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PETROLOGY OF ALUMINOUS SCHIST IN THE BOEHLS BUTTE REGION OF NORTHERN IDAHO: GEOLOGIC HISTORY AND ALUMINUM-SILICATE PHASE RELATIONS

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ABSTRACT. Metapelitic rocks in the Goat Mountain-Boehls Butte area of northern Idaho, correlative with the lowermost units of the Belt Supergroup and the pre-Beltian basement, record a long and complex evolution. Prior to 1600 Ma, anorthositic magma intruded and partially melted portions of the basement complex, thereby producing restites unusually rich in aluminum and magnesium. Three subsequent metamorphic episodes resulted in a plethora of complex stable and metastable mineral assemblages, highlighted by the occurrence of all three aluminum silicate polymorphs. Kyanite and sillimanite grew during the second metamorphic event, M2. The peak M2 mineral paragenesis consisted of kyanite ± sillimanite + biotite + plagioclase ± rutile ± ganet ± muscovite ± staurolite ± corundum or quartz. Following M2, nearly isothermal decompression resulted in the growth of low-pressure M3 minerals accompanied by the the metastable persistence of most M2 phases. Rutile was partially replaced by ilmenite, and cordierite ± corundum ± hercynite formed at the expense of biotite, garnet, and aluminum silicate. Andalusite formed from polymorphic inversion of *strained* kyanite while unstrained kyanite and sillimanite remained.

INTRODUCTION

Metamorphic facies, as originally introduced by Eskola (1915), are defined on the basis of sets of mineral parageneses so that, within any one facies, the mineral assemblage of a rock is determined solely by its chemical composition. Individual metamorphic facies correspond to a certain range of temperature and pressure; to describe the progressive path of metamorphism within a given terrane, the concept of facies series was developed (Fyfe, Turner, and Verhoogen, 1958; Miyashiro, 1961). Miyashiro's (1961) list of five original facies series was expanded to nine by Hietanen (1967a). One of these, which Hietanen named the Idahoan facies series, was based on the widespread occurrence of all three aluminum silicate polymorphs (andalusite, kyanite, and sillimanite) in pelitic

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schists located in the Boehls Butte-Goat Mountain area of northern Idaho. Hietanen (1956) saw no obvious disequilibrium textures involving the aluminum silicates and suggested that pressure and temperature during recrystallization(s) were at or very near the aluminum silicate triple point.

Although metamorphic field gradients passing through, or near, the Al_2SiO_5 triple point have been suggested (New England, Thompson and Norton, 1968), they are rare. In northern Idaho, such a gradient is inconsistent with the lower-grade portion of the progressive sequence which is distinctly Barrovian in character, with pressure definitely above the triple point (Hietanen, 1968; Lang and Rice, 1985a,b,c). Furthermore, studies by Hyndman and Alt (1972), Reid and others (1973), and Lang and Rice (1985a,b,c) have indicated that this terrane is in fact polymetamorphic, with relict minerals persisting through the latest recrystallization event. In spite of these reservations, Carmichael (1978) included the Idahoan facies series in his paper introducing the concept of bathograds and bathozones.

The Boehls Butte-Goat Mountain area consists of an uplifted fault block, approx 450 km^2 in area, surrounded by metasedimentary rocks of the Proterozoic Belt Supergroup (fig. 1). Metamorphism of the overlying Belt series (fig. 2) is characterized by a consistent increase in grade from the biotite zone near the St. Joe River in the north to the sillimanite and sillimanite + K-feldspar zones adjacent to the Idaho batholith in the south (Hietanen, 1969; Lang and Rice, 1985a,b,c; Ruendal, ms; Rice, 1987). Within the Boehls Butte-Goat Mountain block, three large and several small, concordant, lens-shaped bodies of anorthosite occur. The anorthosites, 0.5 to 2 km in thickness, include layered, foliated, and massive varieties containing two or three distinct compositions and generations of plagioclase. They are typically surrounded by highly aluminous, Mg-rich, pelitic schists which exhibit complex textural relationships among the three aluminum silicate minerals, garnet, biotite, muscovite, plagioclase, cordierite, rutile/ilmenite, and either quartz or corundum.

The rocks of the Boehls Butte-Goat Mountain area have been the subject of some controversy since Hietanen's (1956) description of the coexisting[1] andalusite, kyanite, and sillimanite. Uncertainty exists concerning (1) the age of the protolith and the timing of metamorphism; (2) the origin of the anorthosites and the Al-rich schists surrounding them; (3) whether all three Al_2SiO_5 polymorphs actually represent a stable equilibrium assemblage; and (4) the role of polymetamorphism and the persistence of metastable phases in the observed parageneses. In this report we address these and other issues. Observations bearing on the above problems stem primarily from detailed study of the pelites surrounding

[1] Throughout this paper, the term "coexist" is used to describe minerals that simply exist within a given rock or thin section. Minerals that coexist are not necessarily in equilibrium, as is commonly inferred by use of the term.

