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SIGNIFICANCE OF Al SILICATE IN STAUROLITE-GRADE ROCKS, CENTRAL MAINE

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INTRODUCTION

In most medium-grade pelitic metamorphic terranes, staurolite first appears from reaction of garnet-chlorite-muscovite, or chloritoid. At slightly higher grades, the first Al silicate appears from reaction of staurolite-chlorite-muscovite. Generally, most of the staurolite zone includes rocks containing staurolite randomly interspersed with rocks containing staurolite and one of the Al silicates (kyanite, sillimanite, or andalusite), depending on pressure. There are several possible reasons for this apparently random distribution of Al silicate in staurolite-grade rocks. The Al silicate-bearing rocks could be the result of (1) reduced f(H_2O), (2) locally increased T, or (3) bulk compositional effects such as Mg/(Mg + Fe), here designated Mg#, in percent.

Holdaway has been studying the differences between staurolite and staurolite-Al silicate schists in an effort to explain their distribution. In four different metamorphic terranes, the occurrences can be attributed purely to bulk compositional differences, and there is no necessity to call on alternate hypotheses (f(H_2O) or T differences) to explain Al silicate occurrence. The results to date suggest that both T and f(H_2O) behave in very predictable ways in most metamorphic rocks of medium grade.

The primary purpose of this field trip is to observe the distribution of staurolite and Al silicates in medium-grade schists which have undergone one or both of two metamorphic events (M2 and M3), and to illustrate the differences between compositional and thermal instability of staurolite. This field trip will include stops within the Augusta, Farmington, Anson, and Bingham quadrangles (Figs. 1, 2).

METAMORPHIC HISTORY

The metamorphic history of central and west-central Maine has been summarized by Guidotti (1970, 1974), Holdaway et al. (1982, 1988), and Dickerson and Holdaway (1989). Only two of the four metamorphic episodes are of concern here, M2 and M3. These events are mainly regional in scale but owe their origin to thermal effects associated with plutons of the New Hampshire Magma Series.

M2 is defined as an early event (about 400 Ma) in which staurolite reacted thermally to produce andalusite-bearing assemblages, with sillimanite appearing after staurolite had disappeared (Dickerson and Holdaway, 1989). In addition to staurolite and andalusite, cordierite occurred in some rocks which experienced this event. Dickerson and Holdaway suggest that P was about 2.7 kbar in regional M2 rocks of the Bingham area. Contact metamorphic variants are cordierite-rich (M2n, 2.35 kbar), and staurolite-bearing (M2s, 2.75 kbar) as shown in Figure 1. Almost all M2 rocks are slightly to fully retrograded by more recent events.

M3 is defined as an event which took place between 394 and 379 Ma in which staurolite reacted thermally to produce sillimanite-bearing assemblages, with no evidence of intervening andalusite (Holdaway et al., 1982, 1988). M3 is well-developed in Augusta and southern Farmington quadrangles as well as most other areas between Augusta, Rumford, Rangeley, and Madison (Fig. 2). Holdaway et al.(1988) estimate P of M3 to be about 3.1 kbar.

In Augusta quadrangle staurolite breaks down directly to sillimanite without intervening andalusite, but andalusite is widespread among staurolite-grade rocks. This andalusite has its origin in M2, but, as will be shown below, it remained stable during M3 and began reacting to sillimanite at the same grade at which staurolite began producing sillimanite.

ASSEMBLAGE DESIGNATIONS

In order to illustrate the differences between occurrences of Al silicate resulting from thermal instability of staurolite and those resulting from compositional instability of staurolite, an alpha-numeric scheme is utilized which takes into account both grade and composition(Figs. 4, 6, 7). However, this scheme does not designate which Al silicate, andalusite or sillimanite is present; the specific Al silicates are designated in the caption.

Grade is designated by a number: 4 is staurolite zone, 5 is transitional to Al silicate zone, 6 is Al silicate zone. Rocks of grade 4 may be staurolite-biotite-garnet-muscovite, or that assemblage plus an Al silicate. Rocks of grade 5 commonly contain staurolite and must contain Al silicate; they must be spatially located between grades 4 and 6. Rocks of grade 6 cannot contain staurolite but do contain andalusite and/or sillimanite plus muscovite. Quartz is present in all assemblages and available for all reactions. Other accessory phases are also present but excluded from this discussion.

The presence of Al silicate vs. staurolite is indicated by A, B, or C. Thus 4A is a staurolite-grade rock without Al silicate, 4B contains staurolite and Al silicate, and 4C contains Al silicate and no staurolite, but all three assemblages are spatially distributed among each other at the same metamorphic grade. All possible medium-grade assemblages are listed below; those of equivalent grade are given on the same line.

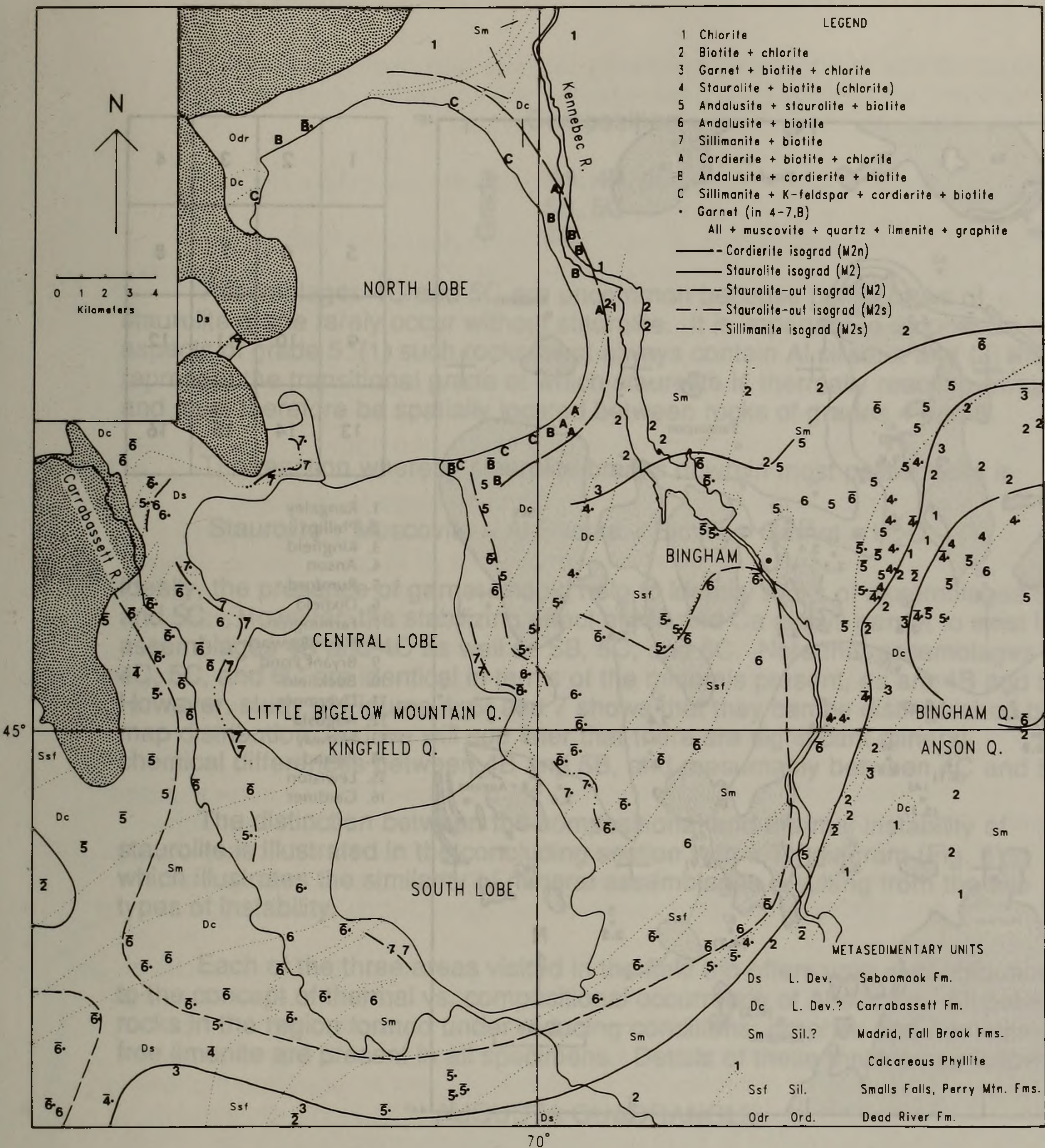

Fig. 1. Mineral assemblage and isograd map for M2 in the region around Bingham. Letters and numbers represent mineral assemblages as given in the legend. Within the staurolite zone assemblages 4, 5, and 6, correspond to 4A, 4B, and 4C in the text. Assemblage 5 immediately below the staurolite-out isograd corresponds to 5B in text, transitional to the Al silicate zone. Overbar indicates highest-grade minerals more than 90% retrograded. Acidic plutonic rocks - white, gabbroic - stipple. Reprinted with permission from American Journal of Science (Dickerson and Holdaway, 1989).

