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Metamorphic Petrology, Mineralogy and Polymetamorphism in a Portion of N. W. Maine

by

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Preliminary Comments: As this trip emphasizes polymetamorphism the subject matter requires development before field stops can be meaningful. Hence, comments on the fabrics and textures and a summary of pertinent mineralogic data is presented.

Acknowledgements: The writer acknowledges the help and encouragement of J. C. Green, D. S. Harwood, D. J. Milton, K. A. Pankiwskyj and J. Fink Warner. R. H. Moench is thanked especially for allowing me to study the petrology of the three quadrangles (Phillips, Rangeley, Rumford) that he has been mapping. Moreover, discussions with Moench made the writer aware of the significance of the staurolite overprint patterns. Discussions with N. Carter of Yale University have also been very helpful in this respect.

Professors M. P. Billings and J. B. Thompson, Jr. of Harvard University originally got me interested in N. W. Maine and guided my early work. Financial support from Harvard at that time is acknowledged.

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Introduction: The area considered includes the Oquossoc, Rangeley, Phillips, Dixfield, Rumford, Old Speck Mountain, Buckfield, Bryant Pond, and Bethel quadrangles (See road log, Fig. 1). It lies at the NNE end of the high grade metamorphic area extending S.W. through much of central and southern New England, (Thompson and Norton, 1968).

Emphasis is on meta-pelites in grades ranging from biotite to Ksp + Sill zone. The trip can be divided into four parts coinciding with specific areas (Areas A, B, C, and D on Fig. I). They are treated separately because of variable amounts of data for each area and possible differences in the metamorphic history. The areas will be seen in the A, B, C, D order.