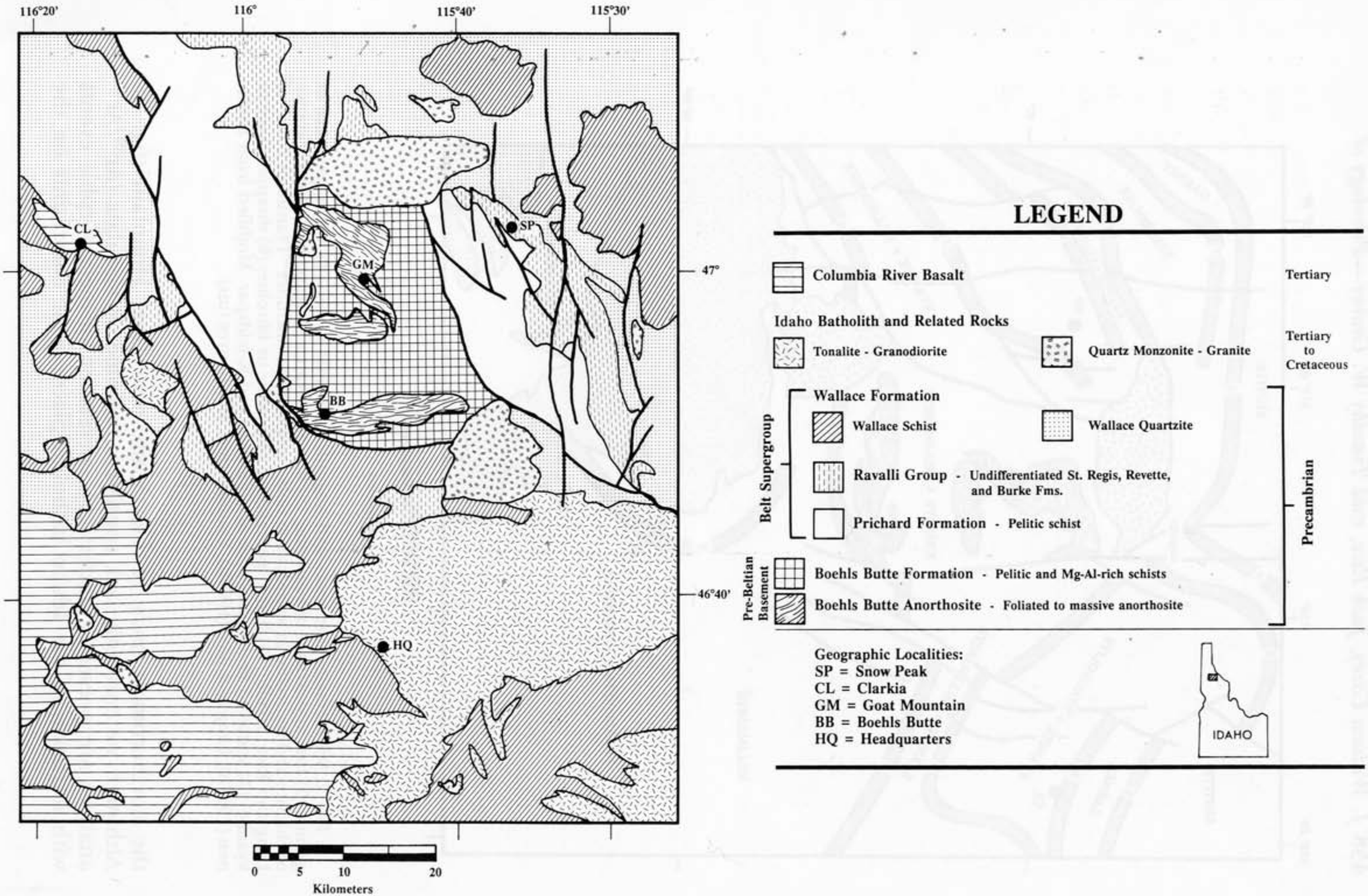


Fig. 1. Generalized geologic map of the region lying between the St. Joe and Clearwater rivers of northern Idaho. Modified from Hietanen (1967b, 1984). Geographic localities: GM = Goat Mountain; BB = Boehls Butte; SP = Snow Peak; CL = Clarkia; HQ = Headquarters.

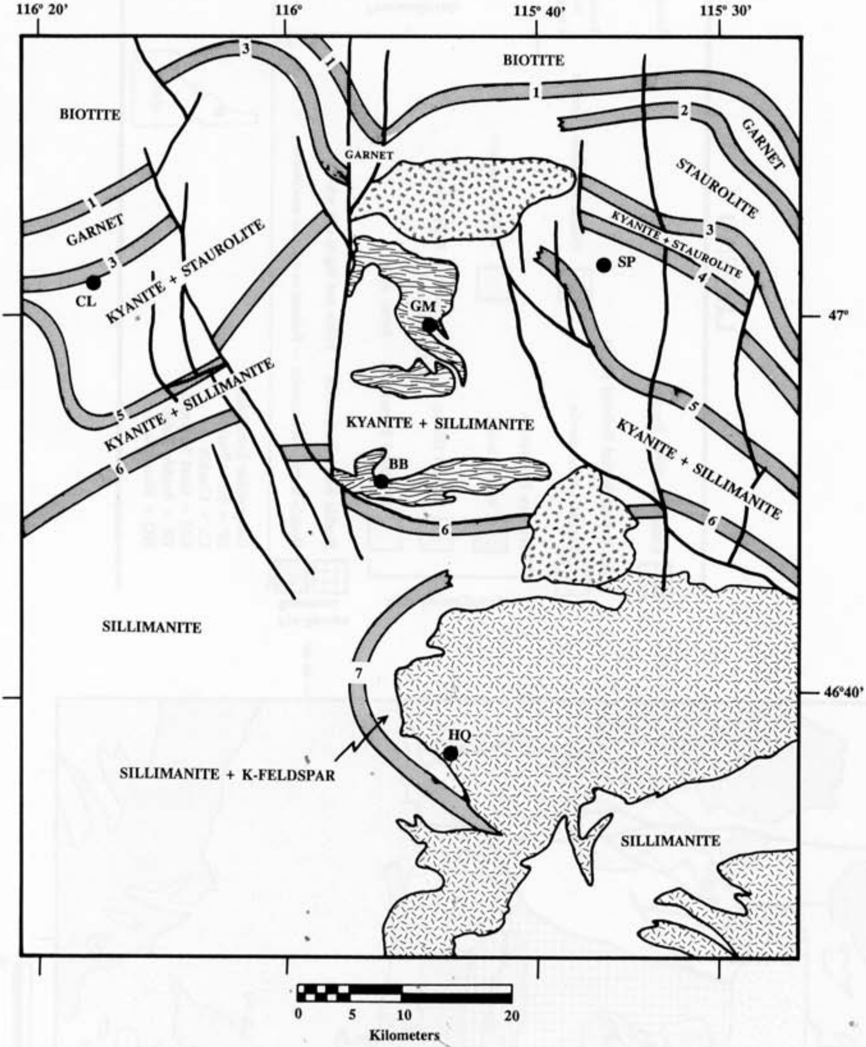


Fig. 2. M2 metamorphic zones and isograds for pelitic schists: (1) first appearance of garnet; (2) first appearance of staurolite; (3) first appearance of kyanite; (4) disappearance of chlorite and staurolite in appropriate bulk compositions (includes "Transition Zone" of Lang and Rice, 1985b); (5) first appearance of sillimanite or fibrolite; (6) disappearance of kyanite; (7) scattered first appearance of sillimanite and K-feldspar. Modified from Hietanen (1967b), Lang and Rice (1983b), Ruendal (ms), and Grover (ms).

the northernmost body of anorthosite near Goat Mountain (fig. 3). Although we currently lack consistent radiometric age data (Ar^{39}/Ar^{40} analyses are presently underway), correlation of metamorphic events with intrusion of the Idaho batholith places some constraints on the

