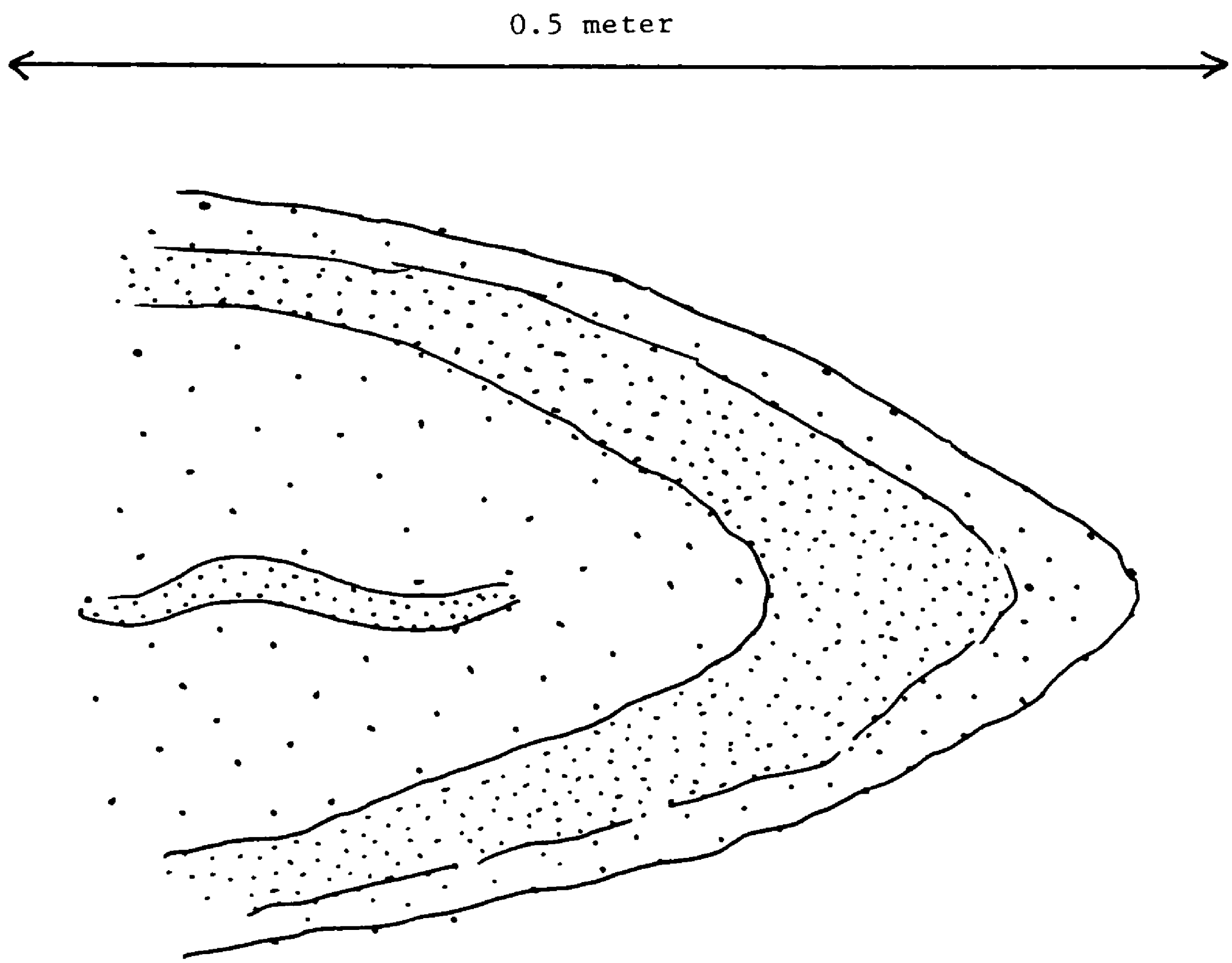


Figure 6. Small-scale isoclinal folds of diffuse compositional layering. Sample 65.

with the assemblage garnet-diopside-hornblende-plagioclase-quartz occur as gneisses. Winkler (1979, p. 267) and Schenk (1984) call these "high pressure granulites," also diagnostic of the regional hypersthene zone. They have a definite lineation produced by hornblende and fine segregations of felsic versus mafic minerals. Besides the difference in mineral assemblage, these gneisses lack the homogeneous and granular appearance of the hypersthene-bearing granulites.

In addition to the mafic rocks described above, pelitic schists/gneisses and carbonate rocks represent a small percentage of the lithologies present. The metapelites form thin discontinuous layers sandwiched within mafic and quartzofeldspathic rocks. They occur as crumbly textured samples, with rusty brown weathering, that appear different from surrounding rocks. The carbonates form continuous layers, approximately 30 m. thick, that form distinct marker beds. These carbonates have a reddish-brown weathering color that makes them stand out. Carbonates range from almost pure limestone to dirty, dolomitic limestone.

2.2 Petrography

The petrography of all samples is summarized in Appendix A, with sample locations shown on Figure 4. The following section highlights specific samples of interest which support the interpretations I have made.

Mafic Rocks

Granulites have a granoblastic texture and amphibolites have a nematoblastic to granoblastic texture. Both have an overall grain size of 0.2 mm - 1mm. Plagioclase forms the most equant and euhedral grains; in some cases it is antiperthitic, a characteristic suggestive of granulite facies (Hyndman, 1985, p. 600). Hornblende, diopside and hypersthene are anhedral. Garnet occurs as poikiloclasts with abundant quartz inclusions and as discrete subhedral crystals. Pleochroism in the hornblende is dark greenish-brown.

Felsic patches of coarser-grained plagioclase and quartz occur within the granulites. The grain size averages 2-5 mm. The plagioclase has well-developed albite twinning and a cleaner-looking appearance than most of the other plagioclase. The quartz has a distinct interstitial and amoeboid texture, dissimilar to the texture of quartz in other samples. In most cases, these felsic patches host coarse-grained (up to 1 cm) mafic minerals.

An interesting texture is developed in rocks with the assemblage diopside-garnet-hornblende-plagioclase-quartz. Diopside and garnet constitute the major mafic phases with hornblende present in amounts as low as 5%. Overall the texture is massive and inequigranular. Aggregates of subhedral garnet, 0.2 mm in diameter, occur in "chains" interposed between plagioclase and diopside. Zoning in the plagioclase produces thin rims and a "mottled complexion." Quartz occurs as very fine grains (<0.1 mm) alongside the garnet chains, and commonly separates diopside from garnet. Figure 7 illustrates these textural relationships in a sketch traced from a photomicrograph. These textures suggest that the general garnet-forming reaction was in progress:

diop + plag = gar + qtz

In this context, the garnet may be a retrograde phase (Gulley, 1985; Harley, 1985) and therefore this assemblage may not represent a true granulite facies assemblage. But other samples with the same mineralogy lack any textural evidence for this reaction (cf.: sample 37). Instead, all phases are in equilibrium, and have a granoblastic texture.

Pelitic gneisses and schists

A particularly spectacular lithology is a garnet-sillimanite gneiss (sample 48). It has the assemblage rutile-biotite-perthite-garnet-sillimanite-plagioclase-quartz. Prismatic sillimanite and bladed biotite define the foliation. Sillimanite is coarse-grained and forms aggregates; it displays undulose extinction and has abundant rutile inclusions. Biotite has red pleochroism and forms stubby blades. Garnet occurs as large poikiloblasts (in some cases aggregates) enclosed in a swirly pod of quartz, plagioclase, and perthite. Since the mineralogy of these enclosing felsic areas has a granite-

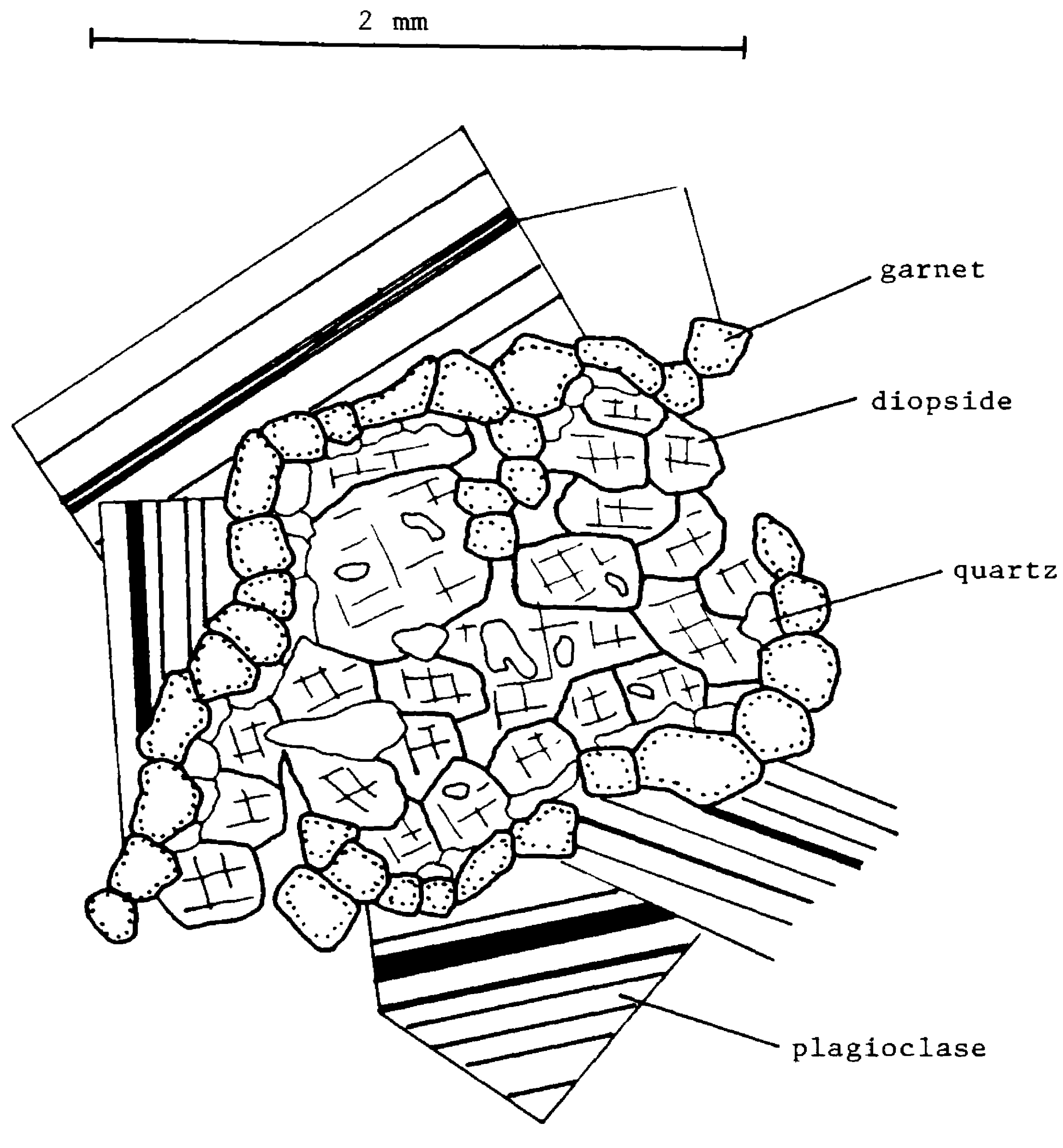


Figure 7. Sketch traced from photomicrograph showing corona of garnet-quartz symplectite separating diopside from plagioclase in mafic granulite. Sample 50.

minimum melt composition, they may represent partial melt segregates (Hyndman, 1985, p. 476; Thompson, 1982). The garnet has inclusions of quartz, sillimanite, biotite, and rutile. Most of the sillimanite inclusions are needles and parallel the gneissic foliation in the rock. Quartz and feldspar are inequigranular to granoblastic with many 120° junctions.