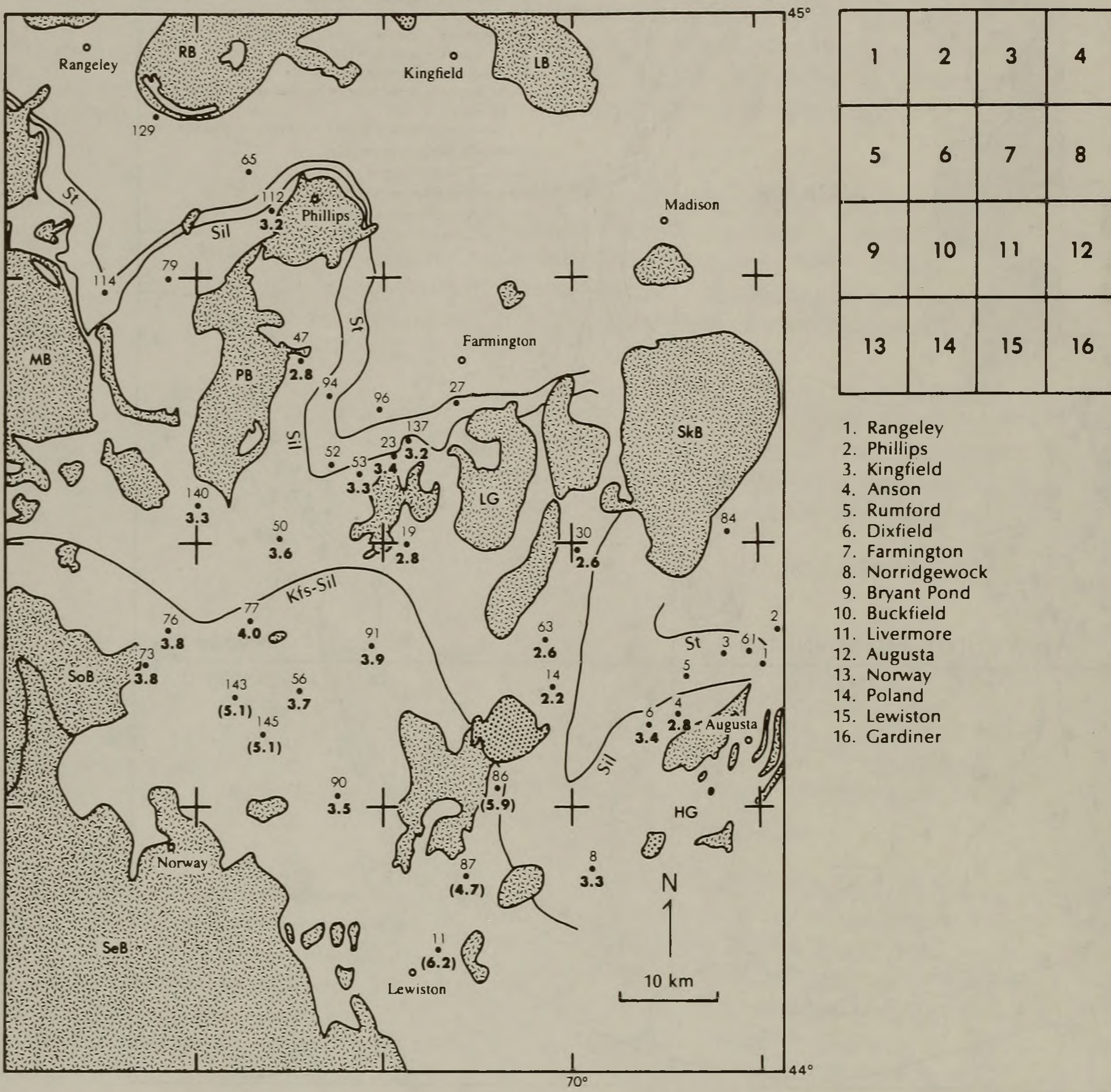

Fig. 2. Isograd map for M3 and M5 events in west-central Maine. Isograds shown are M3 staurolite (St), M3 sillimanite (Sil), and M5 K feldspar-sillimanite (Kfs-Sil). Whole numbers refer to analyzed specimens; bold decimal numbers refer to P determinations using the MABS geobarometer. Pressures in parentheses may represent disequilibrium. Patterns indicate plutonic rocks. Reprinted with permission from American Mineralogist (Holdaway et al., 1988).

	Composition
Grade	4A, 4B, 4C
	5B, 5C
	6C

Assemblages 4C and 5C are uncommon because pelitic rocks of staurolite grade rarely occur without staurolite. It is important to emphasize two aspects of grade 5: (1) such rocks must always contain Al silicate, and (2) they represent the transitional grade at which staurolite is thermally reacting away, and must therefore be spatially located between rocks of grades 4 and 6.

The reaction whereby staurolite breaks down in most pelitic rocks is

Staurolite + Muscovite = Al Silicate + Biotite + Garnet + H_2O. (1)

Ideally, the presence of garnet should help to identify rocks of assemblages 5B and 5C. However, the stabilizing effect of Mn and Ca allows garnet to exist in assemblages 4B and 4C as well as 5B, 5C, and 6C. Note that assemblages 4C, 5C, and 6C are identical in terms of the minerals present, as are 4B and 5B. However, study of Figures 4, 6, and 7 shows that they can be distinguished by map distribution, and we will see later that there are significant mineral chemical differences between 4B and 5B, and presumably between 4C and 5C.

The distinction between the compositional and thermal instability of staurolite is illustrated in the concluding section with a TX diagram (Fig. 8), which illustrates the similarity of mineral assemblages resulting from the two types of instability.

Each of the three areas visited in the field trip offers unique contributions to the concept of thermal vs. compositional occurrence of Al silicate. All pelitic rocks in the region formed under reducing conditions; graphite and hematite-free ilmenite are present in all specimens. Details of these three areas follow.

AUGUSTA QUADRANGLE

In the Augusta quadrangle, Novak and Holdaway (1981), and Holdaway et al. (1988) have suggested that both M2 and M3 affected the area, based primarily on abundance of low-variance assemblages, some polymetamorphic textures, and the coexistence of minerals such as staurolite and cordierite which are incompatible elsewhere. However, it is not possible to distinguish two sets of isograds, implying that the two events were temporally close, perhaps representing a simple P increase during metamorphism.

Despite the fact that staurolite reacts directly to sillimanite, andalusite is very common and cordierite is not uncommon in normal pelitic rocks. Most, if not all, of the minor chlorite found in rocks of grades 4, 5, and 6 is retrograde.

This conclusion is suggested by chlorite textures and confirmed by the widespread occurrence of Al silicate-biotite and cordierite, which are both compositional alternatives to chlorite. The reaction

Staurolite + Chlorite + Muscovite = Andalusite + Biotite + H_2O (2)

destroyed chlorite very early in grade 4 and left andalusite-biotite as the widespread alternative to staurolite-chlorite. The origin of chlorite in medium-grade rocks of M3 is discussed in detail by Holdaway et al. (1988).

In the Augusta area there are several occurrences of the assemblage staurolite-andalusite (or sillimanite)-biotite-cordierite-muscovite-garnet-chlorite, two of which will be examined on the trip. The garnet is minor and is stabilized by Mn + Ca, and the chlorite is retrograde, as discussed above. However, the presence of staurolite-andalusite-cordierite-biotite-muscovite is an enigma. Because Al silicate-biotite is a very common assemblage in all Maine metamorphic rocks, even in the staurolite zone, we believe staurolite and cordierite are not compatible in rocks dominated by AFM components. Novak and Holdaway (1981) suggested that Augusta area rocks experienced early M2 with common AFM assemblages being staurolite-andalusite-biotite-muscovite and andalusite-biotite-cordierite-muscovite, followed immediately by M3 with increasing P producing staurolite-biotite-garnet-muscovite and partially to totally destroying andalusite and cordierite (Fig. 3). In some specimens, this process left the polymetamorphic assemblage present at West Sidney (Stop 2).