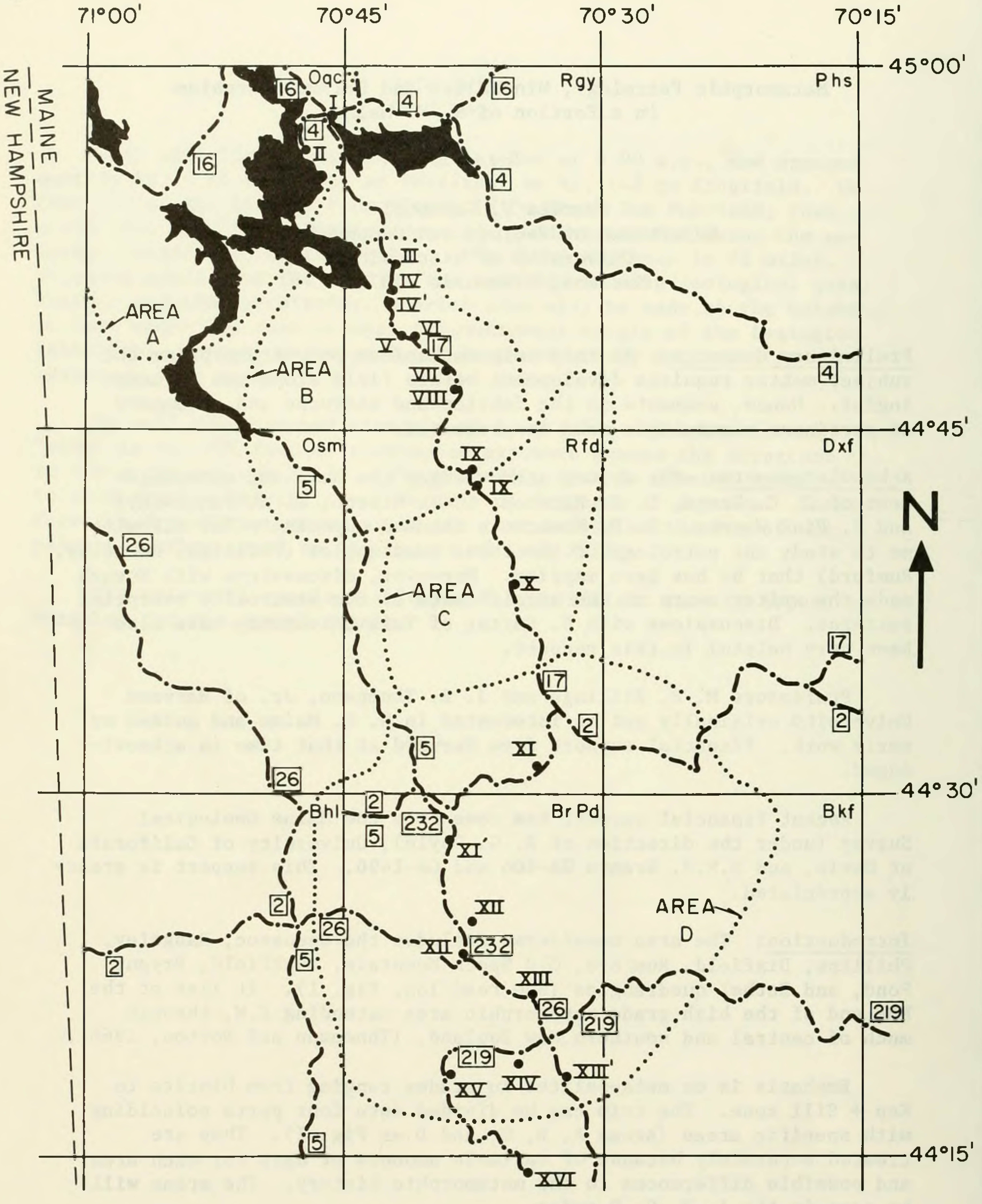

FIG I. ROAD LOG AND LOCATION OF AREAS A,B,C,D.