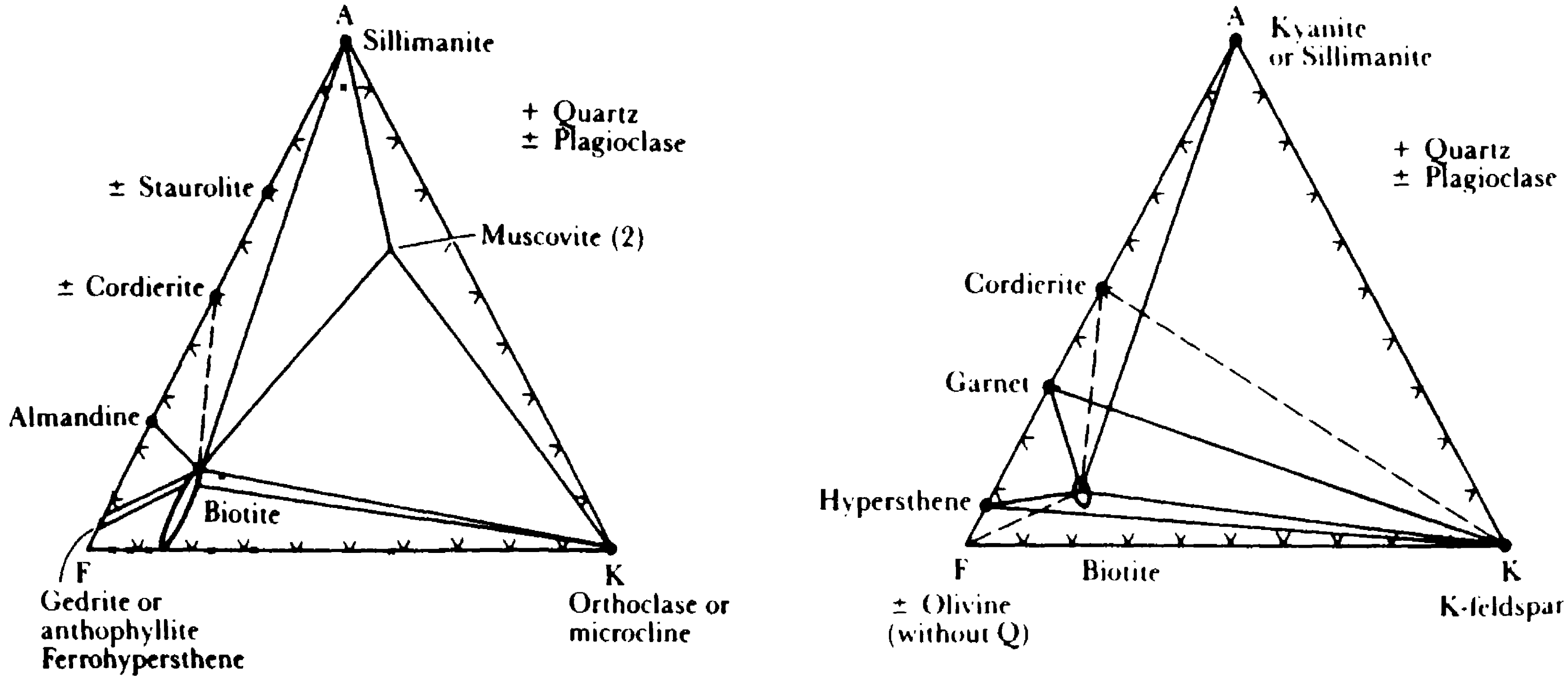
This assemblage is significant because it represents the reaction:

$$\text{bio} + \text{sill} + \text{qtz} = \text{gar} + \text{ksp} + \text{H2O}$$

which is a major dehydration step in pelitic rocks and may document a transition into or within granulite facies (Hyndman, 1985, p. 604). Figure 8 shows an AFK diagram for granulite facies assemblages illustrating the tie line between garnet and K-feldspar which is absent in the AFK diagram for amphibolite facies. A similar reaction which may or may not be represented is:

$$\text{bio} + \text{sill} + \text{qtz} = \text{gar} + \text{ksp} + \text{liq}$$

According to Thompson (1982), Fe-rich pelitic rocks exhibit partial melting through this AFM continuous reaction. The establishment of conditions in which partial melting has occurred is important because it offers a mechanism by which the activity of water is lowered, thereby permitting the formation of granulite facies assemblages. At slightly lower grade, but perhaps transitional into the granulite facies, the reaction:



AMPHIBOLITE FACIES GRANULITE FACIES

Figure 8. AFK triangles illustrating mineral assemblages for amphibolite and granulite facies. Note tie line joining garnet and K-fledspar in the granulite facies. From Hyndman (1985).

$$musc + qtz = sill + orth + H_2O$$

occurs. Hyndman (1981) suggested that this dehydration reaction may trigger partial melting which would aid in the formation of major granitic batholiths. That conditions of partial melting existed is reinforced by 1) the mineralogy of the felsic areas within the metapelite, 2) the dehydration reaction evident in the metapelite, and 3) the existence of other dehydration reactions which may trigger partial melting.

Other assemblages in pelitic rocks include kyanite-biotite-garnet-quartz-plagioclase (sample 49) and sillimanite-biotite-quartz-perthite-plagioclase (sample 10). The significance of these assemblages is:
1) the presence of kyanite with other high-temperature assemblages demonstrates that high pressures existed; 2) the occurrence of two different aluminosilicate polymorphs nearly adjacent in the field indicates that conditions were probably at or very close to the stability boundary between kyanite and sillimanite, and 3) the overall dominance of sillimanite occurrences over kyanite occurrences suggests that for most of the time, rocks were in the sillimanite stability field and not in the kyanite field. Muscovite is absent in all the metapelites except one, where it occurs as a retrograde phase from sillimanite.

2.3 Chemical Analyses

Five samples of amphibolites and granulites were analyzed for major elements using XRF techniques (Table 1). Three of these are hypersthene-bearing granulites, one is a hornblende-plagioclase amphibolite, and one is a garnet-diopside granulite. All five samples have essentially identical basaltic chemical composition, except that the two samples lacking hypersthene have less Mg and more Ti. In addition, the rock with the highest percentage of hypersthene and lowest percentage of hornblende has the lowest amount of CaO. Figure 9 illustrates the bulk compositions of each rock in an AFC triangle. Except for one rock, which is relatively poor in Al and Ca, all the rocks cluster in the same area. Despite the similarities in bulk composition, each sample has a different mineral assemblage. Figures 10 and 11 are ACF diagrams which illustrate the different mineral assemblages found in each sample, and each sample's corresponding bulk composition. In Figure 10, the hornblende is plotted out of the range of its average composition field. This was necessary in order that the analytically determined bulk composition of the sample falls within the triangle of the equilibrium mineral assemblage ascertained from petrography. That it is

TABLE 1. CHEMICAL ANALYSES

Sample No.	31	50	53	54	57
SiO_2	52.90	52.05	49.96	52.47	50.66
Al_2O_3	14.34	13.82	14.32	11.26	17.35
TiO_2	1.413	1.080	0.546	0.673	0.381
TOTFeO*	13.23	13.67	10.82	13.15	9.99
FeO*	11.91	12.30	9.74	11.83	8.99
Fe_2O_3*	1.47	1.52	1.21	1.46	1.11
MnO	0.213	0.249	0.261	0.412	0.232
CaO	9.12	10.47	11.75	5.66	10.16
MgO	5.49	6.41	10.95	14.59	11.03
K_2O	0.64	0.25	0.12	0.21	0.22
Na_2O	2.73	2.09	1.57	1.99	1.42
P_2O_5	0.113	0.072	0.046	0.098	0.022
SUM	100.19	100.46	100.34	100.51	101.47
$\frac{FeO}{(FeO + MgO)}$	0.6844	0.6574	0.5206	0.4478	0.4491

TOTFeO* = calculated as though all Fe were FeO
FeO* = 0.9 TOTFeO as FeO
Fe_2O_3* = 0.1 TOTFeO as Fe_2O_3

Normative Mineralogy

	31	50	53	54	57
Quartz	2.84	2.83	0.00	0.00	0.00
Orthoclase	3.78	1.48	0.71	1.24	1.30
Albite	23.02	17.60	13.20	16.75	11.85
Anorthite	24.89	27.42	31.53	21.03	39.67
Diopside	16.29	21.02	21.32	5.04	7.97
Hypersthene	24.11	25.28	22.91	48.77	33.00
Olivine	0.00	0.00	7.46	3.58	3.87
Magnetite	2.13	2.19	1.74	2.10	1.58
Ilmenite	2.68	2.03	1.03	1.27	0.72
Apatite	0.25	0.16	0.12	0.23	0.05

Modal Mineralogy

31	50	53	54	57
hbl	hbl	hbl	opx	plag
plag	plag	plag	plag	hbl
gar	diop	opx	hbl	opx
qtz	gar	diop		
	qtz			