If the rocks contained significant amounts of non-AFM and non-saturated components, then there is the possibility that staurolite-andalusite-cordierite-biotite-muscovite might locally have been stable. Such a case probably occurs at East Winthrop (Stop 3) where Zn stabilizes staurolite and Li stabilizes both staurolite and cordierite relative to andalusite-biotite (Dutrow et al., l986).

Figure 4 shows the distribution of andalusite in staurolite-grade rocks of the Augusta area. Throughout M3, staurolite, biotite, and garnet of assemblage 4A have consistently lower Mg# than those minerals of assemblage 4B. In addition, the garnets of assemblage 4B contain more Mn + Ca than those of 4A (Fig. 5). This suggests the following: (1) andalusite was an equilibrium phase in these M3 rocks despite its probable formation during M2; (2) the appearance of andalusite in M3 is related to local variation in bulk composition; (3) the limiting Mg#, beyond which andalusite-biotite must form instead of more Mg-rich staurolite, is more or less constant over the T range of the staurolite zone. In the transitional rocks of assemblage 5B, staurolite of all compositions is breaking down; therefore there is little compositional control on the first appearance of sillimanite. Biotite, staurolite, and garnet with a wide range of compositions occur in grade 5B (Fig. 5). Comparable ranges of biotite and garnet compositions occur in the staurolite-free rocks of grade 6C. In M3 the sillimanite isograd coincides with the beginning of the thermal breakdown of staurolite (5B), and this combined with garnet-biotite geothermometry provides an accurate way to estimate pressure (Holdaway et al., l988).

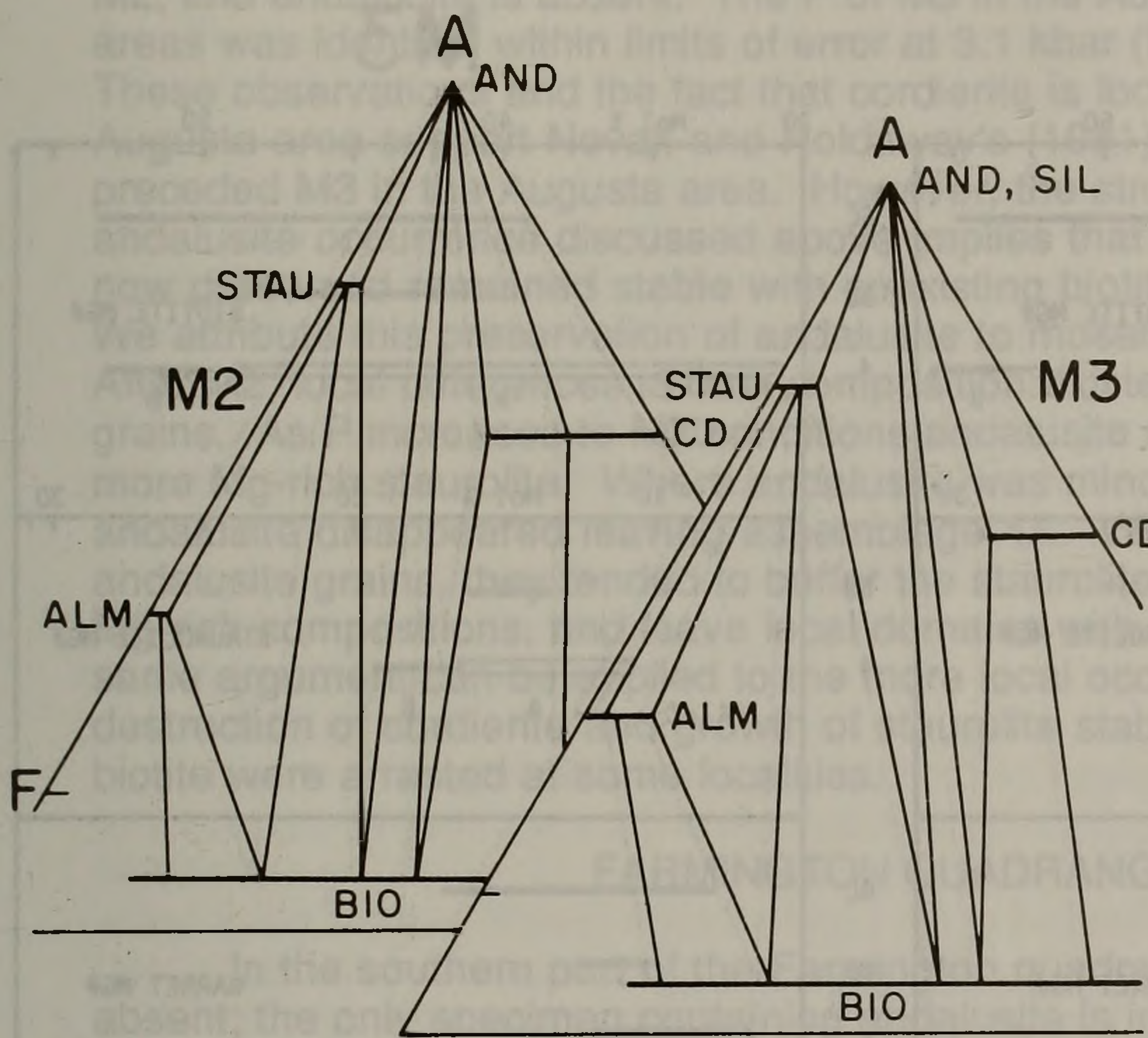

Fig. 3. Schematic AFM diagrams for medium-grade M2 and M3. As pressure decreases, the Al silicate-biotite tie lines rotate clockwise, decreasing the compositional field of staurolite, and increasing the compositional field of cordierite. M2n (Fig. 1) corresponds to staurolite-unstable conditions with a still-greater clockwise rotation of tie lines than that shown for M2.