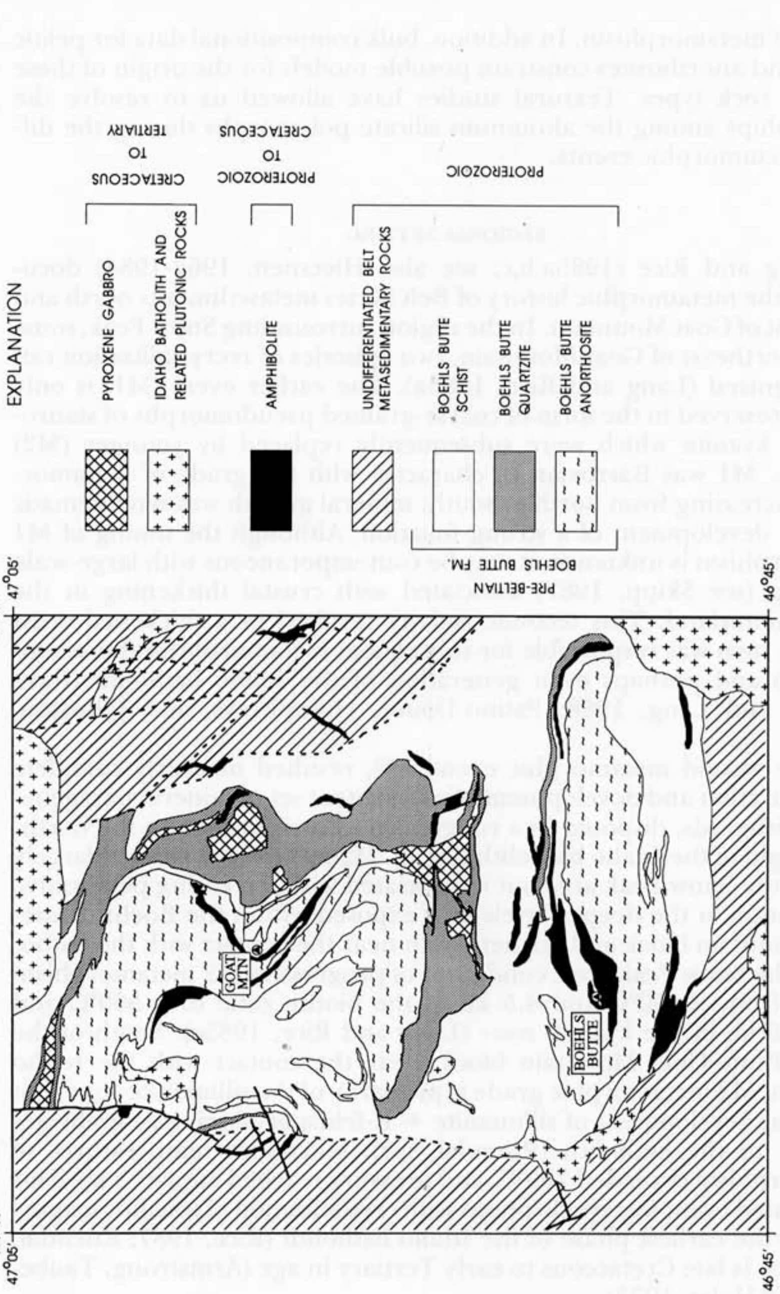


Fig. 3. Geologic map of the Goat Mountain-Boehls Butte area. Modified from Hietanen (1963), Carey (ms), and Grover (ms).

timing of metamorphism. In addition, bulk compositional data for pelitic schists and anorthosites constrain possible models for the origin of these unusual rock types. Textural studies have allowed us to resolve the relationships among the aluminum silicate polymorphs during the different metamorphic events.

REGIONAL SETTING

Lang and Rice (1985a,b,c; see also Hietanen, 1962-1984) documented the metamorphic history of Belt Series metasediments north and northeast of Goat Mountain. In the region surrounding Snow Peak, some 30 km northeast of Goat Mountain, two episodes of recrystallization can be recognized (Lang and Rice, 1985a). The earlier event, M1, is only locally preserved in the form of coarse-grained pseudomorphs of staurolite and kyanite which were subsequently replaced by younger (M2) minerals. M1 was Barrovian in character with the grade of metamorphism increasing from north to south; mineral growth was synkinematic with the development of a strong foliation. Although the timing of M1 metamorphism is unknown, it may be contemporaneous with large-scale thrusting (see Skipp, 1987) associated with crustal thickening in the Sevier hinterland. This tectonic activity resulted in a thickened crust which in turn was responsible for subsequent metamorphism (for example, M2) and perhaps even generation of the Idaho batholith (Rice, Grover, and Lang, 1988; Patino-Douce, Humphreys, and Johnston, 1990).

The second metamorphic event, M2, resulted in nearly complete reequilibration and development of a consistent set of mineral parageneses and isograds, disposed in a roughly concentric fashion to the northern margin of the Idaho batholith (fig. 2). M2 metamorphism was largely static in the Snow Peak area but is associated with increasing penetrative deformation in the deeper levels now exposed within the Boehls Butte-Goat Mountain block and farther south near the contact with the batholith. In the Snow Peak area, conditions of progressive M2 metamorphism ranged from <450°C and 4.5 kb. in the biotite zone to >560°C and approx 6 kb in the kyanite zone (Lang and Rice, 1985c). South of the Boehls Butte-Goat Mountain block, near the contact with the Idaho batholith, M2 metamorphic grade is primarily of the sillimanite zone, but with local development of sillimanite + K-feldspar-bearing assemblages adjacent to the batholith (Ruendal, ms). Maximum temperatures of metamorphism exceeded 700°C, and pressure reached approx 8 kb. This deep-seated event was synchronous with crystallization of tonalitic magma forming the earliest phase of the Idaho batholith (Rice, 1987; Ruendal, ms) which is late Cretaceous to early Tertiary in age (Armstrong, Taubeneck, and Hales, 1977).

Rocks within the Boehls Butte-Goat Mountain block are anomalous relative to the surrounding metasediments. The anorthositic rocks and their associated Mg-Al-rich schists do not have counterparts outside the fault block. The occurrence of the three aluminum silicate minerals implies either a different facies series, as suggested by Hietanen (1967a), or metastability owing to polymetamorphism. As noted above, however, the two metamorphic events recognized in the Snow Peak area are Barrovian in character and lack evidence for low-pressure recrystallization. Our detailed studies, summarized below, demonstrate that andalusite, cordierite, ilmenite, hercynite, and corundum formed during a third event, M3, which is recorded throughout the Boehls Butte-Goat Mountain block and is locally developed elsewhere in the St. Joe-Clearwater region.