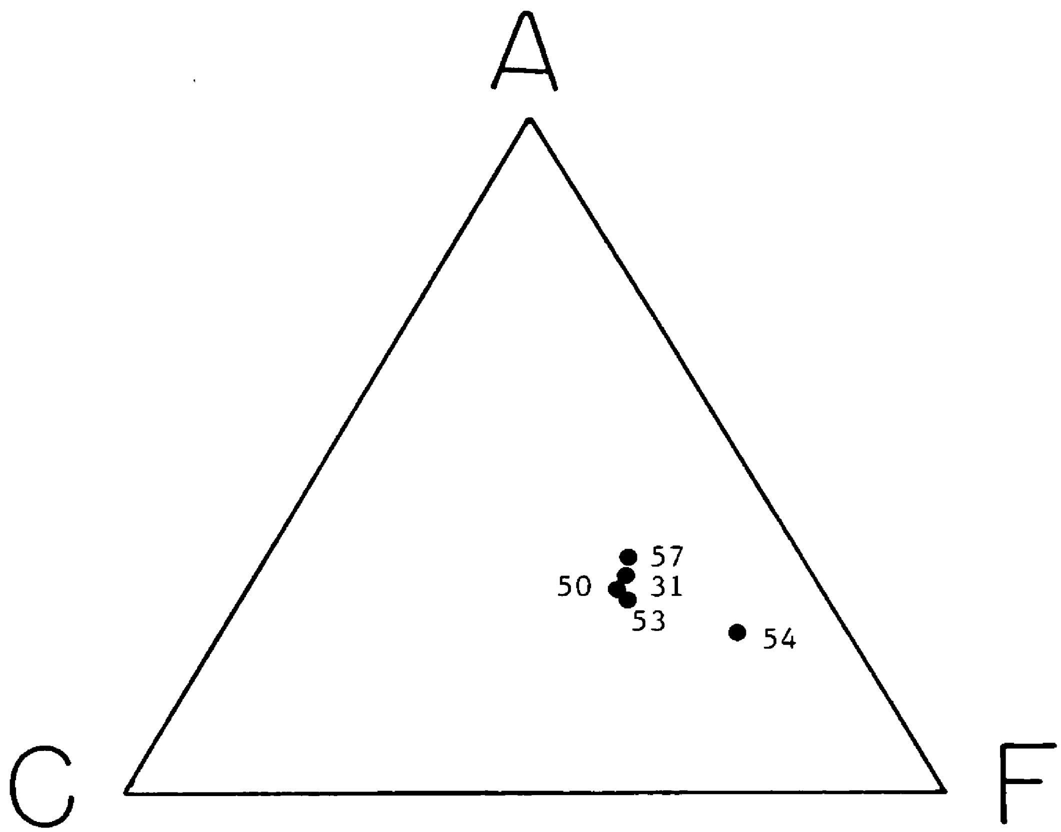


Figure 9. Bulk chemical composition of amphibolites and granulites plotted in an ACF triangle.

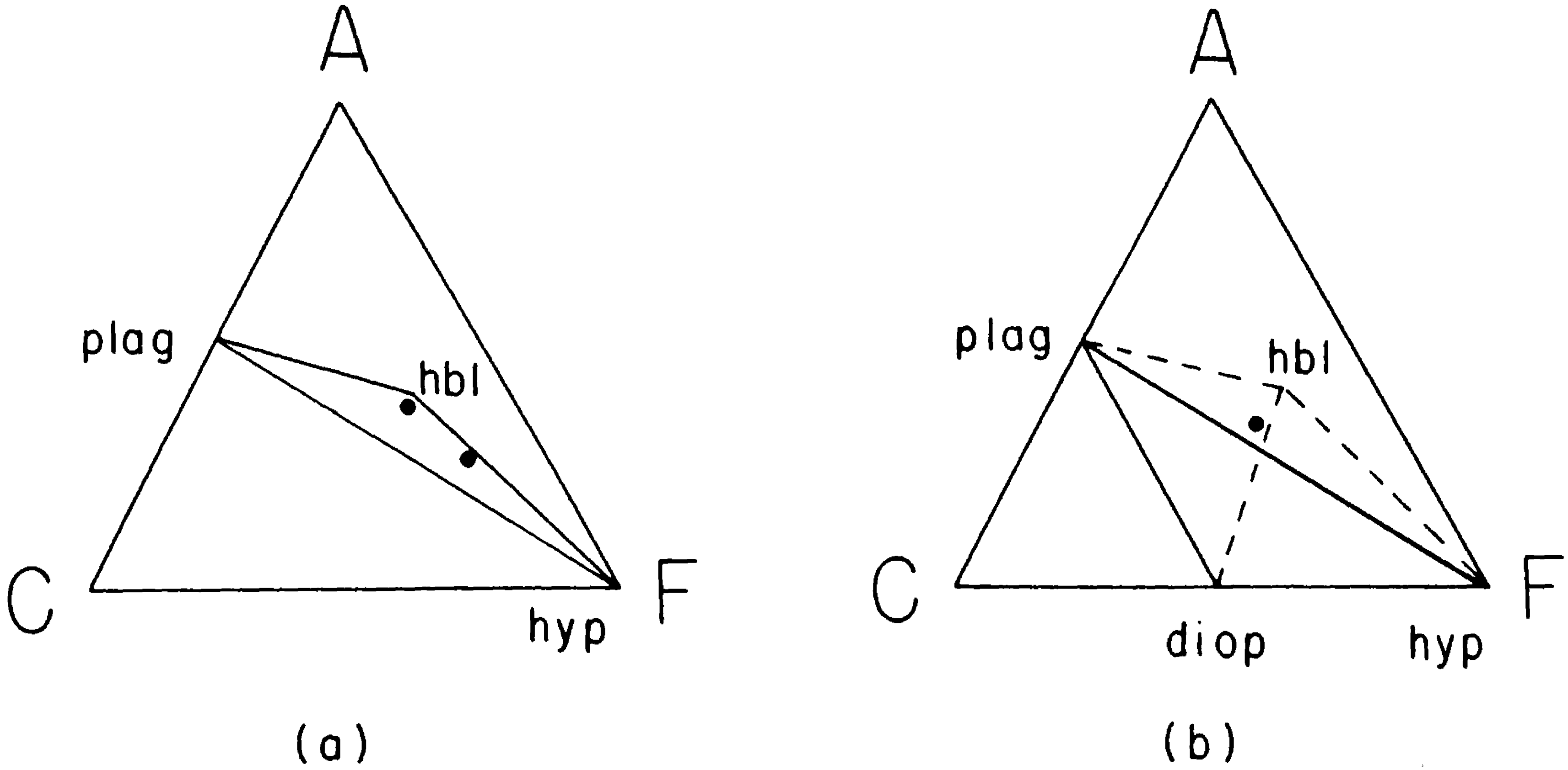


Figure 10. ACF diagrams showing granulite facies assemblages in mafic rocks. a) samples 54 and 57; b) sample 53. Closed circle denotes bulk composition of sample.

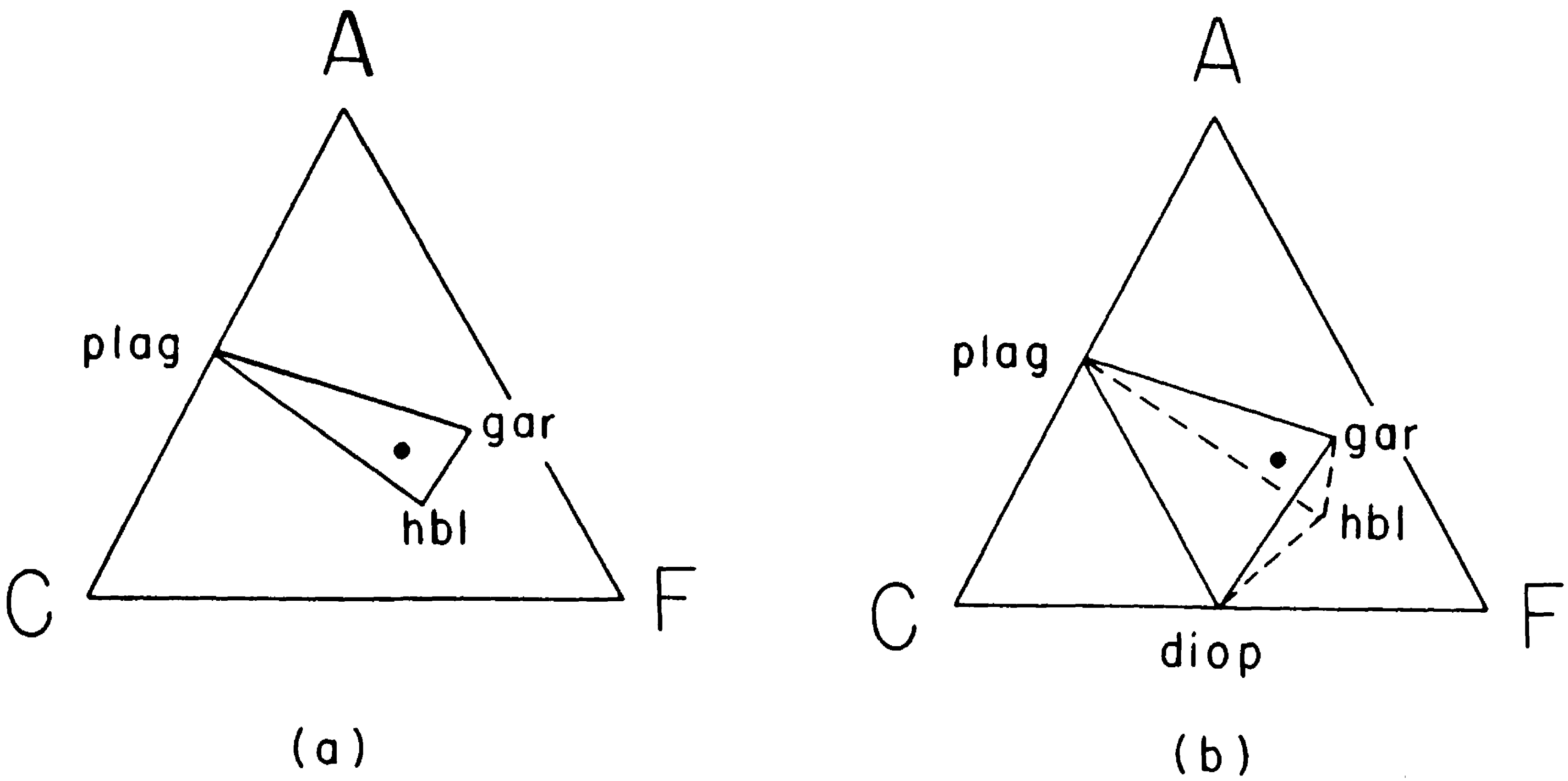


Figure 11. ACF diagrams showing amphibolite and granulite facies assemblages in mafic rocks. a) sample 31; b) sample 50. Closed circle denotes bulk composition of sample.

necessary to plot the hornblende in such a manner is an unresolved discrepancy, but may be related to using anorthite as an idealized plagioclase composition, thereby ingnoring the albite component that is present. In Figure 11 the hornblende plots within its average composition field and this discrepancy does not exist.