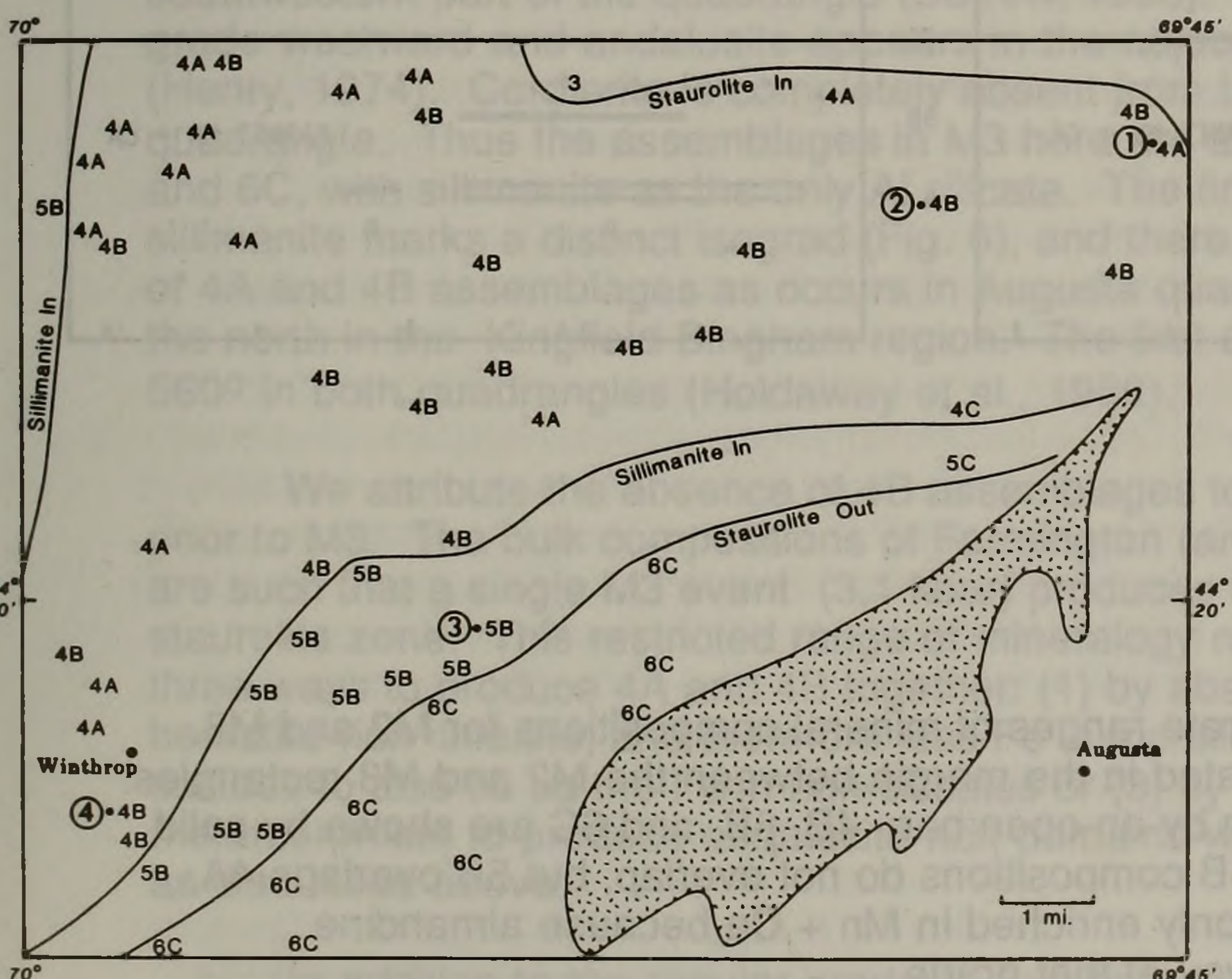

Fig. 4. Mineral assemblage and isograd map for M3 of the Augusta area. Mineral assemblages are defined in the section entitled ASSEMBLAGE DESIGNATIONS. Also, 1 - chlorite z., 2 - biotite z., 3 - garnet z. Circled numbers refer to field trip stops. Pattern shows granitic rocks. All 5B and 6C assemblages contain sillimanite, but a few also contain relict andalusite.

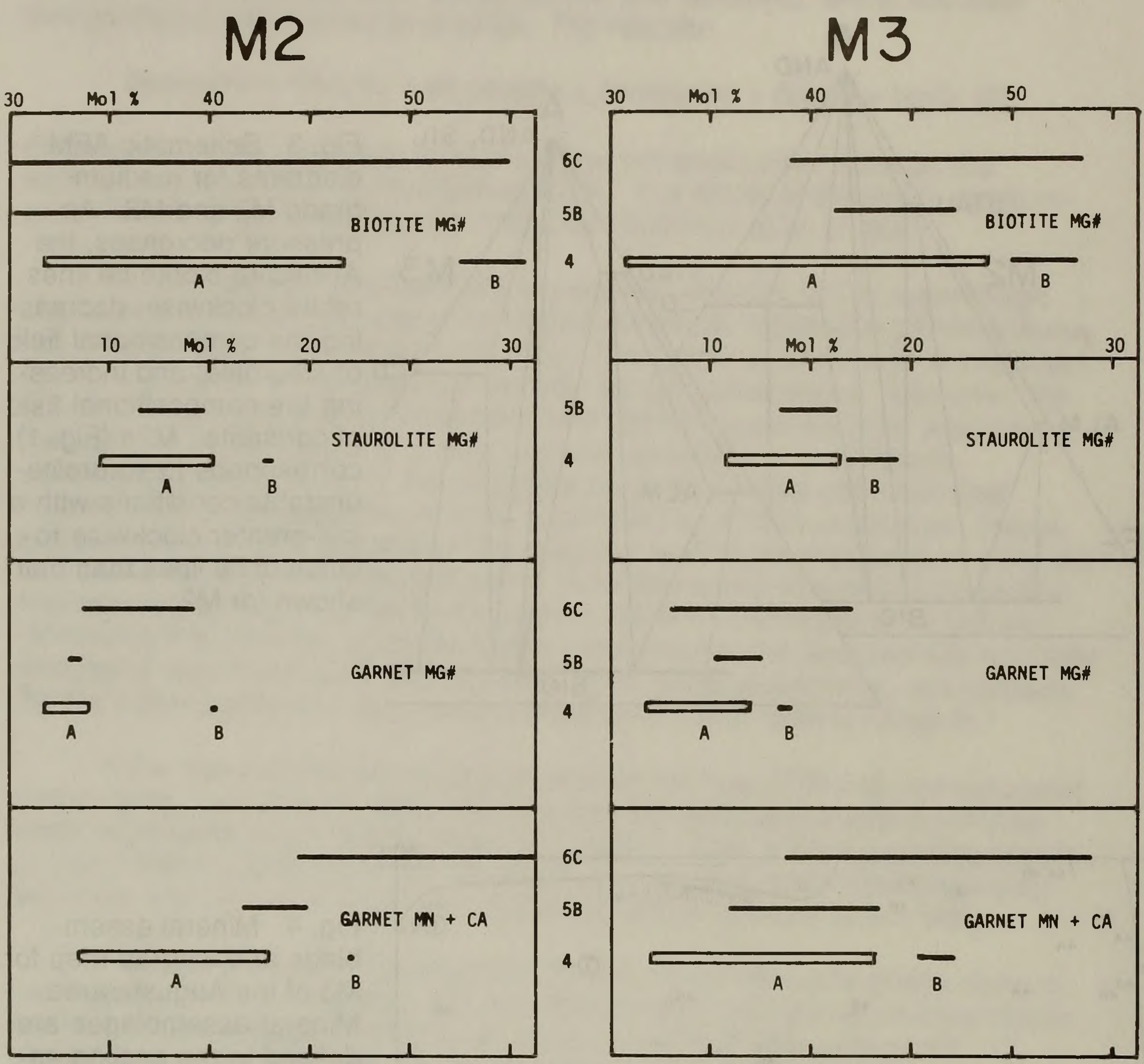

Fig. 5. Diagrams to illustrate ranges of mineral compositions for M2 and M3. Assemblages are designated in the margin between the M2 and M3 rectangles. Assemblage 4A is shown by an open bar; 4B, 5B, and 6C are shown by solid lines. Note that 4A and 4B compositions do not overlap, but 5B overlaps 4A. Garnets of 6C are commonly enriched in Mn + Ca because almandine component is reacting away at that grade.

In the Farmington area (discussed below) most M3 was not preceded by M2, and andalusite is absent. The P of M3 in the Augusta and Farmington areas was identical within limits of error at 3.1 kbar (Holdaway et al., l988). These observations and the fact that cordierite is locally developed in the Augusta area support Novak and Holdaway's (1981) conclusion that M2 preceded M3 in the Augusta area. However, the strong compositional control of andalusite occurrence discussed above implies that the andalusite which is now preserved remained stable with coexisting biotite and staurolite during M3. We attribute this preservation of andalusite to mosaic equilibrium during M3. After M2, local differences in bulk composition existed near larger andalusite grains. As P increased to M3 conditions andalusite and biotite reacted to make more Mg-rich staurolite. Where andalusite was minor or fluids abundant, andalusite disappeared leaving assemblage 4A. Where there were larger andalusite grains, they tended to buffer the staurolite and biotite at their most Mg-rich compositions, and leave local domains with higher bulk Mg#. The same argument can be applied to the more local occurrences of cordierite. The destruction of cordierite and growth of staurolite stable with andalusite and biotite were arrested at some localities.

FARMINGTON QUADRANGLE

In the southern part of the Farmington quadrangle, andalusite is virtually absent; the only specimen containing andalusite is in the northern part of the staurolite zone, 4 km south-southeast of Farmington (Fig. 6). Most of southern Farmington quadrangle has been affected by M3, but highly retrograded M2 rocks occur along the western edge and are truncated by M3 isograds in the southwestern part of the quadrangle (Dutrow, 1985). The M2 effects increase in grade westward and andalusite appears in the adjacent Dixfield quadrangle (Henry, 1974). Cordierite is completely absent from the Farmington quadrangle. Thus the assemblages in M3 here are almost exclusively 4A, 5B, and 6C, with sillimanite as the only Al silicate. The first appearance of sillimanite marks a distinct isograd (Fig. 6), and there is no random distribution of 4A and 4B assemblages as occurs in Augusta quadrangle and in M2 rocks to the north in the Kingfield-Bingham region. The first sillimanite appears at about 560^{o} in both quadrangles (Holdaway et al., 1988).