THE BOEHLS BUTTE FORMATION

Age.—At the present time, relatively few radiometric age determinations exist for metamorphic rocks in the St. Joe-Clearwater region. In addition, many of those that have been published are ambiguous; some Pb-Pb and U-Pb analyses are complicated by contamination from inherited zircons, and many K-Ar ages reflect resetting during Eocene hydrothermal activity associated with shallow intrusion of the latest phases of the Idaho batholith. In spite of these complexities, some consistent data emerge. Reid, Morrison, and Greenwood (1973) report U-Pb ages of 1665 Ma for Al-rich schist surrounding anorthosite and 1625 Ma for anorthosite proper. These ages are consistent with the pre-Beltian age of the anorthosite complex and with the hypothesis that anorthositic magma intruded pre-Beltian basement rocks. K-Ar ages on several mafic tonalites and granodiorites, representing the early phases of batholithic intrusion, range from 95 to 60 Ma (Hietanen, 1969, 1984; Armstrong, Taubenech, and Hales, 1977; Fleck and Criss, 1985). Recognition of coeval M2 metamorphism and crystallization of early tonalites (Ruendal, ms) leads us to suggest that this span of time also includes M2 metamorphism. Two K-Ar ages (biotite) from Al-rich schists are 61 and 46 Ma (Hietanen, 1969, 1984). These ages may be representative of M3 metamorphism and/or the latest closure temperatures. The youngest intrusive rocks of the batholith record ages of 41 to 43 Ma (Hietanen, 1969, 1984; Reid and Greenwood, 1968). Finally, the entire region was uplifted to approximately its present elevation by 17 Ma when Columbia River flood basalts overlapped the westernmost outcrops.

Origin of anorthosite and aluminous schist.—Anorthosites in the Boehls Butte-Goat Mountain block are unlike typical Proterozoic or Archean anorthosites (Anderson and Morin 1969); hence their origin — igneous, metasedimentary, or metasomatic — has been a subject of some debate. Features such as local relict cumulus textures, Carlsbad twinning in labradorite, and certain geochemical signatures imply an igneous origin (Nord, ms; Juras, ms; Goldberg, ms). On the other hand, features such as large andesine megacrysts embedded within a find-grained bytownite groundmass (Nord, ms), the presence of layers and remnants of metasedimentary composition (assemblages containing biotite, aluminum silicate, and garnet), and the presence of layers and schlieren of plagioclase-rich compositions within the surrounding pelitic schists led Hietanen (1962, 1963, 1969, 1986) to invoke a metasomatic origin. Hietanen's model involves the metamorphism of alternating layers of calcareous shale and aluminum-rich shale and short-distance migration of elements between these layers to produce a calcic plagioclase rock subsequently altered by sodium metasomatism causing the partial replacement of calcic plagioclase by andesine.

The geochemistry of Boehls Butte-Goat Mountain anorthosites has recently been studied by Goldberg (ms). If layers and schlieren containing abundant aluminum silicate, garnet, mica, and cordierite are excluded, massive and foliated anorthosites are compositionally equivalent. They are characterized by high contents of alumina (>29 wt percent), calcium (>11 wt percent), and strontium (>450 ppm), and very low transition and large ion lithophile (for example, K, Rb, Hf, Th, U) elemental abundances. Transition element abundances for Sc, Cr, Co, and Ni are each less than 5 ppm, commonly less than 1 ppm, and therefore are among the lowest observed values for anorthosites (Papezik, 1965). K/Rb ratios of approx 400 are also among the lowest observed in anorthosites. Rare earth element patterns are light REE enriched (La/Sm ≈ 6) and exhibit large positive Eu anomalies (Eu/Sm ≈ 8). These fractionated patterns are nearly identical to those from other Proterozoic anorthosites thought to have formed by cumulate processes (Simmons and Hanson, 1978; Ashwal and Seifert, 1980). $^{87}Sr/^{86}Sr$ ratios for massive anorthosite from the northernmost body range from 0.7039 to 0.7049 and average 0.7046 for anorthosite samples throughout the Boehls Butte-Goat Mountain complex (Heath and Fairbairn, 1969). These values are within the range observed for other massif anorthosites thought to have had an upper mantle or lower crustal origin. The values are noticeably lower than those for shale ($^{87}Sr/^{86}Sr = 0.720$) and Proterozoic marine limestone ($^{87}Sr/^{86}Sr > 0.705$). We argue that such anorthosites could not be derived by anatexis or metasomatism of argillaceous limestones or other sedimentary material.

We conclude that the Boehls Butte-Goat Mountain anorthosites originated by magmatic crystallization prior to 1600 Ma. The original anorthosites underwent substantial alteration during their subsequent (sub-liquidus) history. Intrusion of the anorthositic magma was associated with lit-par-lit injection and partial assimilation of country rocks in the contact zone. Original textures and mineralogies have been largely obliterated by at least three episodes of metamorphism (Carey, ms; this study) and at least four phases of deformation (Reid and Greenwood, 1968; Juras, ms). Recrystallization of plagioclase created foliated anorthosites, many of which exhibit plagioclase containing inclusions of metamorphic minerals such as aluminum silicate, garnet, and corundum. The occurrence of bimodal (andesine-anorthite) and trimodal (andesine-labradorite-anorthite) plagioclase-bearing anorthosites led Hietanen to discount an igneous origin. Although the subsolidus phase relations of the plagioclase solid solution are complex and incompletely understood, unmixing during metamorphism and deformation is, to us, the most reasonable explanation. The phase diagram proposed by Grove, Ferry, and Spear (1983, 1986) predicts that an original magmatic labradorite may unmix to coexisting andesine and anorthite as a result of spinodal decomposition associated with the $C\bar{1} = I\bar{1}$ transition.

Metapelitic schists surrounding the Boehls Butte-Goat Mountain anorthosite bodies are unusual in their bulk compositions, paragenetic diversity and grain size. Spectacular occurrences of aluminum silicate- and plagioclase-rich, garnet, biotite schists with kyanite porphyroblasts up to 25 cm in length and garnet porphyroblasts as large as 15 cm in diam are found in the Goat Mtn. area. These rocks, termed feldspathized schists by Nord (ms), typically are crenulated schists and gneisses containing plagioclase-rich layers and schlieren segregated from biotite- and aluminum silicate-rich zones. Megascopically, petrographically, and chemically, they are characterized by considerable heterogeneity. Chemically, they differ markedly from common sedimentary protoliths (Goldberg, ms). As shown in table 1, relative to NASC (Gromet and others, 1985) or to Shaw's (1956) average metamorphic shale, they are significantly enriched in aluminum and magnesium and locally depleted in potassium. Mineralogically this is reflected in unusually high modal abundances of aluminum silicate, plagioclase, cordierite, and corundum. Only 50 percent of our samples have sufficient K_2O to be saturated with muscovite, about 25 percent lack sufficient SiO_2 to be saturated with quartz, and 10 percent are sufficiently aluminous to be saturated with corundum.