The Fe/Mg ratio correlates to the amount of hypersthene in the rock. Those samples without hypersthene have the highest Fe/Mg ratio, whereas those with hypersthene have the lowest ratio (see Figure 12). Despite some differences in bulk chemistry, all the rocks have a tholeiitic basalt composition when compared with the average chemical compositions of igneous rocks (Hyndman, 1985, pp. 205, 47, 257). The normative mineralogy of these rocks also indicates that they have a tholeiitic basalt composition.

3. SYNTHESIS OF INTEGRATED DATA

3.1 The role of water, temperature, and pressure

The essential condition for the formation of granulite assemblages is that water pressure be significantly less than total pressure. The ordinary temperature and pressure range of high-grade regional metamorphism is sufficient provided that water pressure is reduced (cf.: Winkler, 1979, p. 271, 264).

In order to assess the significance of granulite facies rocks in the Tobacco Root Mountains several questions must be answered. Is the occurrence of granulite facies

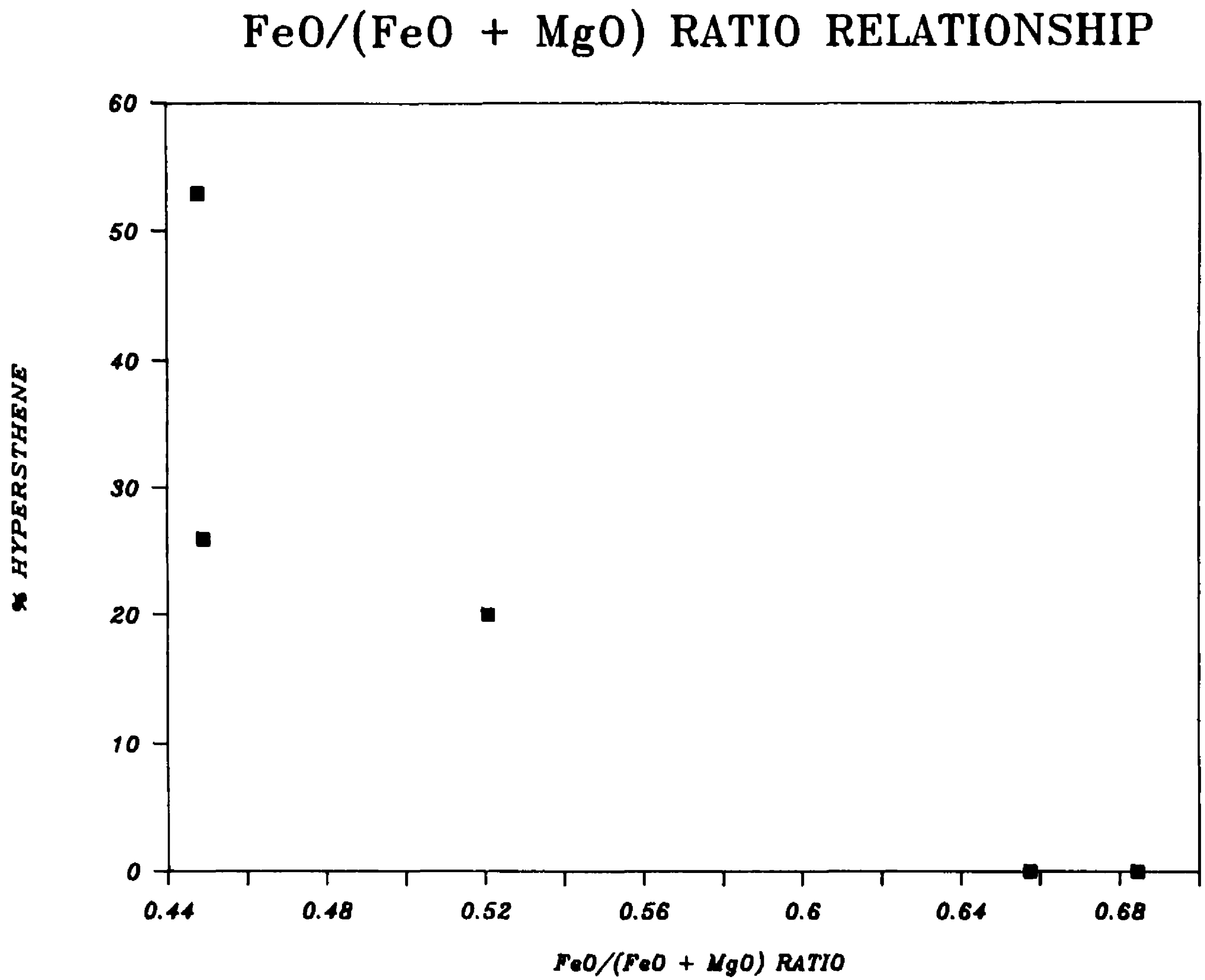


Figure 12. Plot of data from Tables 1 and 2 showing correlation between amount of hypersthene and $\frac{FeO}{(FeO + MgO)}$ ratio in the mafic rocks.

restricted to certain rock compositions? Do specific reactions document the transition into granulite facies? Is more than one period of metamorphism responsible for the different facies? What parameter(s) is responsible for controlling the formation of granulite facies rocks?

The fact that diagnostic granulite facies assemblages are restricted to mafic rocks suggests rock composition as a governing influence in the formation of granulites in this area. It is clear from their mineralogy that mafic rocks tend to be drier than sedimentary and other rock types. The water content of hornblende < biotite < muscovite. One can argue that it is the original or inherent dryness of these mafic rocks which allows granulite-facies assemblages to grow.

The association of granulites with or without hornblende is attributed to the metamorphism of rocks having different original water contents in closed systems. Reactions involving hornblende are continuous with a "sliding" equilibrium (Winkler, 1979, p. 264). This means that the reaction will start at different temperatures at various given total pressures and water pressures. Thus, although hypersthene will be produced from hornblende, the reaction need not proceed to completion, and decreasing amounts of hornblende will coexist with the newly formed hypersthene. De Waard (1965, 1967a, 1971) recognized several reactions to account for the diagnostic appearance of hypersthene, and the decrease of hornblende:

(1) hbl + qtz = hyp + cpx + plag + H_2O

(2) hbl + gar + qtz = hyp + plag + H_2O

(3) hbl + bio + qtz = hyp + plag + H_2O

In a simplified manner these reactions can be viewed as:

(4) $Ca_2Mg_3Al_4Si_6O_{22}(OH)_2 + SiO_2 = 2\ CaAl_2Si_2O_8 + 3\ MgSiO_3 + H_2O$

amphibole quartz anorthite opx

From the above it can be seen that rocks rich in hornblende will tend to have either less plagioclase, or less anorthite-rich plagioclase, than those rocks rich in hypersthene if the hypersthene was generated by reaction (4). The latter observation is documented in the rocks I sampled which have high mafic:felsic ratios where hornblende is abundant and lower mafic:felsic ratios where hypersthene is abundant. Table 2 and Figure 13 show these relationships. Another reaction which may document a transition into the granulite facies is one observed in the pelitic rocks:

bio + sill + qtz = gar + ksp + H_2O

To assess whether or not two different periods of metamorphism are responsible for the two different metamorphic facies it would be helpful to find retrograde and prograde reactions which will identify a past reaction. The presence of a past reaction is significant because it

TABLE 2. RELATIONSHIP BETWEEN AMOUNT OF HORNBLENDE AND FELSIC CONTENT OF ROCK

Sample #	% Hbl	% Opx	Mafic:Felsic Ratio	
25A	49	16	1.86:1	
25B	26	23	1:1	*
31	58	0	1.63:1	
53	40	20	1.86:1	
54	12	53	1.86:1	
57	30	26	1.3:1	*
58	20	35	1.2:1	*
60B	65	0	2.4:1	
60D	25	38	1.7:1	*
61A	67	0	2:1	
61C	44	23	2:1	
63A	66	15	2.4:1	
65C	30	25	1.2:1	*