0 5
MILES

-ROADS
2 -STATE ROUTE NUMBERS
X -STOPS

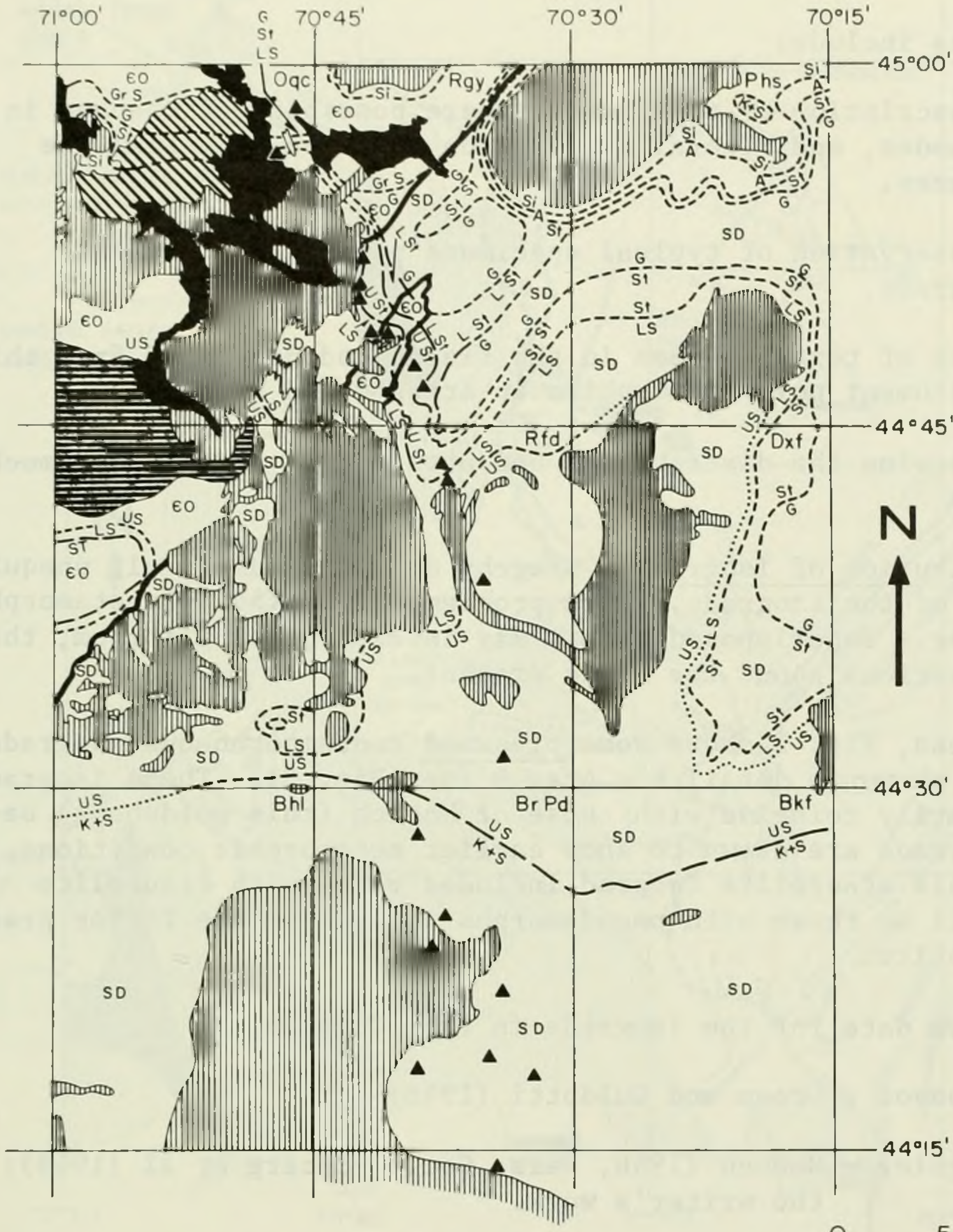

FIG 2. LOCATION OF ISOGRADS

▥ GRANITIC ROCKS (N.H. MAGMA SERIES)
▧ GRANITE (HIGHLANDCROFT PLUTONIC SERIES)
▤ UMBAGOG GRANODIORITE
▲▲▲ FIELD TRIP STOPS

ISOGRADS

— — — GOOD CONTROL - - - - - - APPROXIMATE
.... INFERRED
━━━ CONTACT CAMBRO-ORDOVICIAN (ЄO) AND SILURO-DEVONIAN (SD)

METAMORPHIC GRADES

K+S = KSP + SILL
US = UPPER SILLIMANITE ZONE ⎤ Si = SILLIMANITE
LS = LOWER SILLIMANITE ZONE ⎦
A = ANDALUSITE St = STAUROLITE
U St = UPPER STAUROLITE
L St = LOWER STAUROLITE
G = GARNET
Gr S = GREEN SCH. FACIES (CHLORITE + BIOTITE)

Objectives include:

(1) Description or tabulation (where possible) of changes in assemblages, modes, and mineral composition in order to define the metamorphic zones.

(2) Observation of typical specimens noting any textural changes with grade.

(3) Use of textures seen in the field (and described from thin section) to document polymetamorphism in Areas B and C.

(4) Showing the distribution and attitude of isograds in much of N. W. Maine.

General Distribution of Isograds: Sketchy data make difficult unequivocal location of the isograds. More problematic is the polymetamorphism mentioned above. Superimposed events may involve disequilibrium, thereby raising questions about the grade present.

Nonetheless, Fig. 2 shows some presumed contemporaneous isograds; the same ones shown in detail for Area B (see Fig. 3). These isograds do not necessarily coincide with those of Moench (this guidebook) because his isograds are drawn to show earlier metamorphic conditions. For example, his staurolite isograd includes rocks with staurolite present as well as those with pseudomorphs indicating the former presence of staurolite.

Sources of data for the isograds in Fig. 2 include:

Oquossoc - Green and Guidotti (1968)

Rangeley - Moench (1966, Pers. Com.); Osberg et al (1968); the writer's work.

Phillips - Osberg et al (1968); the writer's work.

Dixfield - Pankiwskyj (1964); the writer's work.

Rumford - the writer's work.

Old Speck Mountain - Milton (1961) with minor modification by the writer.

Buckfield - Warner (1967) modified by the writer.

Bryant Pond - Evans and Guidotti (1966).

Bethel - Fisher (1962); the writer's work.