We attribute the absence of 4B assemblages to the absence of M2 effects prior to M3. The bulk compositions of Farmington (and Augusta) area pelites are such that a single M3 event (3.1 kbar) produces only assemblage 4A in the staurolite zone. This restricted range of mineralogy may be changed in one of three ways to produce 4A and 4B together: (1) by absence of graphite, more hematite-rich ilmenite, and therefore less Fe in the silicates; (2) by presence of sulfides to also tie up the Fe in non-silicates or (3) by an earlier lower P metamorphism to produce andalusite-rich domains which remain richer in Mg as discussed above.

In addition to the regular grade sequence, the Farmington quadrangle exemplifies well the control of isograds by adjacent plutonic bodies (Fig. 6). We

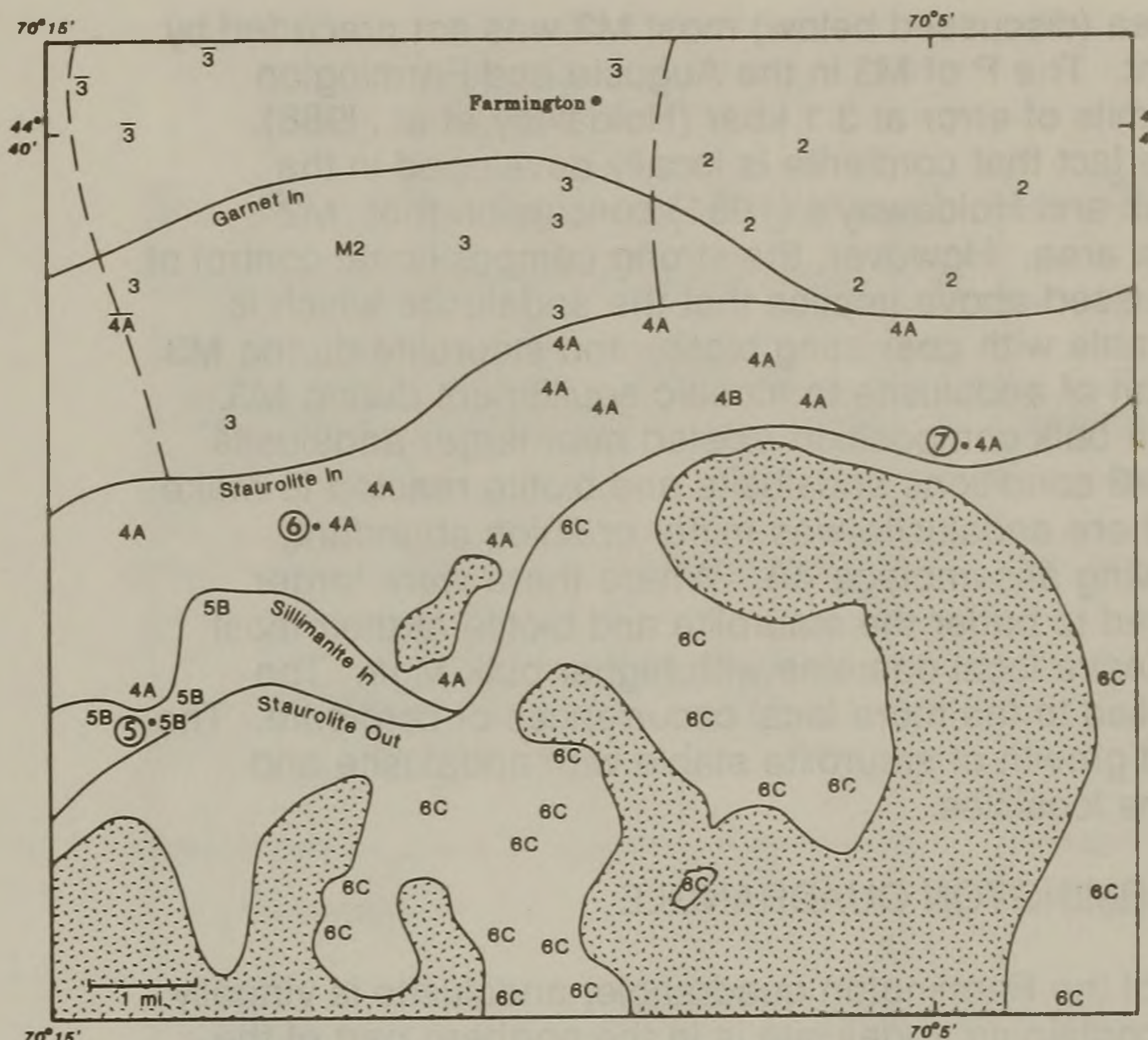

Fig. 6. Mineral assemblages and isograd map for M3 of the Farmington area. Dashed lines are M2 isograds. All 5B and 6C assemblages contain sillimanite; the only andalusite occurs at the one 4B locality. See caption of Figure 4 for additional details.

believe the plutonic bodies came in over a short time interval and P increased slightly southward (Holdaway et al., 1988).

East of Farmington and north of Augusta, in the northeastern part of Norridgewock quadrangle, the contact metamorphism near the Skowhegan batholith shows indications of P lower than that for M3 near Farmington . In this eastern area, andalusite and cordierite are both more prevalent than staurolite. There is no evidence for polymetamorphism in these rocks, and the isograds are continuous with M3 isograds to the west and south. The interpretation of this area was left open by Holdaway et al. (1988) as shown on Figure 2, but it now appears that the area is best interpreted as a northeastward extension of M3 at anomalously low P. The metamorphism might have begun during M2 time, but continued into M3 time without a P increase. This area presents a challenge to our method of identifying events. Strictly speaking, it should not be interpreted as M3 because it has P more typical of M2; however, the lack of truncation of isograds and possible synchrony of time with M3 supports the determination as M3.

ANSON AND BINGHAM QUADRANGLES

The M2 rocks of Anson, Bingham, Kingfield, and Little Bigelow Mountain quadrangles formed at lower P (about 2.7 kbar) than the younger M3 rocks to the south, evidenced by the presence of andalusite as a product of staurolite breakdown (Reaction 1) instead of sillimanite (Dickerson and Holdaway, 1989).

Andalusite is also very widespread among staurolite-grade rocks, assemblages 4A, 4B, and 4C (Figs. 1, 7) all being present. (Note that assemblages 4, 5, and 6 in Figure 1 all intermixed in the staurolite zone represent assemblages 4A, 4B, and 4C respectively in Figure 7).

Cordierite is totally absent from the regionally developed M2 and from the slightly younger contact metamorphic rocks (M2s) around the central and south lobes of the Lexington batholith; however cordierite is widespread in contact metamorphic rocks around the (earlier?) northern lobe of the batholith (M2n, 2.35 kbar), and staurolite is absent from these northern rocks (Fig. 1). Throughout the region of the Lexington batholith, staurolite and cordierite are mutually exclusive. The alternative assemblages staurolite-andalusite-biotite and cordierite-andalusite-biotite are very common. These observations provide strong evidence that staurolite-cordierite-biotite-muscovite is not a stable assemblage except possibly in the presence of significant amounts of non-AFM components such as Zn and Li.

As with M3, the M2 staurolite, biotite, and garnet of assemblage 4B are more Mg-rich than those minerals in 4A, and in addition the garnets contain higher Mn + Ca (Fig. 5). The 4B assemblage corresponds to bulk compositions with higher Mg# or higher Al/(Al + Mg + Fe) as shown in Figure 3. Some garnet persists in 4B as a result of its increased Mn + Ca which stabilizes the andalusite-biotite-garnet assemblage of Reaction 1 to lower T along with staurolite. The 5B compositions overlap 4A and 4B as is the case for M3 (Fig. 5). The most Mg-rich staurolite, biotite and garnet of assemblage 4A in M2 are slightly more Fe-rich than analogous minerals of that assemblage in M3, suggesting that staurolite in pelitic rocks is stabilized to more Mg-rich compositions by increased P. For this reason andalusite is much more prevalent in these M2 rocks than in the Augusta area.