* low mafic:felsic ratios relative to other samples

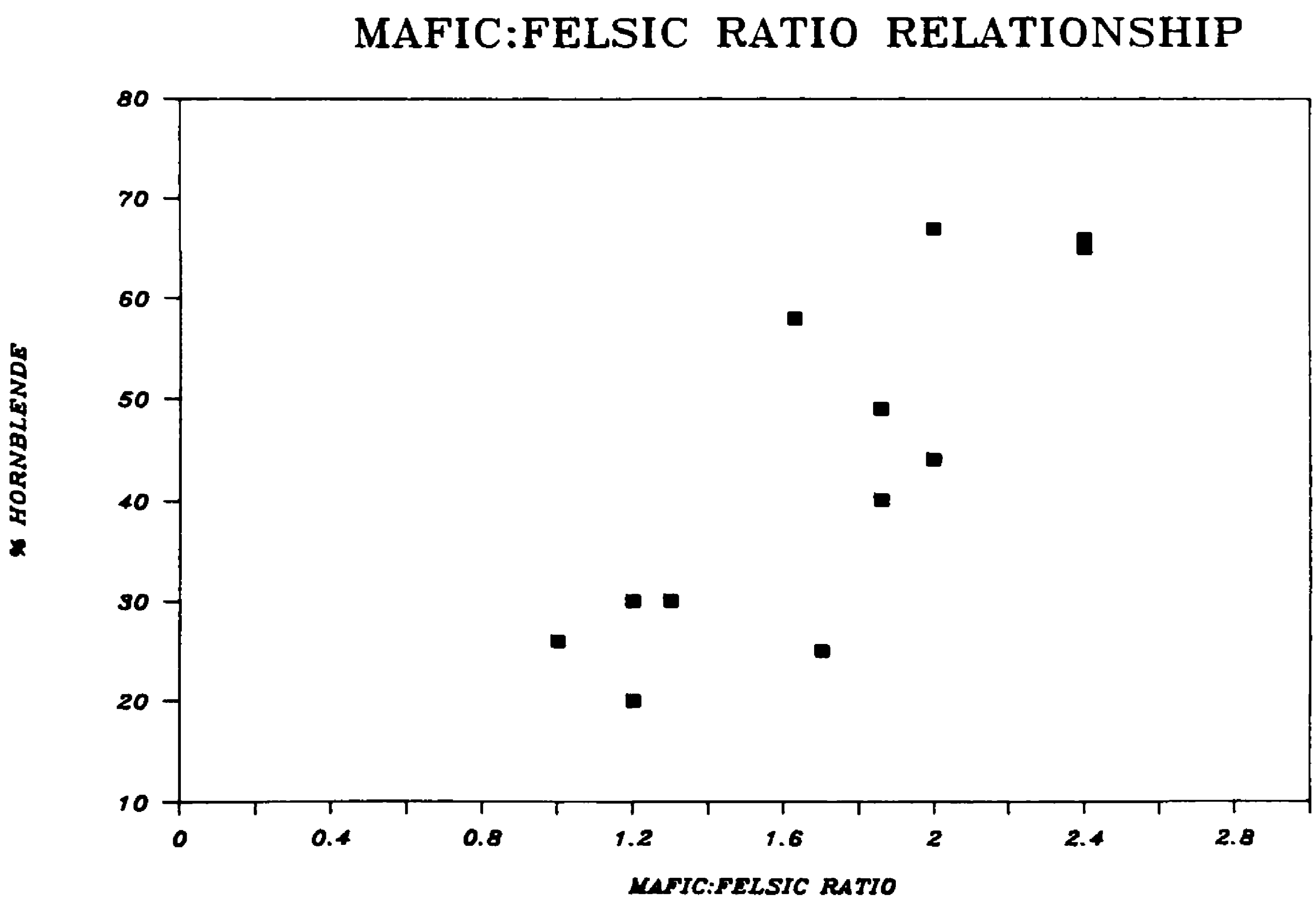


Figure 13. Plot of data from Table 2.

positively identifies a past event. Only two retrograde reactions are preserved in the rocks: 1) sillimanite reverting to muscovite and 2) orthopyroxene altering to hornblende. Neither of these reactions is pervasive; nor are they diagnostic because they might also represent a "natural" cooling and hydration from peak conditions.

Another method to assess the existence of two distinct periods of metamorphism is to examine the composition and texture of hornblende. If a second event did occur, then one might expect to see a different type of hornblende generated during each event. This is not the case. All the hornblende, in either amphibolites or granulites appears identical. The grain size, color, composition, and texture of all the hornblendes appear uniform. Also, all of the hornblende is strain free.

Parameters controlling the formation of any metamorphic assemblage are temperature, lithostatic pressure, fluid pressure, fluid composition, and rock composition. In the granulite facies, temperature, fluid pressure, and fluid composition are the most important. That this package of rocks in the field is conformable with those of the amphibolite facies, coupled with the absence of any major fault zones separating rock types, demonstrates that the entire rock sequence was metamorphosed under similar conditions of temperature and lithostatic pressure. Distances between areas traversed and sampled are not so great as to warrant the option of deeper burial for one rock type versus another.

A P-T diagram representing the conditions of metamorphism for this area also supports the interpretation that lithostatic pressure and temperature were the same for various units. In figure 14 the area shaded with horizontal lines represents the stability field inferred from the metapelites. The area shaded with vertical lines represents the stability field inferred from the metabasites. Temperatures are restritced by the reactions shown, and pressures are restricted by the presence of kyanite and sillimanite. The grid pattern represents the area of overlap between the two different stability fields and demonstrates that both amphibolite- and granulite-facies assemblages could develop under similar P-T conditions. An alternative view of the same data is that the metabasites represent higher temperatures of formation. I prefer the former interpretation because of 1) the intermingled nature of metamorphic facies within the metabasites themselves, and 2) the presence of partial melt segregations which supports the interpretation that a lowered activity of water was the governing influence for the presence of granulites in this area.

The question of fluid pressure is a bit more difficult to assess, but can be linked with fluid and rock composition. Although I have no quantitative data to

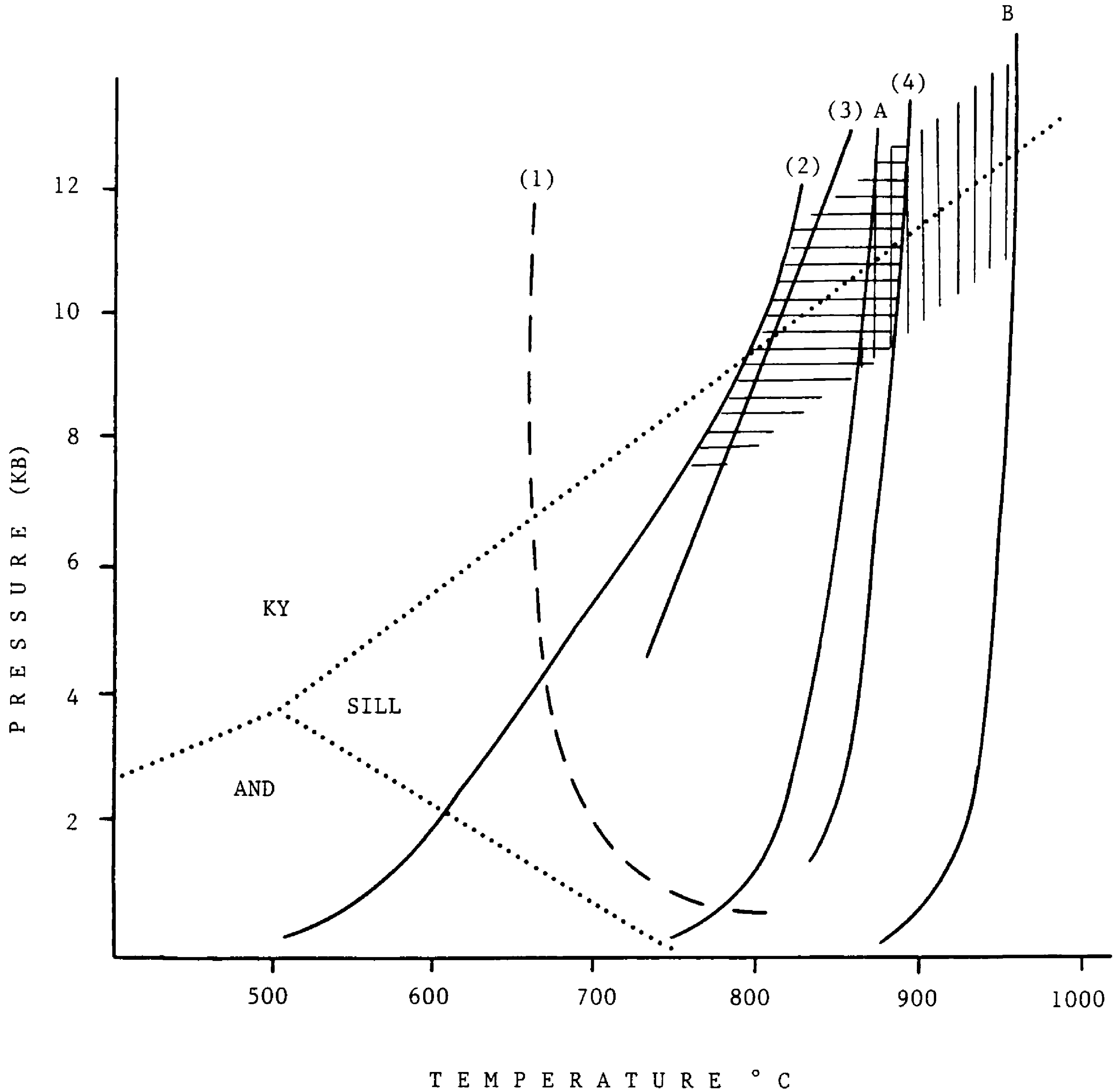


Figure 14. P-T diagram illustrating overlap (grid pattern) of stability fields for metapelitic rocks (horizontal lines) and mafic rocks (vertical lines). Reactions shown include: (1) incipient melting of wet granite; (2) musc + qtz = sill + ksp + H_2O; (3) alkali feldspar = perthite; (4) approximate biotite dehydration; (A) "opx-in"; (B) "amphibole-out". From Hyndman (1985).

support a low activity of water in some of the rocks, qualitative inferences are made on the basis of rock composition. The following points lead me to the conclusion that the activity of water was the governing influence in the formation of these granulites:

1. The restriction of hypersthene to mafic lithologies points towards a compositional control. The inherent dryness of the mafic rocks can easily be held responsible for the presence of hypersthene.

2. However, the intimately mixed facies within a single outcrop of mafic rock points towards another factor besides bulk composition for the control of granulite facies assemblages. One sample (65) is irregularly layered with hypersthene-rich and hypersthene-poor bands. Another sample (58) contains small amorphous pods of amphibolite (hornblende-plagioclase) mixed in with granulite (hypersthene-plagioclase-hornblende).

3. The presence of ferromagnesian minerals in the quartzofeldspathic gneisses permits the plausible interpretation that the quartzofeldspathic rocks have a composition compatible with the formation of hypersthene. The presence of biotite, garnet, and hornblende in these rocks neither proves nor disproves that these gneisses have a compatible composition. However, if the quartzofeldspathic gneisses contained only muscovite or sillimanite, and no Fe- and Mg- bearing minerals, one might

conjecture that they lacked the correct composition for forming mafic minerals.

4. Under the assumption that these quartzofeldspathic gneisses have a suitable bulk composition to form hypersthene, the lack of hypersthene in such rocks points to another control besides composition for the generation of granulite facies assemblages, the activity of water. Since field evidence demonstrates that the mafic rocks were metamorphosed at the same P-T conditions as sourrounding rocks, and it is plausible that rock composition is not the limiting control, I believe that the activity of water played a dominant role in the formation of granulite facies assemblages in the Tobacco Root Mountains.