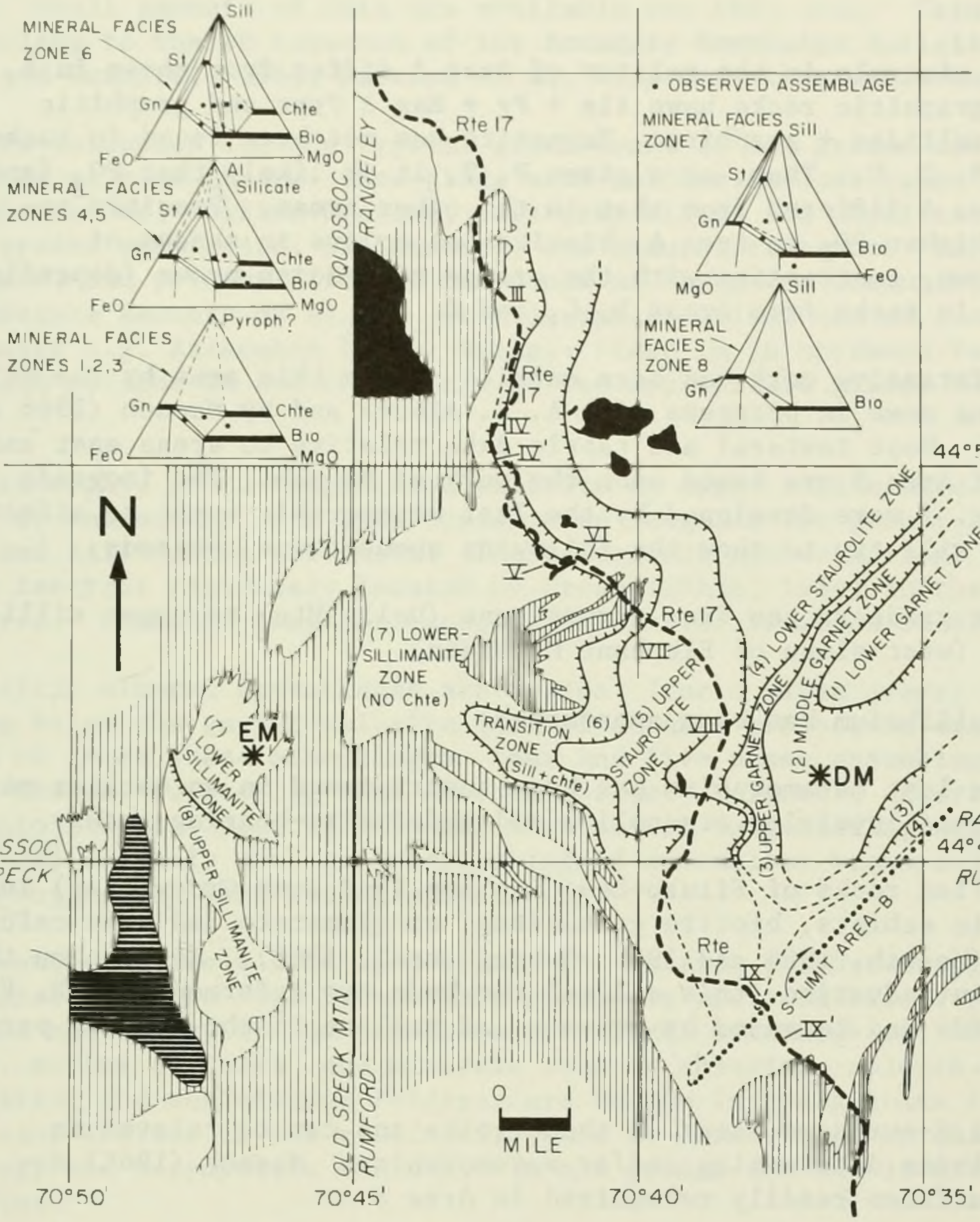

FIG 3. DETAILED ISOGRADS OF AREA B

✳ DM = DOLLY MTN.
✳ EM = ELEPHANT MTN.

Opaque minerals in the pelites of Area A differ from those in B, C, D. Non-graphitic rocks have ilm + Py + Mag ± Pyrr and graphitic ones ilm + sulfides + graphite. Magnetite has not been found in rocks from Areas B, C, D. Thus, at a given P, T, it is likely that PO_2 (and PH_2O) in Area A differed from that in the other areas. Possibly reflecting a higher PO_2 in Area A, biotite has colors in shades of greenish brown, contrasting with the orange to reddish brown (depending upon grade) in rocks from Areas B, C, and D.

AREA - B: Extensive work has been carried out in this area by the writer (including some in progress with A. L. Albee) and by Moench (1966 and pers. comm.) Most textural and fabric data relative to areas east and northeast of Area B are based upon the work of Moench. The isograds shown on Fig. 3 were developed by the last metamorphic event to affect Area B. We will try to show the following about these isograds.

(1) The grade ranges from garnet zone (Dolly Mtn) to upper sillimanite zone (west slope of Elephant Mountain).

(2) Equilibrium has been approached.

(3) The last metamorphism has been superimposed on an earlier metamorphic terrane involving staurolite and andalusite-bearing rocks.

Stratified rocks of Siluro-Devonian age (and some Ordovician) include pelitic schists, biotite granulites, conglomerate and some calc-silicates, (Moench, 1966 and 1969; Osberg et al, 1968). As seen on the map in the introduction (this volume) the beds are deformed into N. E. trending folds and intruded by two-mica adamellite in the western parts of the area.

Several S-surfaces occur in these rocks and can be related to events involving deformation and/or metamorphism. Moench (1966) described 3 surfaces readily recognized in Area B.

(1) S_1 = bedding, now deformed by large N. E. trending folds.

(2) S_2 = an older foliation ranging from a slaty cleavage to coarsely foliated schistosity depending upon grade. It reflects strong dimensional and crystallographic orientation of minerals and seems to be related to the formation of the large N. E. trending folds although recrystallization may be later.