Stop 9 in Bingham quadrangle represents the only known locality in M2 or M3 where chlorite occurs with staurolite in significant amounts and has a foliated texture suggesting that it is a prograde mineral. The rocks here also contain andalusite. This locality represents the lower part of the staurolite zone, 300 m from rocks transitional to the garnet zone. Staurolite is reacting with chlorite to produce andalusite-biotite (Reaction 2). The fact that this locality represents the lower part of the staurolite zone and the beginning of the disappearance of staurolite-chlorite reinforces our contention that throughout much of the staurolite zone Al silicate and biotite represent the compositional alternative to more Mg-rich staurolite, and chlorite in most such rocks is retrograde.

CONCLUSIONS

The combination of chemical and field data from M2 and M3 in central and west-central Maine provides for a number of useful petrologic conclusions. These may be applied to the interpretation of metamorphic history in Maine and elsewhere.

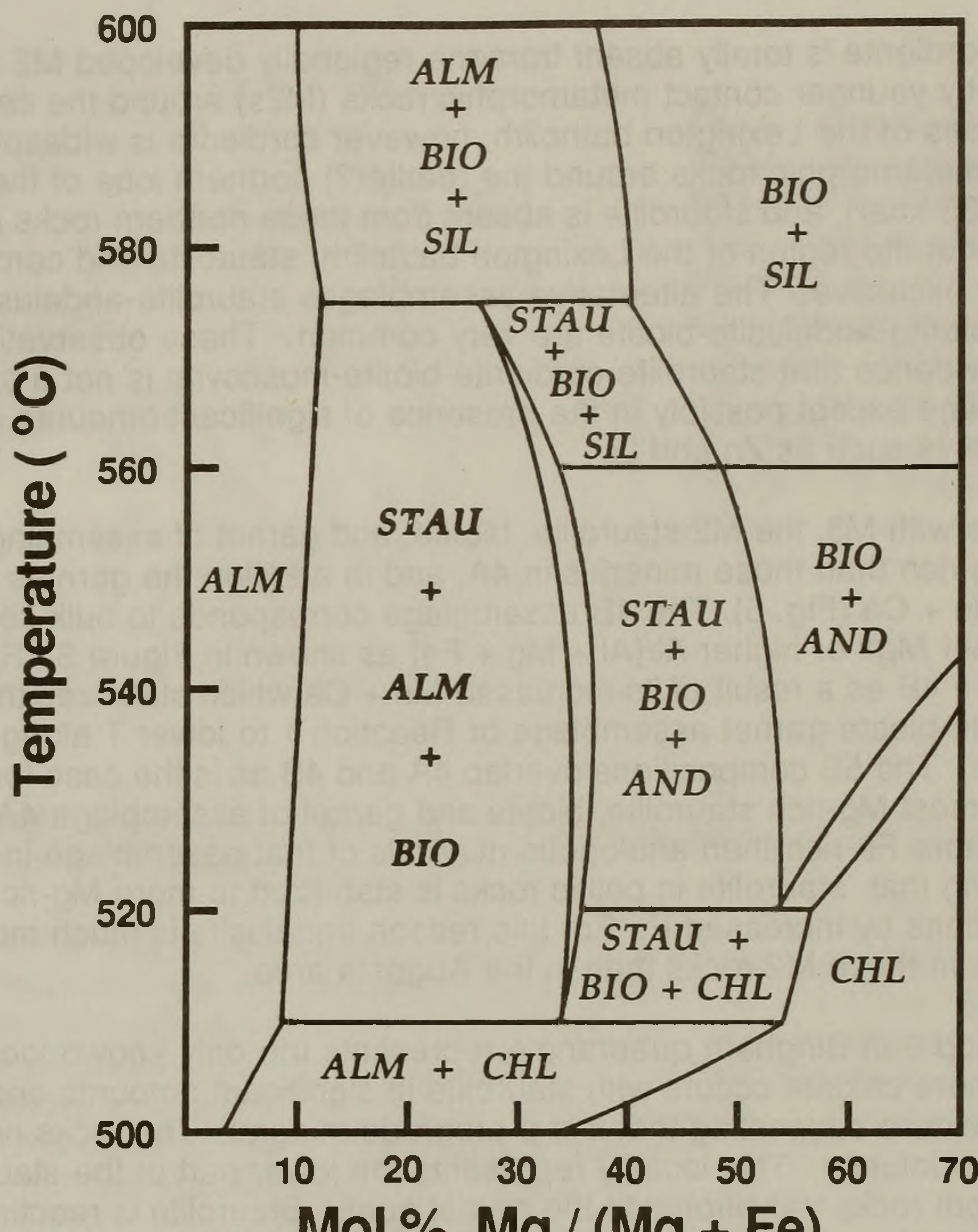

Fig. 8. Schematic TX diagram for the almandine-chlorite join at 3.1 kbar based on compositions and geothermometry from M3 in Maine. At this pressure, biotite-sillimanite is the thermal alternative to staurolite and biotite-andalusite is the compositional alternative. Garnet is present with both assemblages, stabilized by Mn + Ca in the latter. Chlorite is the compositional alternative to staurolite near the beginning of the staurolite zone. Narrow sliver at 35% = staurolite-biotite; narrow sliver at 60% = biotite-andalusite-chlorite.

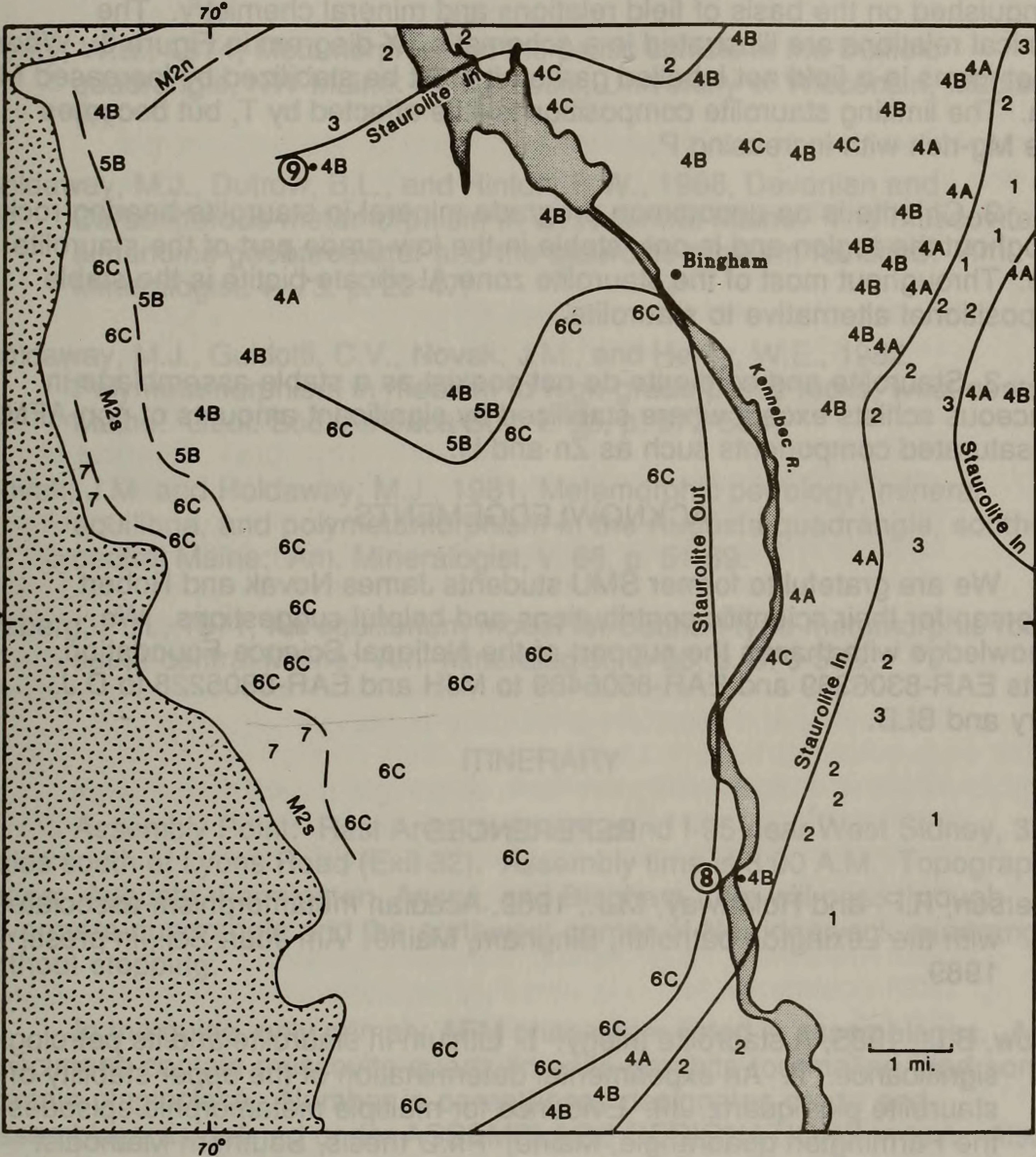

Fig. 7. Mineral assemblage and isograd map for M2 of the Anson and Bingham quadrangles. Mineral assemblages shown correspond to M2 and M2s, which occurred at similar P. No isograd is shown for the disappearance of assemblage 4A, but localities immediately below the staurolite-out isograd are transitional to the Al silicate zone, and shown as 5B. Sillimanite does not appear until assemblage 7, the sillimanite-bearing equivalent of 6C. See caption of Figure 4 for additional information.