Since hypersthene is restricted to the mafic rocks and displays an unusual mode of occurrence, it may be that the composition of the rock is controlling the activity of water. If so, then some internal process may be generating a variable activity of water which then controls the presence or absence of granulite facies assemblages. The other possibility is that microfractures within the rock permitted fluids to seep into or percolate through the rock, thus creating areas of variable water activity. I believe that this external source is less likely than an internal compositional control, because if the control were external, I would expect other rock types to be similarly affected. The lack of evidence for a low activity of water in other rock types does not prove that an external source is not responsible, but it does allow the option of internal buffering within the mafic rocks as a means for lowering the activity of water.

4. DISCUSSION

4.1 Implications for the control and/or mechanisms of granulite facies metamorphism

Through field and petrographic evidence I have demonstrated the patchy occurrence of granulite facies assemblages. I have determined that the main controlling factor for the presence of granulite facies in the Tobacco Root Mountains is indeed the activity of water. Still to be addressed is the mechanism by which the activity of water is lowered. To a certain extent the mafic composition of the rocks, and their inherent dryness, has controlled the activity of water, but even within the mafic rocks there is a high degree of variability. Based on field observations and petrographic study I believe that internally buffered melting reactions provide the local distribution of granulite-facies assemblages. The granulites are neither associated with massive carbonate bodies that could provide large amounts of CO_2, nor is there any pervasive "granulitization." The presence of small felsic segregations, or partial melts, within the mafic rocks indicates that melting has occurred. Since water is strongly partitioned into a melt phase, formation of a melt will effectively decrease the activity of water in the coexisting solid phases. According to Powell (1983) a small amount of melting will drive a rock to lower a(H2O) by internal buffering along melting reactions, unless a considerable supply of water is available to keep the melt saturated with water as the temperature increases. Figure 15 shows the mineralogical evolution of an amphibolite facies assemblage (garnet + plagioclase + hornblende + quartz) under internal buffering starting at a high or low a(H2O). Although this diagram indicates that a rise in temperature is necessary for the different reactions to be encountered, especially orthopyroxene ---> clinopyroxene + liquid, it is useful to look at the diagram from a another perspective. Given a constant temperature, different assemblages are encountered at different a(H2O). The horizontal dash-dot line illustrates the field observations I have made. In order to get the different a(H2O) a rise in temperature may be needed unless the activity of water is externally buffered.

Another reason to invoke partial melting as the mechanism which lowers the activity of water thereby producing granulite facies assemblages is that other rock types in the area show evidence of partial melting. In the garnet-sillimanite gneiss swirly areas of felsic material may suggest partial melting via the reaction:

bio + sill + qtz = gar + ksp + liq.

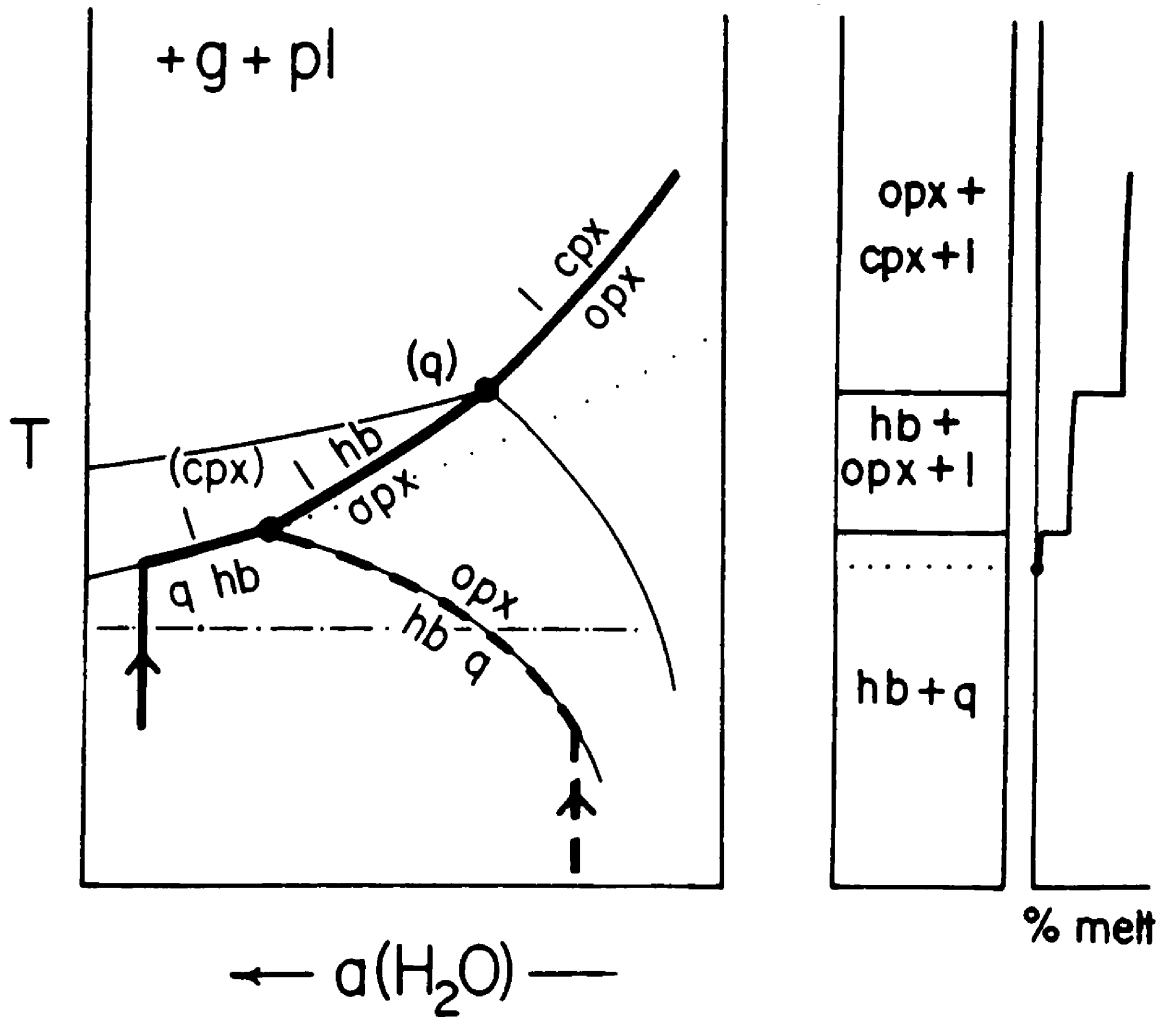


Figure 15. Mineralogical evolution of an amphibolite facies assemblage, hb + q + g + pl, under internal buffering. Melting steps occur at the intersections. The dashed line is for internal buffering of an initially low $a(H_2O)$ but hornblende-bearing assemblage, showing that major melting will start at the same intersection as for high $a(H_2O)$ assemblages. The horizontal dash-dot line represents the field observations I have made. From Powell (1983).

4.2 Implications for tectonic regime

Recently a new model for granulite formation has been suggested which is based on a different tectonic regime than continental collision. Bohlen (1987) proposes magmatic heating of the lower crust before and during tectonic loading, with initial, nearly isobaric cooling from peak conditions. This contrasts with the "time-honored" scenario of continent-continent collision where rocks also undergo nearly isobaric cooling from peak conditions. Both models provide a mechanism for thickened continental crust, but the differences exist in the inferred P-T-time paths that each model requires. The distinction between these two models is best viewed in P-T space. Figure 16 illustrates the P-T-time path for granulite-facies metamorphism consistent with continent-continent collision. The salient feature of this graph is that it depicts the prograde metamorphic conditions prevailing in the kyanite stability field. Figure 17 shows the P-T-time path for granulite-facies metamorphism generated by magmatic heating. In this graph the prograde metamorphic event resides in the sillimanite stability field. The main difference between these two models is the location in P-T space through which the rocks pass during the prograde event. In order to evaluate which model better fits the Tobacco Root Mts one needs to consider the following: 1) are supracrustal rocks or intrusive meta-

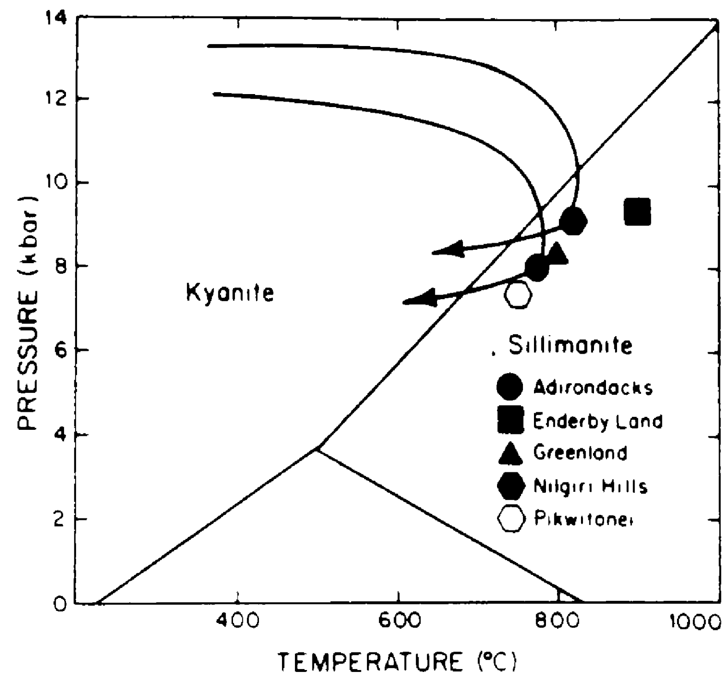


FIG. 16—P-T-time path for granulites consistent with continent-continent collision and initial, nearly isobaric cooling from peak conditions (symbols). From Bohlen (1987).