The distribution of Al–Mg–rich compositions is systematically related to the metapelite-anorthosite contact: they occur adjacent to anorthosite or as schlieren within anorthosite, whereas more normal pelitic compositions are found farther from the contact. In the transition zone, layers and lenses of aluminous schist are locally intermixed with normal pelites. Compositional variations throughout the schist transition zone

TABLE 1

Major element analyses of Boehls Butte metapelites

	NASC Shale	Boehls Butte Metapelite						
		BBM6	BBM18	BBM23	BBM2	BBM14	BBM3	BBM7
SiO_2	64.8	64.9	50.8	49.7	53.2	46.2	47.6	53.6
TiO_2	0.78	0.83	0.05	0.01	0.04	0.06	0.04	0.13
Al_2O_3	16.9	19.8	31.9	30.6	26.9	32.9	33.5	28.6
FeO	5.70	6.93	2.24	3.36	3.97	6.93	3.61	2.84
MnO	0.06	0.04	0.05	0.04	0.01	0.04	0.03	0.06
MgO	2.85	3.04	4.82	9.56	6.20	11.28	6.83	9.07
CaO	3.56	0.72	2.60	2.53	3.57	0.60	4.68	0.69
Na_2O	1.15	0.31	4.18	3.41	5.76	1.40	2.86	1.99
K_2O	3.99	3.28	3.26	0.76	0.30	0.52	0.83	2.90

Recalculated to 100 percent on a volatile-free and reduced iron basis. NASC Shale: North American Shale Composite from Gromet and others (1985). All other data from Goldberg (ms).

are neither continuous nor systematic (Goldberg, ms). Such features are best explained in terms of partial melting of pre-Beltian, pelitic country rock that left a Mg- and Al-enriched restite surrounding the anorthositic intrusion. Lit-par-lit injection of anorthosite and assimilation of pelitic rock resulted in complex intermixing within both the contact zone and the foliated anorthosite. Subsequent mass transfer and recrystallization during multiple metamorphic events has further modified textures, mineralogies, and bulk compositions.

ALUMINUM SILICATE PHASE RELATIONS

The Al-rich nature of schists adjacent to anorthosite has resulted in spectacular occurrences of the Al_2SiO_5 minerals, which locally comprise up to 40 percent of the mode. Other minerals include biotite, plagioclase, garnet, muscovite, cordierite, staurolite, rutile and/or ilmenite, hercynite, and quartz and/or corundum. Although kyanite is predominant, half the samples we have studied contain all three polymorphs. Kyanite ranges in size from small (< 1 mm) fragments to porphyroblasts up to 25 cm in length. Such porphyroblasts lie in the plane of foliation and locally exhibit a moderate-to-strong lineation. Larger grains show evidence of intense deformation in the form of kink bands, fractures, bent cleavage planes, and splintered halos (fig. 4A). Andalusite crystals occur in optically discontinuous, mosaic-patterned aggregates (fig. 4B and C). Sillimanite generally occurs as fibrolite in habits ranging from small scattered fibers, rimming either kyanite or andalusite, to tightly bound, and locally folded, ropes. Coarser-grained sillimanite is less common but has been observed as foliated needles intergrown with biotite and/or cordierite and as inclusions within cordierite.

Textural relationships among the various aluminum silicate polymorphs are complex and have been the subject of several previous studies (Hietanen, 1956, 1963; Hyndman and Alt, 1972). The most obvious textures are those of andalusite replacing kyanite (fig. 4B) and fibrolite overgrowths on both kyanite and andalusite (fig. 4D). Such textures led Hietanen (1956) to conclude that sillimanite formed last in the paragenetic sequence, and that recrystallization occurred at or near the aluminum silicate triple point. Geobarometry, presented by Grover, Rice, and Carey (1992), indicates that these assemblages record pressures as high as 11 kb — within the kyanite stability field. Resolution of this paradox has resulted from examination of andalusite-kyanite textures and the relationship of mineral growth to a distinct crenulation cleavage.

Our interpretation of the textural relationships suggests that all andalusite originated by pseudomorphic replacement of strained kyanite, late in the metamorphic evolution. This is demonstrated by observing that both kyanite and andalusite occur in the same idiomorphic, tabular habit (fig 5A), that kyanite with undulatory extinction is often present as ragged islands within some andalusite crystals (fig. 4B, C), and that andalusite developed preferentially along cleavage planes or strained areas within kyanite (fig 5B). Andalusite formed by direct pseudomorphic replacement of kyanite. The distinctive optical mosaic habit of the andalusite is probably a consequence of the large volume change (about 15 percent) and the apparent epitaxial growth relationship (see Nord, ms, for optical data).

The primary foliation is defined by a moderate-to-strong preferred orientation of micas and large aluminum silicate porphyroblasts. This foliation is disrupted by a later deformational event manifested as a widely-spaced crenulation cleavage. In thin section, the crenulation is characterized by bent and fracture porphyroblasts (fig. 4A), granulated feldspar and mica (fig. 4B), and less commonly microfolds (fig. 4D). We believe that the fractured minerals reflect grain size reduction during ductile deformation and not cataclasis at low temperatures (that is <350°C). The crenulation postdates kyanite growth as well as sillimanite (fig 4D). Splintered fragments of kyanite surrounding deformed porphyroblasts are common products of the crenulation (fig 4A). Figure 5C illustrates a pseudomorph of kyanite that has completely inverted to andalusite. Above this porphyroblast is a typical halo of splintered aluminum silicate including both kyanite and andalusite. Kyanite fragments in the halo suggest that the crenulation event acted on the original large kyanite porphyroblast prior to inversion to andalusite. We infer that andalusite grew subsequent to development of the crenulation cleavage and following the growth of kyanite and sillimanite. In those samples were fibrolite is observed to rim andalusite, the andalusite replaced preexisting kyanite rimmed by fibrolite.

Andalusite replaced only part of the preexisting kyanite and apparently none of the sillimanite. Large porphyroblasts of kyanite have inverted, whereas the smallest ones have remained. The largest crystals were most likely to have been markedly strained during the crenulation, and strain energy may have been critical to overcoming the non-equilibrium kinetic barriers to inversion. Incomplete replacement is characteristic of kinetic barriers to polymorphic inversion in response to decompression (Rubie and Thompson, 1984). Kerrick (1986) has discussed the role of dislocation strain energy in the Al_2SiO_5 polymorphs and concluded that dislocation densities on the order of $10^{10}/cm^3$ are required to produce elastic strain energy exceeding 100 J/mol. Whereas this magnitude of excess energy results in a relatively small perturbation of the P-T positions of the *equilibrium* boundaries, we suggest that it may be important in overcoming kinetic barriers associated with the kyanite-andalusite inversion far removed from equilibrium. On the other hand, dislocation densities of $10^{10}/cm^3$ are very large. TEM examination of our strained kyanite would be necessary to evaluate the proposed model more fully.