1. Al silicate-bearing assemblages may be produced by either compositional or thermal instability of staurolite. These two possibilities may be distinguished on the basis of field relations and mineral chemistry. The chemical relations are illustrated in a schematic TX diagram in Figure 8. When garnet forms in a field not labelled garnet, it must be stabilized by increased Mn + Ca. The limiting staurolite composition is little affected by T, but becomes more Mg-rich with increasing P.

2. Chlorite is an uncommon prograde mineral in staurolite-bearing rocks throughout the region and is only stable in the low-grade part of the staurolite zone. Throughout most of the staurolite zone Al silicate-biotite is the stable compositional alternative to staurolite.

3. Staurolite and cordierite do not coexist as a stable assemblage in micaceous schists except where stabilized by significant amounts of non-AFM, non-saturated components such as Zn and Li.

ACKNOWLEDGEMENTS

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ITINERARY

Assembly Point: Rest Area on southbound I-95 near West Sidney, 3.8 miles south of Lyons Road (Exit 32). Assembly time is 8:00 A.M. Topographic maps: Augusta, Farmington, Anson, and Bingham. We will pass through Livermore quadrangle and the northwest corner of Norridgewock quadrangle without stopping.

In the guide, only primary AFM phases are listed in assemblages. All specimens contain muscovite-quartz-ilmenite-graphite-tourmaline, and some contain plagioclase. Number in parentheses designates grade and assemblage as defined under ASSEMBLAGE DESIGNATIONS in text. Also: 1 = chlorite zone; 2 = biotite zone; 3 = garnet zone; 7 = sillimanite-muscovite zone in M2s.

Mileage

0.0 STOP 1. Roadcut immediately south of Rest Area on west side of I-95. CAREFUL! Pelitic rocks of the Waterville Formation at the staurolite isograd (?). At north end are garnet-biotite-chlorite schists (3). Green color indicates chlorite, interpreted to be primary. At 300 m south are staurolite-biotite-garnet schists (4A). The green color disappears, but garnet content does not decrease noticably. The Mg# of staurolite is 14.9, that of biotite is 47.8, showing that the mineral chemistry is within the range of 4A for M3 (Fig. 5). Return to cars and drive south on I-95.

3.9 First roadcuts of Hallowell Granite, a biotite muscovite quartz monzonite which may have acted as a heat source for M3.

4.4 Turn right at Exit 31 and proceed north on ME-8-11-27.

5.0 Sillimanite-andalusite biotite-garnet schist (6C) at the sillimanite isograd.

5.6 Andalusite-biotite-garnet schist (5C).

8.1 STOP 2. Take right fork on ME-23 and park on right beyond low roadcut. West Sidney locality, staurolite-grade rocks of the Waterville Formation about 2 km south of the staurolite isograd. Roadcut at intersection is mainly biotite-quartz-rich rocks. At 60 m south on east side are exposures of staurolite-andalusite-biotite-cordierite-garnet schist (4B) and subsets of this assemblage, with minor retrograde chlorite. A specimen of the maximum 4B assemblage collected from the middle of the outcrop has staurolite with Mg# 19.2 and biotite with Mg# 52.8 (Fig. 5). Staurolite of the 4B assemblage does not contain high Zn or Li. At 500 m south are roadcuts of staurolite-biotite-garnet schist (4A) and staurolite-andalusite-biotite-garnet schist (4B).

There is an interesting evolution of thought regarding the large number of phases in the maximum 4B assemblage. Osberg (1971) suggested that the whole was an equilibrium assemblage. Novak and Holdaway (1981) suggested two equilibrium assemblages: M2 - andalusite-biotite-cordierite; M3 - staurolite-biotite-chlorite. We now think there were three phases of metamorphism: M2 - andalusite-biotite-cordierite; M3 - staurolite-andalusite-biotite; retrograde stage - chlorite. By any interpretation, the trace amount of garnet was stabilized by Mn. Turn around and reverse direction.

8.7 Turn right on Summer Haven Rd.

9.0 Take left fork on Old Belgrade Rd.

12.1 Proceed south on ME-135.

12.7 Take right fork on Puddle Duck Rd.

14.4 Turn right (west) on US-202, ME-11-100 at Manchester.

16.3 Turn right on side road.

16.4 Turn right on Case rd.

16.9 STOP 3. Park on hill at right beyond roadcut. East Winthrop locality, semipelitic rocks of the Waterville Formation south of the sillimanite isograd. Several of the rocks contain sillimanite, biotite, and garnet (5C). A single more pelitic specimen was collected from about 15 m south of the north end of the roadcut, a staurolite-sillimanite-biotite-garnet schist (5B). John Ferry has collected a similar specimen which also contains cordierite. Both the staurolite and the cordierite contain about 1% Li_2O, and the staurolite also contains 1% ZnO (Dutrow et al.,1986). The staurolite has Mg# 12.9, and the biotite has Mg# 48.3, but the high Li has affected the Fe-Mg partitioning (Holdaway et al., I988). The staurolite and cordierite are minor phases, and may be stabilized together with micas by the Li and Zn. Turn around in next driveway and return to highway.

17.4 Turn right on side road.

17.8 Rejoin US-202, ME-11-100, turn right, and proceed west.

18.6 Staurolite-sillimanite-andalusite-biotite-garnet schist (5B).

20.8 Biotite schist

21.9 Turn right (north) on ME-133 at Winthrop.

22.0 STOP 4. Park on right. Low roadcut on left of staurolite-zone rocks of the Sangerville Formation. At the southwest end, staurolite-biotite-garnet schist (4A) is most common, and at the northeast end staurolite-andalusite-biotite-garnet schist (4B) is more common. Andalusite occurs as a few large sievy crystals. This locality is in the reentrant between the sillimanite isograd of the Hallowell lobe of M3 and the Livermore Falls lobe of M3 (Figs. 2, 4). A 4A specimen contains staurolite with Mg# 15.0 and biotite with Mg# 47.1. Continue north and west on ME-133.

23.2-23.5 Staurolite-andalusite-biotite-garnet schist (4B) on left. The only andalusite seen in M3 of the Livermore Falls lobe is along the eastern edge, suggesting that earlier M2 decreased in grade west from here.

24.5 Enter Livermore quadrangle on ME-133.

25.5 Staurolite-sillimanite-andalusite-biotite-garnet schist (5B).

28.0 Sillimanite-biotite-garnet schist (6C).

28.4 Wayne, stay on ME-133. Several poorly exposed two-mica granites provided heat for the Livermore Falls lobe of metamorphism (Fig. 2). A gabbroic pluton of Carboniferous age is poorly exposed south of Wayne.