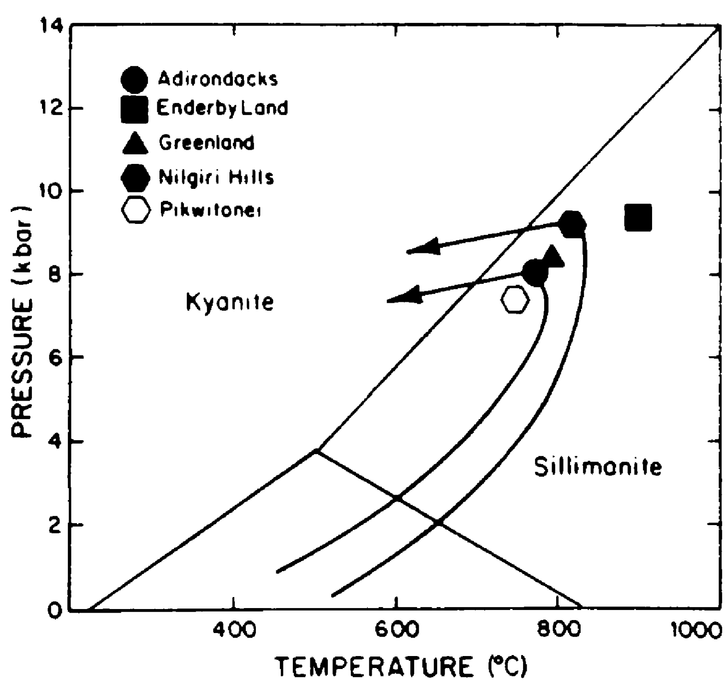


FIG. 17—P-T-time path for granulites consistent with magmatic heating of the lower crust before and during tectonic loading and initial, nearly isobaric cooling from peak conditions (symbols). From Bohlen (1987).

igneous rocks dominant, 2) is there evidence for magmatic pulses which accompanied the metamorphism, 3) is kyanite or sillimanite present?

In the Tobacco Root Mountains, coarse-grained primary sillimanite is abundant, whereas occurrences of kyanite are scarce. Mafic gneisses and amphibolites constitute a significant percentage of the rocks present, but quartzofeldspathic gneisses of possible sedimentary origin (Schaeffer, 1986) are more voluminous. Abundant mafic dikes and intrusions have reached granulite facies metamorphism and therefore are at least as old as the granulite facies metamorphism (Hanley and Vitaliano, 1983). The exact relationship of these mafic bodies to the granulite event is uncertain, but one could conjecture that they represent magmatic heating of the lower crust. More precise documentation of the timing and relationship between these mafic bodies and the granulite facies metamorphism would shed considerable insight into the tectonic framework in which granulite facies developed in the Tobacco Root Mountains.

Hyndman and Foster (1988) and Hyndman, Alt, and Sears (1988) have documented intrusion of mafic dikes into a major batholithic terrane during sillimanite-zone regional metamorphism and overlapping and following deep-seated emplacement of a granitic batholith. At deeper levels of the mid- to lower continental crust beneath the batholith, the same mafic dikes and sills would be expected to raise temperatures into the range of the granulite facies. Generation of batholithic magmas would concurrently dehydrate the remaining rocks.

I believe that magmatic heating of the lower crust in a collisional island arc setting may account for the widespread occurrence of mafic sills and granulite facies mineral assemblages in the Tobacco Root Mountains. Mafic sills intruding the lower crust are probably drier than the surrounding metamorphic environment. The inherent dryness of these sills appears to foster the development of granulite facies assemblages restricted to mafic lithologies in an otherwise upper amphibolite facies terrane.

5. SUMMARY

The following factors lead to the conclusion that granulite facies rocks in the Tobacco Root Mountains near Sheridan are the result of local variation in the activity of water:

1. Field evidence demonstrates that P-T conditions were the same for amphibolite and granulite facies mineral assemblages. Petrographic evidence demonstrates that P-T conditions could have been the same for amphibolite and granulite facies mineral assemblages.
2. Hypersthene is restricted to mafic lithologies, that is, the drier rocks.

3. Within the mafic rocks hypersthene is variably present on the scale of an outcrop or even a handspecimen, and produces a mixed pattern of facies. This points to a very local control for the low activity of water.

4. The mineralogical variation within the mafic rocks fits well into Powell's (1983) model for internal buffering.

5. Evidence for melting, which lowers the activity of water, is present in both pelitic gneisses and mafic granulites.

REFERENCES

Baker, A. J., and Droop, G. T. R., 1983, Grampian metamorphic conditions deduced from mafic granulites and sillimanite-K-feldspar gneisses in the Dalradian of Glen Muick, Scotland: Journal of the Geological Society of London, vol. 140, pp. 489-497.

Bhattacharya, A., and Sen, S. K., 1986, Granulite metamorphism, fluid buffering, and dehydration melting in the Madras charnockites and metapelites: Journal of Petrology, vol. 27, Part 5, pp. 1119-1141.

Bohlen, S. R., 1987, Pressure-temperature-time paths and a tectonic model for the evolution of granulites: Journal of Geology, vol. 95, pp. 617-632.

Burger, H. R., 1966, Structure, petrology, and economic geology of the Sheridan district, Madison County, Montana: Ph.D. thesis, Indiana University, Indiana, 156 p.

Chacko, Thomas, Ravindra Kumar, G. R., and Newton, R. C., 1987, Metamorphic P-T conditions of the Kerala (south India) khondalite belt, a granulite facies supracrustal terrain: Journal of Geology, vol. 95, pp. 343-358.

Condie, K. C., and Allen, P., 1984, Origin of Archaean charnockites from southern India, <u>in</u> Kroner, A., et. al., eds., Archaean Geochemistry: Heidelberg, Springer-Verlag, pp. 182-203.

Condie, K. C., Allen, Philip, and Narayana, B. L., 1982, Geochemistry of the Archean low-to high-grade transition zone, southern India: Contribution to Mineralogy and Petrology, vol. 81, pp. 157-167.

de Waard, D., 1965, A proposed subdivision of the the granulite facies: American Journal of Science, vol. 263, pp. 455-461.

Fountain, D. M., and Salisbury, M. H., 1981, Exposed cross-sections through the continental crust: implications for crustal structure, petrology, and evolution: Earth and Planetary Science Letters, vol. 56, pp. 263-277.

Glassley, W. E., 1983a, The role of CO2 in the chemical modification of deep continental crust: Geochimica et Cosmochimica Acta, vol. 47, pp. 597-616.

Glassley, W. E., 1983b, Deep crustal carbonates as CO2 fluid sources: evidence from metasomatic reaction zones: Contributions to Mineralogy and Petrology, vol. 84, pp. 15-24.

Glassley, W. E., and Sorensen, Kai, 1980, Constant Ps-T amphibolite to granulite facies transition in Agto (West Greenland) Metadolerites: implications and applications: Journal of Petrology, vol. 21, Part 1, pp. 69-105.

Gulley, G. L., Jr., 1985 A Proterozoic granulite terrane on Roan Mountain, western Blue Ridge belt, North Carolina-Tennessee: Geological Society of America vol. 96, p. 1428-1439.

Hanley, T. B., and Vitaliano, C. J., 1983, Petrography of Archean mafic dikes of the Tobacco Root Mountains, Madison County, Montana: Northwest Geology, vol. 12, pp. 43-55.

Hansen, E. C., Janardhan, A. S., Newton, R. C., Prame, W. K. B. N., and Kumar, G. R. Ravindra, 1987, Arrested charnockite formation in southern India and Sri Lanka: Contributions to Mineralogy and Petrology, vol. 96, pp. 225-244.

Hansen, E. C., Newton, R. C., and Janardhan, A. S., 1984, Pressures, temperatures and metamorphic fluids across and unbroken amphibolite facies to granulite facies transition in southern Karnataka, India, in Kroner, A., et. al., eds., Archaean Geochemistry: Heidelberg, Springer-Verlag, pp. 161-181.

Harley, S. L., 1985, Garnet-orthopyroxene bearing granulites from Enderby Land, Antarctica: Metamorphic pressure-temperature-time evolution of the Archaean Napier Complex: Journal of Petrology, vol. 26, Part 4, pp. 819-856.

Holt, R. W., and Wightman, R. T., 1983, The role of fluids in the development of a granulite facies transition zone in S India: Journal of the Geological Society of London, vol. 140, pp. 651-656.

Hooper, P. R., and Johnson, D.,1987, Major and trace element analyses of rocks and minerals by automatic x-ray spectrometry: Washington State University, Pullman, unpublished report, 9 p.

Hyndman, D. W., 1981, Controls on source and depth of emplacement of granitic magma: Geology, vol. 9, pp.

244-249.

Hyndman, D. W., 1985, Petrology of Igneous and Metamorphic Rocks, Second Edition: McGraw Hill, New York 786 p.

Hyndman, D. W., Alt, D., and Sears, J. W., 1988, Post-Archean metamorphic and tectonic evolution of western Montana and northern Idaho, in Ernst, W. G., ed., Metamorphism and Crustal Evolution of the Western United States: Prentice Hall, Englewood Cliffs, NJ.

Hyndman, D. W., and Foster, D. A., 1988, The role of tonalites and mafic dikes in the generation of the Idaho batholith: Journal of Geology, vol. 96, no. 1, pp. 31-46.

James, H. L., and Hedge, C. E., 1980, Age of the basement rocks of southwest Montana: Geological Society of America Bulletin, vol. 91, pp. 11-15.

Janhardhan, A. S., Newton, R. C., and Hansen, E. C., 1982, The transformation of amphibolite facies gneiss to charnockite in southern Karnataka and northern Tamil Nadu, India: Contributions to Mineralogy and Petrology, vol. 79, pp. 130-149.

Janardhan, A. S., Newton, R. C., and Smith, J. V., 1979, Ancient crustal metamorphism at low PH2O: charnockite formation at Kabbaldurga, south India: Nature, vol. 278, pp. 511-514.

Lamb, R. C., Smalley, P. C., and Field, D., 1986, P-T conditions for the Arendal granulites, southern Norway: implications for the roles of P, T, and CO2 in deep crustal LILE-depletion: Journal of Metamorphic Geology, vol. 4, pp. 143-160.

Lamb, William, and Valley, J. W., 1984, Metamorphism of reduced granulites in low-CO2 vapour-free environment: Nature, vol. 212, pp. 56-58.

Lamb, W. M., and Valley, J. W., 1985, C-O-H fluid calculations and granulite genesis, in Tobi, A. C., and Touret, J. L. R., eds., The Deep Proterozoic Crust in the North Atlantic Provinces: D. Reidel Publishing Company, pp. 119-131.

Lamb, W. M., Valley, J. W., and Brown, P. E., 1987, Post-metamorphic CO2-rich fluid inclusions in granulites: Contributions to Mineralogy and Petrology, vol. 96, pp. 485-495.

Moorbath, S., 1984, Origin of granulites: Nature, vol. 312, p.290.