There exist other reaction textures that occur late in the paragenetic sequence that must also be linked to decompression. The most striking of these textures is a reaction among biotite and kyanite (or andalusite after kyanite) that produces cordierite, cordierite + corundum, or cordierite + hercynite (figs. 5A, D; 6). The detailed nature of these reactions is

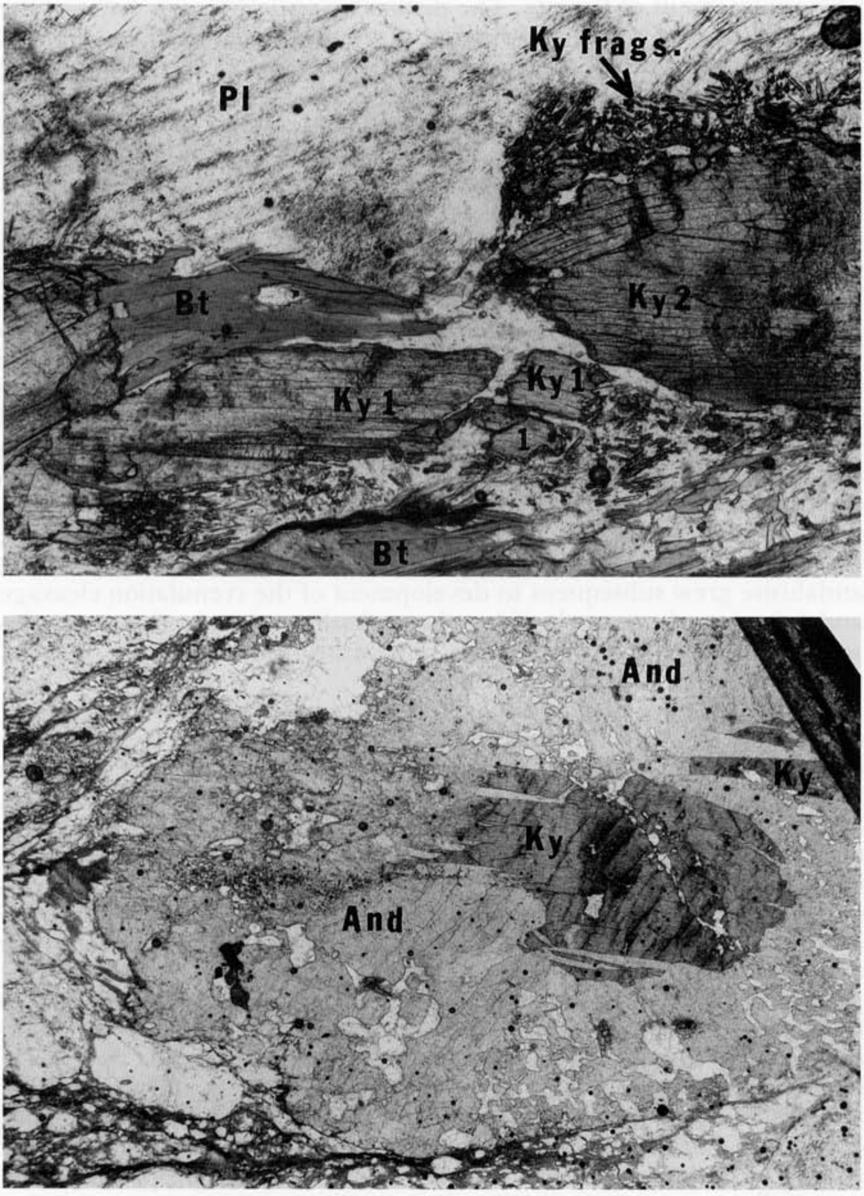
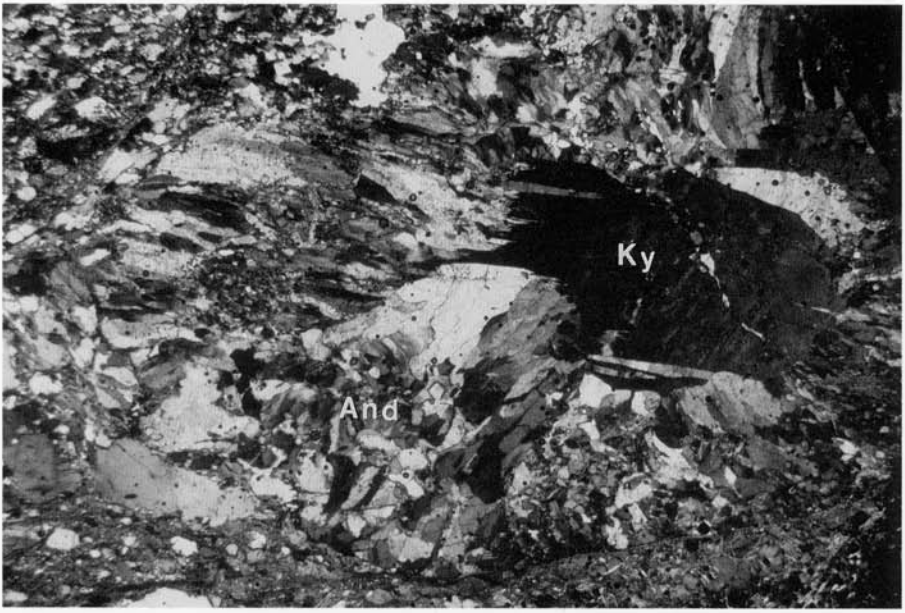
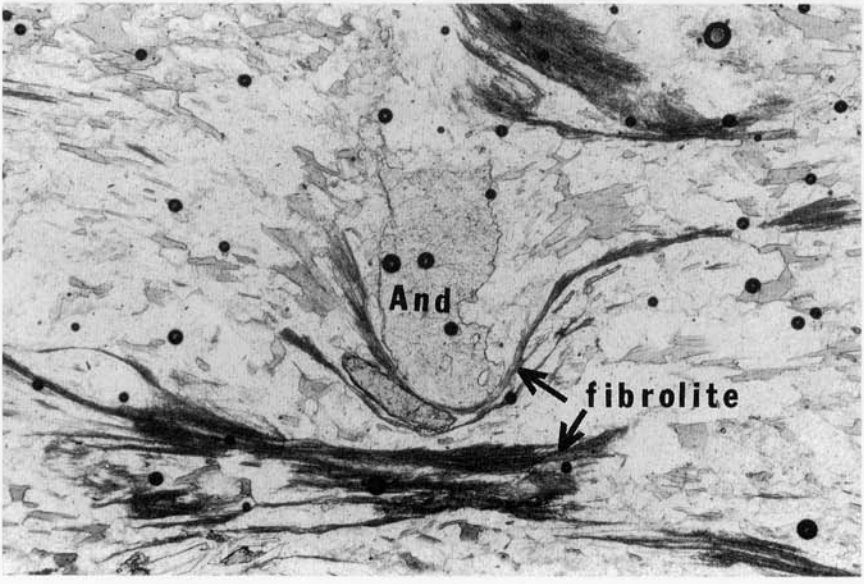


Fig. 4(A) Deformed kyanite porphyroblasts are broken into pieces (Ky-1) and splintered along borders (Ky-2). Ky-1 pieces correlate by optical continuity. Width of photomicrograph is 2.7 mm.