30.4 Biotite quartzites exposed on left.

38.6 ME-17 joins ME-133 from the right, continue northwest through Livermore Falls on ME-17-133.

39.4 ME-133 turns right, continue northwest on ME-17 through Chisholm and Jay.

41.8 Enter Farmington quadrangle on ME-17-4.

45.6 ME-17 turns left, continue north on ME-4.

48.1 Turn left (west) on US-2.

48.5 Turn right here for lunch materials in Wilton. (Foodland 0.5 miles on left).

49.2 LUNCH STOP. Turn left into Rest Area. After lunch reverse direction, east on US-2.

50.1 STOP 5. Park on right adjacent to large roadcuts. Lower sillimanite zone rocks of the Sangerville Formation. Most of the pelites are staurolite-sillimanite-biotite-garnet schists (5B) of M3. The schists locally contain coarse muscovite pseudomorphs of staurolite (spangles) described by Guidotti (1968). In such specimens, most of the staurolite occurs as remnants within the muscovite pseudomorphs. Spangles are best seen near the middle of the exposure on the left side. At a locality east of here, the spangles occur with very little sillimanite in the rock, implying that K-bearing fluids from the nearby pluton affected the rock. A specimen from near the locality of Stop 5 has staurolite with Mg# 13.5 and biotite with Mg# 41.2, typical of 5B specimens (Fig. 5). Stop 5 is about 2 km north of a two-mica granitoid (Fig. 6), and the M3 isograds trend east-northeast in this area paralleling the contacts of granitic plutons. About 5 km north of here, the M2 staurolite isograd trends north-south and is truncated by M3 isograds, suggesting that this locality may have experienced M2 previously. This interpretation is also suggested by small euhedral staurolites within micaceous pseudomorphs in the M3 staurolite zone northwest of here. Continue east and then northeast on US-2 and ME-4.

53.1 STOP 6. Park on right. Extensive exposures on right are staurolite-zone rocks of the Sangerville Formation. Staurolite-biotite-garnet schist (4A) is common. As is the case elsewhere in this quadrangle, andalusite has not been seen. A typical 4A specimen has staurolite with Mg# 15.9 and biotite with Mg# 46.9. Some specimens contain pods of medium-grained muscovite similar to spangles but smaller. These may be related to previous M2 effects which were garnet-grade in this area. The exposure shows significant alteration, and greener portions are extensively altered to chlorite, perhaps by the Hercynian (M5) metamorphism which almost reached the southwest corner of Farmington quadrangle (Fig. 2).

53.5 Extensive roadcuts on right of staurolite-biotite-garnet schist (4A).

53.7 Roadcuts on left and right are mica schists, biotite quartzites, and calcareous rocks.

56.1-56.4 Sparce roadcuts of staurolite-biotite-garnet schist (4A).

57.6 Roadcuts on the southwest side of Farmington are garnet-biotite-chlorite schists (3) and biotite schists. These rocks were in the garnet zone of both M2 and M3. They show two distinct stages of growth with an abrupt transition from Mn-Ca-rich cores to Fe-rich rims.

58.1 Cross Sandy River on US-2 and ME-4 in Farmington.

58.3 Take right fork southeast on US-2 and ME-27.

62.1 Roadcuts on left of vesuvianite-bearing calc-schist in calcareous horizons of the Sangerville Formation, and granitic dike.

62.7 Turn right on ME-41-156 to Farmington Falls.

63.2 STOP 7. Park on either side of road before bridge. Outcrops under bridge and west of bridge are staurolite-zone rocks of the Sangerville Formation. Rocks are staurolite-biotite-garnet schists (4A) with idioblastic staurolite, generally with two stages of growth and a chemical break between the main crystal and the outer rim. From two specimens, staurolite has Mg# 13.6 and 14.1, and biotite has Mg# 48.0 and 45.0. About 1 km south of here are plutonic rocks (Fig. 6) of the Livermore Falls group.

Although andalusite is almost totally absent from M3 rocks of the Farmington quadrangle, 14 km east-northeast of Farmington Falls at East Mercer, andalusite occurs and becomes common as does cordierite around the north side of the Skowhegan (or Rome, or Norridgewock) batholith. Staurolite is absent here. In addition, there is an eastward narrowing of metamorphic zones. These observations and absence of evidence of polymetamorphism suggest a decrease in P of M3 at its northeastern extreme, perhaps due to a decrease in surface volcanic activity during Acadian magmatism. Turn around and turn right toward New Sharon.

63.3 Rejoin US-2 and ME-27, turn right (east).

67.3 Turn left (north) on ME-134 right before bridge over Sandy River. Most of the route between here and Stop 8 is over chlorite- and biotite-zone rocks.

68.9 Enter Norridgewock quadrangle.

75.3 Outcrops in stream of quartzite and chlorite phyllite.

75.8 Turn right (east) on ME-43.

76.9 Roadcuts on left of biotite quartzite and biotite-chlorite phyllite.

79.9 Enter Anson quadrangle.

80.2 Roadcuts on right of Old Point pluton, a small northern satellite of the Norridgewock batholith.

82.7 ME-148 joins ME-43 from the left, proceed right on ME-43-148.

84.1 Without crossing bridge over Kennebec River, proceed straight (north) on US-201A and ME-8.

88.7 Extensive outcrops left of bridge over Carrabassett River are quartzite, biotite quartzite, and slightly calcareous rocks of the Fall Brook Formation.

95.6 Cross Kennebec River. The M2 staurolite isograd occurs in this area, trending northeast.

96.8 Turn left (north) on US-201 in Solon. Outcrops on right in stream are Madrid quartzites and biotite quartzites.

97.4 Turn left on Falls Rd.

97.7 Proceed straight on poorer road.

97.8 STOP 8. Park along dirt road to left. NOTE SPILLWAY SIGN. Arnolds Landing, staurolite-grade pelites of the Carrabassett Formation. Large porphyroblasts are retrograded andalusite, and smaller ones are partly retrograded staurolite and garnet. Assemblages include staurolite-biotite-garnet schist (4A), staurolite-andalusite-biotite-garnet schist (4B), and andalusite-biotite schist (4C). Retrograde chlorite is common and biotite is extensively altered. The bulk chemical control on mineral assemblages is obvious in the bed to bed variation. The 4A and 4B rocks are more pelitic in character and generally have smaller porphyroblasts. The 4C assemblage is seen in more quartz-rich horizons with coarse andalusites (up to 4 cm). Redox is not a factor in this variation as all oxides are hematite-free ilmenite, and graphite is ubiquitous. A possible sedimentological explanation for these observations is increased kaolinite/illite ratio in the siltier layers. Chlorite-grade phyllites are exposed 2 km east-southeast on the east side of Solon. West of here about 6 km is a rapid increase in grade (M2s) near the Lexington batholith (Fig. 7).

The heat source for M2 is believed to have been a deeper, more extensive phase of the Lexington batholith which heated the overlying rocks. Contact metamorphism around the central and south lobe (M2s, Figs. 1, 7) slightly postdates regional M2. Return to US-201.

98.1 Turn left on US-201.

100.0 Enter Bingham quadrangle. (Note 45° N. Lat. sign. Elevation is 420 feet, not 352).

100.7 Road cuts on right of Madrid Psammitic rocks.

101.6 Road cuts of staurolite schist, Carrabassett Formation(?).

105.3 Turn left (west) across Kennebec River on ME-16 in Bignham.

105.5 Turn right (north) after bridge. Road cuts are Smalls Falls sulfidic-pelitic schists and quartzite. Andalusite is rare.

107.1-107.6 Muscovite-rich pelites of Perry Mountain Formation.

107.6-107.9 Smalls Falls Formation.

109.8 Take left fork toward Rowe Pond.

111.7 STOP 9. Park on right. Carrabassett pelites near the base of the staurolite zone. Here metamorphic grade increases south. Much of the roadcut contains staurolite without andalusite, but a 10 m zone near the middle also contains andalusite as slender 10 cm porphyroblasts. Assemblages are staurolite-biotite-garnet-chlorite (4A) and staurolite-andalusite-biotite-garnet-chlorite (4B). Some chlorite appears to be primary. Analyses of a 4A specimen give staurolite Mg# 11.9 and biotite Mg# 33.7. North-northwest 300 m staurolite and chloritoid coexist in rocks transitional to the M2 garnet zone. The Stop 9 locality may represent Reaction 2, with all reacting minerals present in some specimens. North-northwest 3 km are cordierite-bearing, staurolite-absent contact metamorphic rocks of M2n around the north lobe of the Lexington batholith, which are earlier (?) and formed at lower P (2.35 kbar). Proceed straight ahead.

112.3 Turn right down hill.

113.2 Turn right. Return to Farmington without crossing the Kennebec River via this road to ME-16-west, south to US-201A, south to North Anson. Here take ME-234 west from south of bridge in North Anson to ME-17, and ME-17 south through the New Vinyard Mountains to Farmington.