Mueller, P. A., and Cordua, W. S., 1976, Rb-Sr whole rock age of the gneiss from the Horse Creek area, Tobacco Root Mountains, Montana: Isochron/West, no. 17, pp. 33-36.

Newton, R. C., 1985, Temperature, pressure and metamorphic fluid regimes in the amphibolite to granulite facies transition zones, in Tobi, A. C., and Touret, J. L. R., eds., The Deep Proterozoic Crust in the North Atlantic Provinces: D. Reidel Publishing Company, pp. 75-104.

Newton, R. C., Smith, J. V., and Windley, B. F., 1980, Carbonic metamorphism, granulites and crustal growth: Nature, vol. 288, pp. 45-49.

Oliver, G. J. H., 1980, Geology of the granulite and amphibolite facies gneisses of Doubtful Sound, Fiordland, New Zealand: New Zealand Journal of Geology and Geophysics, vol. 23, no. 1, pp. 27-41.

Philips, G. N., 1980, Water activity across an amphibolite-granulite facies transition, Broken Hill, Australia: Contributions to Mineralogy and Petrology, vol. 75, pp. 377-386.

Powell, R., 1983, Fluids and melting under upper amphibolite facies conditions: Journal of the Geological Society of London, vol. 140, pp. 629-633.

Powell, R., 1983, Processes in granulite-facies metamorphism, in Atherton, M. P. and Gribble, C. D., eds., High grade metamorphism, migmatites and melting: Orpington, Shiva Publishing Company, pp. 127-139.

Raase, P., Raith, M., Ackermand, D., and Lal, R. K., 1986, Progressive metamorphism of mafic rocks from greenschist to granulite facies in the Dharwar craton of south India: Journal of Geology, vol. 94, pp. 261-282.

Schaefer, M. J., 1986, Petrology, origin, and tectonic interpretation of an Archean rock package in the Ruby Range, southwestern Montana: M.S. Thesis, University of Montana, 111 p.

Schenk, Volker, 1984, Petrology of felsic granulites, metapelites, metabasics, ultramafics, and metacarbonates from southern Calabria (Italy):

prograde metamorphism, uplift and cooling of a former lower crust: Journal of Petrology, vol. 25, Part 1, pp. 255-298.

Thompson, A. B., 1982, Dehydration melting of pelitic rocks and the generation of H2O-undersaturated granitic liquids: American Journal of Science, vol. 282, pp. 1567-1595.

Thompson, A. B., 1983, Fluid-absent metamorphism: Journal of the Geological Society of London, vol. 140, pp. 522-547.

Touret, J. and Dietvorst, P, 1983, Fluid inclusions in high-grade anatectic metamorphites: Journal of the Geological Society of London, vol. 140, pp. 635-649.

Turner, F. J., 1981, Metamorphic Petrology: Mineralogical, Field and Tectonic Aspects: McGraw-Hill, New York, 524 p.

Valley, J. W., 1986, Fluid-absent metamorphism in the Adirondacks, in Ashwal, L., ed., Early Crustal Genesis: The World's Oldest Rocks: L.P.I. Technical Report 86-04.

Valley, J. W., McLelland, J., Essene, E. J., and Lamb, William, 1983, Metamorphic fluids in the deep crust: evidence from the Adirondacks: Nature, vol. 301, pp. 226-228.

Valley, J. W., and O'Neil, J. R., 1984, Fluid heterogeneity during granulite facies metamorphism in the Adirondacks: stable isotope evidence: Contributions to Mineralogy and Petrology, vol. 85, pp. 158-173.

Vitaliano, C. J., Cordua, W. S., Hess, D. F., Burger, H. R., III, Hanley, T. B., and Root, F. K., 1979, Geologic map of the southern Tobacco Root Mountains, Madison County, Montana: Geologic Society of America Map and Chart Series, MC-31.

Waters, D. J., and Whales, C. J., 1984, Dehydration melting and the granulite transition in metapelites from southern Namaqualand, S. Africa: Contributions to Mineralogy and Petrology, vol. 88, pp. 269-275.

Weaver, B. L., and Tarney, J., 1983, Elemental depletions in Archaean granulite-facies rocks, in Atherton, M. P., and Gribble, C. D., eds., High grade metamorphism, migmatites and melting: Orpington, Shiva Publishing Company, pp. 250-263.

Wilson, M. L., and Hyndman, D. W., 1988, Tectonic interpretation of an Archaean litholgic package enclosing iron-formation in the southern Tobacco Root and northern Ruby Ranges of southwest Montanta, USA, in Augustithis, S. S., ed., Precambrian iron-formations: Theophrastus Publishing, Athens, Greece.

Windley, B. F., 1972, Regional geology of early Precambrian high-grade metamorphic rocks in West Greenland: Gronland Geologiske Undersogelse Rapport Nr. 46.

Winkler, H. G. F., 1979, Petrogenesis of Metamorphic Rocks, Fifthe Edition: Springer-Verlag, New York, 348 p.

APPENDIX A

Appendix A is a summary of the petrographic data. The minerals present are listed in increasing abundance. The occurrence of serpentine in these samples is as an alteration product. Rock types followed by an asterisk (*) indicate that textural evidence for a reaction is visible in thin section.

Sample	Stable mineral assemblage	Rock type	Facies
1A	bio-gar-hbl-ksp-plag-qtz	gneiss	amphibolite
1B	hbl-gar-plag-qtz	gneiss	amphibolite
2B	gra-mica-trem-calcite	marble	amphibolite
2D	mica-trem-diop-for-calcite	marble	amphibolite
2E	hbl-plag-qtz-perthite	gneiss	amphibolite
3A	bio-qtz-hbl-gar-diop-plag	gar granulite	granulite
3B	bio-qtz-diop-gar-hbl-plag	gar granulite	granulite
3C	bio-ksp-plag-qtz	gneiss	amphibolite
4	bio-gar-sill-ksp-plag-qtz	gneiss	amphibolite
6A	qtz-diop-gar-plag-hbl	gar granulite	granulite
9C	gar-plag-hbl	amphibolite	amphibolite
9D	gar-bio-ksp-plag-qtz	gneiss	amphibolite
9E	qtz-gar-hbl-plag	amphibolite	amphibolite
9G	gar-bio-qtz-plag	gneiss	amphibolite
10A	mica-serp-calcite	marble	amphibolite
10D	plag-qtz-bio-sill-ksp	schist	amphibolite
10E	sph-ksp-carb-diop-qtz	quartzite	amphibolite
12A	bio-qtz-gar-hbl-plag	amphbilolite	amphibolite
12B-1	gar-qtz-orthoamph-hbl-plag	gneiss *	amphibolite
12B-2	qtz-orthoamph-hbl-plag-gar	gneiss *	amphibolite
12B-3	bio-qtz-gar-hbl-plag	gneiss	amphibolite
12D	mica-diop-carb	marble	amphibolite
12E	bio-plag-gar-qtz	gneiss	amphibolite
13A	diop-hbl-plag	amphibolite	amphibolite

Sample	Stable mineral assemblage	Rock type	Facies
13B	bio-gar-plag-ksp-qtz	gneiss	amphibolite
13C	plag-ksp-qtz	gneiss	amphibolite
15	qtz-gar-diop-hbl-plag	gneiss	granulite
16B	for-mica-serp-carb	marble	amphibolite
19B	rut-opaque-cpx-serp	serpentinite	granulite
19D	qtz-gar-diop-hbl-plag	gar granulite	granulite
20B	hbl-diop-gar-plag	gneiss	granulite
20F	bio-hbl-gar-diop-plag	gneiss	granulite
21	bio-diop-hbl-gar-plag	gneiss	granulite
22	gar-sill-gra-ksp-bio-qtz	schist	amphibolite
23	sph-plag-bio-for-diop-carb	calc-silicate	amphibolite
24A	qtz-gar-orthoamph-plag	gneiss	amphibolite
25A	qtz-hyp-plag-hbl	granulite	granulite
25B	hyp-hbl-plag	granulite	granulite
25C	qtz-plag-hyp-hbl	hornblendite	granulite
27	qtz-hbl-gar-diop-plag	gar granulite *	granulite
29A	qtz-diop-gar-hbl-plag	gar granulite *	granulite
29B	hbl-qtz-gar-diop-plag	gneiss	granulite
31	gar-qtz-hbl-plag	amphibolite	amphibolite
34C	mica-diop-for-carb	marble *	amphibolite
37A	bio-qtz-ksp-plag	gneiss *	amphibolite
37B	qtz-hbl-diop-gar-plag	gneiss	granulite
42B	carb-trem	calc-silicate *	amphibolite
43B	bio-sill-plag-qtz	schist *	amphibolite
44C	bio-gar-sill-ksp-qtz	schist	amphibolite
45C-1	bio-qtz-diop-plag-hbl	gneiss	amphibolite
45C-2	qtz-bio-gar-hbl-plag	gneiss	amphibolite
47	orthoamphibole	orthoamphibolite	amphibolite
48A	qtz-orthoamph-gar	ultramafic	amphibolite
48B-1	rut-bio-ksp-gar-sill-plag-qtz	gneiss	transitional
48B-2	rut-bio-perthite-gar-sill-plag-qtz	gneiss	transitional
49	qtz-bio-gar-ky-plag	gneiss	amphibolite

Sample	Stable mineral assemblage	Rock type	Facies
50	qtz-gar-diop-plag-hbl	gar granulite	granulite
53	diop-hyp-hbl-plag	granulite	granulite
54A	hbl-plag-hyp	granulite	granulite
55A-1	qtz-gar-diop-plag	gneiss *	granulite
57	hbl-hyp-plag	granulite	granulite
57B	qtz-gar-hbl-hyp-plag	granulite *	granulite
58	hbl-hyp-plag	granulite	granulite
60B	diop-plag-hbl	amphibolite	amphibolite
60C-1	diop-hbl-plag	amphibolite	amphibolite
60C-2	qtz-diop-hbl-plag	amphibolite	amphibolite
60D	hbl-hyp-plag	granulite	granulite
61A	qtz-plag-hbl	amphibolite	amphibolite
61C	hyp-plag-hbl	granulite	granulite
62	diop-plag-hbl	amphibolite	amphibolite
63	diop-hyp-plag-hbl	granulite	granulite
65	hyp-hbl-plag	granulite	granulite
68B	qtz-gar-bio-hyp-plag	granulite	granulite
69	bio-hbl-qtz-diop-gar-plag	gar granulite *	granulite