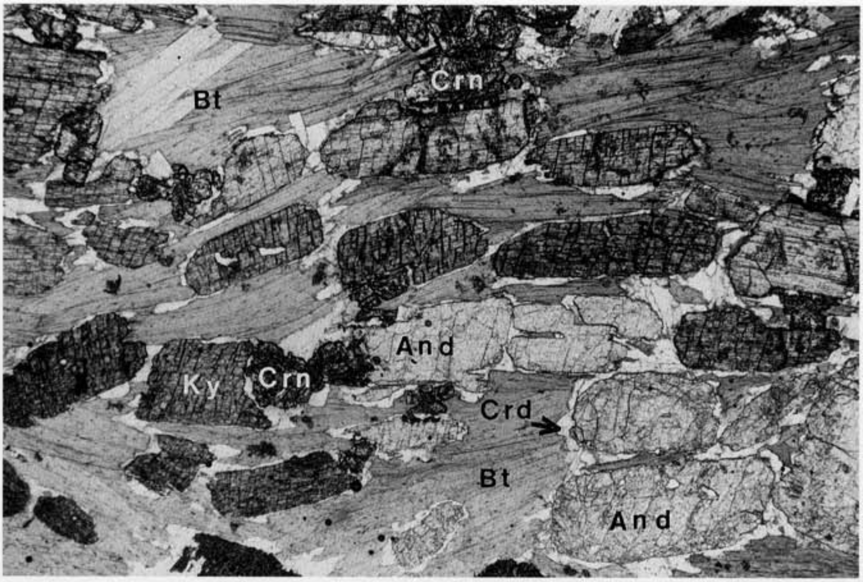
(B) Large porphyroblast of andalusite containing a ragged core of kyanite. Note zones of granulation on either exposed side of the porphyroblast. Width of photomicrograph is 8.9 mm.





(C) Same as (B) with crossed polars. Kyanite shows undulatory extinction/strain. Andalusite exhibits an optical mosaic with a crude radial orientation.

(D) Fibrolite developed on both kyanite and andalusite grain borders. Note that fibrolite has been deformed by the crenulation folds that post-date M2 and pre-date M3. Width of photo is 1.3 mm.



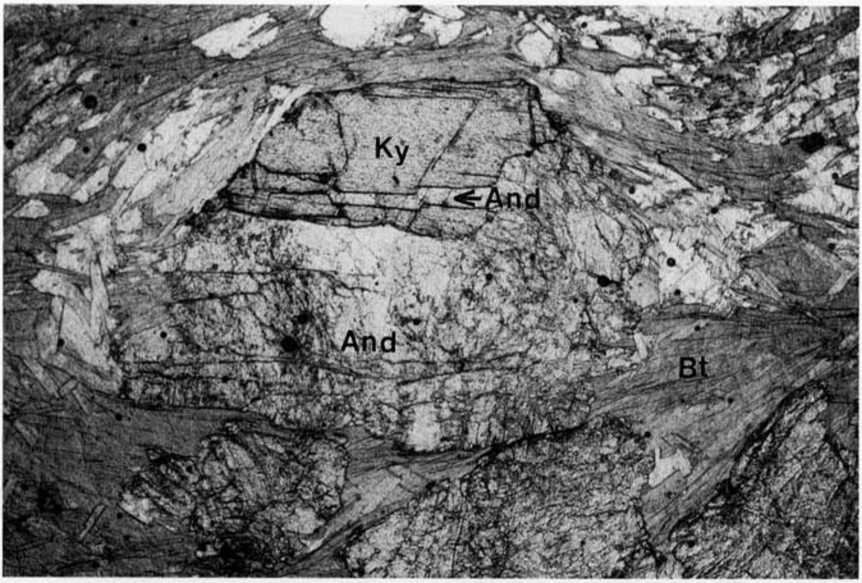
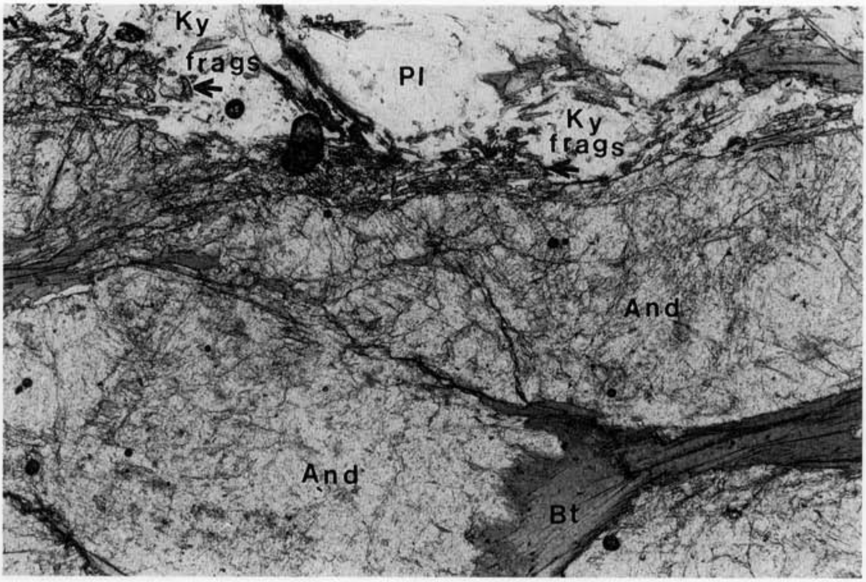
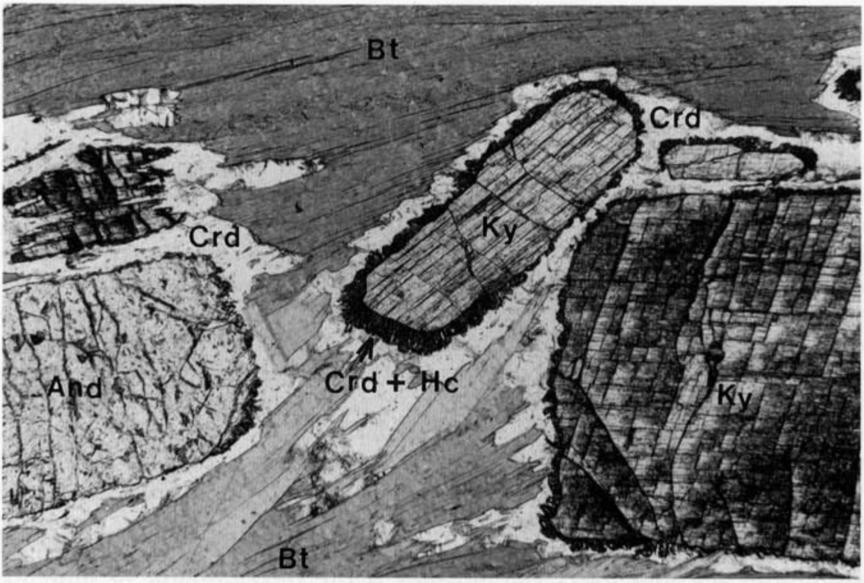


Fig. 5(A) Kyanite and andalusite of identical habit lying in the plane of the dominant foliation. Cordierite rims both aluminum silicates, and corundum appears to replace both. Width of photomicrograph is 5.2 mm.

(B) Kyanite porphyroblast almost wholly replaced by andalusite shows andalusite replacement occurring along cleavage fragments of kyanite. Width of photomicrograph is 5.2 mm.





(C) Andalusite (after kyanite) surrounded by a rim of splintered kyanite fragments. Comparison with figure 4(A) suggests that the splintered halo formed from an initial kyanite porphyroblast during crenulation. The larger kyanite crystals were strained by this deformation and subsequently inverted to andalusite, whereas the small fragments were left unstrained and unaltered. Width of photomicrograph is 2.7 mm.

(D) Kyanite and andalusite (after kyanite) porphyroblasts surrounded by biotite but separated by a thin halo of cordierite and hercynite. Width of photomicrograph is 1.3 mm.

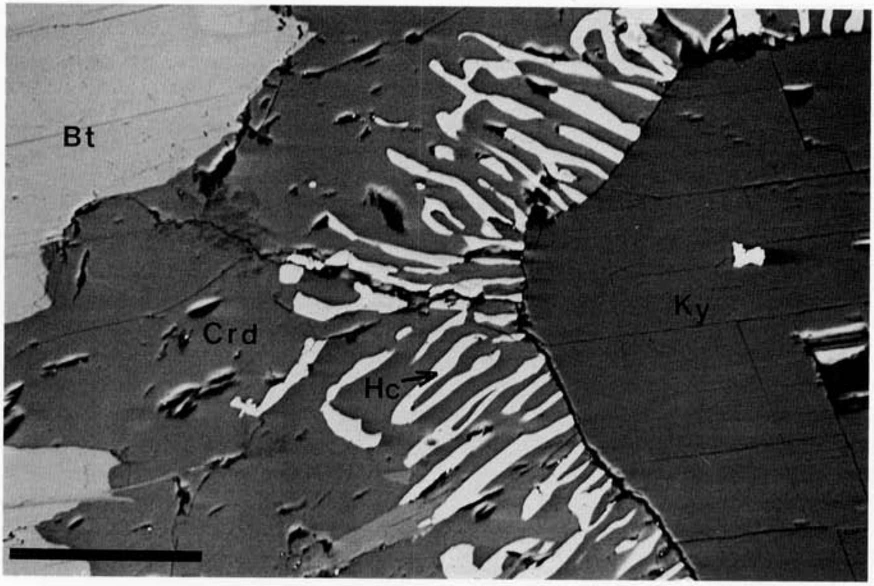


Fig. 6. Backscattered electron image of symplectic intergrowth of cordierite and hercynite forming between kyanite and biotite. Image from southwest corner of kyanite grain in center of figure 5D. Scale bar is 50 microns in length.

discussed by Grover, Rice, and Carey (1992), but we note here that they imply the stable coexistence of aluminum silicate, cordierite, ± corundum, ± hercynite, with the modal abundance of the latter three minerals increasing at the expense of the former. Corundum occurs with cordierite in a reaction relationship that destroys aluminum silicate. For example, in the left-central portion of figure 5A, a partially digested kyanite crystal is linked to andalusite by a clot of corundum. The corundum crystals are elongated along the c-axis and are typically oriented at a high angle to the aluminum silicate interface. Intergrowths of cordierite and hercynite surrounding kyanite provide additional evidence for reaction during decompression. Although not common, they develop as a fine, vermicular intergrowth perpendicular to surfaces of kyanite that are separated from adjacent biotite by a zone of monomineralic cordierite (figs. 5D; 6). Another late-stage reaction relationship observed in garnet–aluminum silicate–quartz assemblages is the development of ilmenite replacing rutile. Locally, pristine rutile is found as inclusions within kyanite accompanied by matrix rutile rimmed by ilmenite.

The timing of the development of cordierite, and by association, corundum and hercynite, is constrained by the occurrrence of inclusions of sillimanite (some of which are folded by the crenulation event) within cordierite. This suggests that the development of these minerals postdates growth of sillimanite and may be linked to the formation of andalusite during decompression.

CONCLUSIONS

The paragenetic sequence implied by the aluminum silicates, the relationships between mineral growth and deformation, and the textural relations among phases such as cordierite, corundum, hercynite, and ilmenite require a polymetamorphic evolution. During the earlier metamorphic phase, synkinematic recrystallization took place within the kyanite stability field. Following peak metamorphism, the P-T path extended into the sillimanite field, resulting in growth of fibrolite and a small amount of coarser grained sillimanite. Geothermometry and barometry, described by Grover, Rice, and Carey (1992), suggest that peak M2 conditions in the Boehls Butte-Goat Mountain area reached temperatures in excess of 700°C and pressures in the range of 9 to 11 kb. A later metamorphic episode, which we term M3, is characterized by growth of low-pressure phases such as andalusite, cordierite, ilmenite, and hercynite. The products of M3 metamorphism are locally developed throughout the entire St. Joe-Clearwater region but are most obvious in the Al-rich schists found in the Boehls Butte-Goat Mountain area. To the extent that our barometric estimates are correct, substantial decompression and/or uplift occurred between peak M2 conditions and growth of M3 minerals. We must emphasize, however, that we do not believe M3 represents a separate thermal event but instead represents recrystallization during the decompression/uplift path followed by these rocks during a single tectonic episode. As described in our companion paper (Grover, Rice, and Cary 1992), aluminous schists in the Boehls Butte-Goat Mountain area record a nearly continuous transition from high-pressure, M2 conditions to the low-pressure regime resulting in growth of andalusite, cordierite, hercynite, ilmenite, and corundum.

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