(3) S_3 = a younger foliation which is especially well developed along the western part of the Rangeley quadrangle but also occurs throughout much of the remaining parts of Area B. S_3 consists of a slip cleavage (White, 1949) in low grades and a schistosity in higher grades. Near the western border of the Rangeley quadrangle it strikes N. W. and dips gently N. E.

AREA A: Small amounts of data are available for this area. Stratified rocks belong to the εO sequence of the Boundary Mountains Anticlinorium. (Green and Guidotti, 1968; Harwood et al, Trip A-3, this conference)

Meta-volcanics include typical greenstones at low grades and amphibolites at high grades. Low grade meta-pelites include green phyllites and carbonaceous, sulfide-bearing, dark grey slates and phyllites. At higher grades andalusite, sillimanite, and staurolite occur. Paragonite, chloritoid, and pyrophyllite are not found at any grade presumably due to only moderate amounts of Al_2O_3. Stratigraphic equivalents of some of these units e.g. Aziscohos fm (N. Maine) ≈ Stowe fm in northern Vermont) do contain paragonite and chloritoid at the appropriate grades (Albee, 1968).

Metamorphic grade ranges from chlorite to upper sillimanite zone. Because of inadequate data only approximate isograds for garnet, staurolite and sillimanite are shown. These isograds are extensions of similar isograds rigorously located by Green (1963A, 1964) in the Errol area. Possibly they correspond with similar isograds in Area B.

Pelitic mineral assemblages are typical (for a given grade) of rocks plotting below the garnet-chlorite join of an AKFm projection except that instead of three phase assemblages, four and five phase assemblages are common, thereby suggesting some disequilibrium. Moreover, chlorite in the staurolite and lower sillimanite zone occurs as radiating aggregates (to 1/2 cm) commonly with an interleaving of anormalous brown and blue layers--suggesting some retrograde effects.

A contact aureole developed around the coarse, porphyritic, Ordovician granite (X on Fig. 2) has been partially recrystallized. Textures and mineralogy of the granite also reflect metamorphism. For example. mortar textures, and minerals such as chlorite, epidote (and/or zoisite), and sericitized feldspar are common in the granite in the garnet zone whereas in the sillimanite zone it consists of "granite" mineralogy and porphyritic texture. In all grades the Ksp is maximum microcline.

Mineral assemblages in Area A are quite similar to those in Area B suggesting a similar facies series (Miyashiro, 1961), i.e. low pressure intermediate. Contact aureoles around some Acadian plutons intrusive into low grade rocks (Green, 1963A, Harwood and Larson, 1969, and N. W. Oquossoc) may represent a lower pressure metamorphism but this is not yet established. Cordierite is quite common in such aureoles.

Preliminary basal spacing work on muscovite shows the most sodic muscovite in pelites of staurolite grade just as in rocks of Area B.

In places S_3 is more pronounced than S_2. Commonly the muscovite laths showing S_3 superimposed upon S_2 have been polygonized (Zwart, 1962). Clearly it represents a shearing event post-dating the formation of S_2.

Garnet zone (See Fig. 3) rocks are fine-grained, greenish-grey phyllites (ignoring the Smalls Falls fm which is black due to graphite and disseminated sulfide) containing qtz + plag + bio + musc + chte + garn (See Table 1 for estimated modes etc.).

Textural features include:

(1) Biotite as isolated 1-2mm tablets.

(2) Garnet as 3-4mm euhedra commonly rimmed epitaxially by coarse laths of Fe-chlorite.

(3) Muscovite, chlorite, quartz, and plagioclase make up the groundmass and orientation of these minerals defines S_2.

(4) Aggregates of medium grained muscovite and chlorite form pseudomorphs after staurolite in some parts of the garnet zone. The pseudomorphs as well as garnets mentioned above cross cut S_2.

(5) S_3 is weak to moderately well developed. The Muscovite laths defining S_3 are partially polygonized. S_3 is generally truncated by the pseudomorphs after staurolite and the garnets although sometimes partially bending around these features. Biotite tablets and coarser laths of chlorite tend to line up along S_3 but nonetheless truncate it as shown by graphite trains within plates of biotite or chlorite. Quartz inclusions occasionally follow the graphite trains in the chlorite. In no case does S_3 deform pseudomorphs after staurolite, coarse chlorite rimming garnet, biotite tablets, or the isolated coarser laths of chlorite.

Some of the garnet zone was once in the staurolite zone but delicate sedimentary features (especially cross beds and graded beds) and clastic textures are retained in many specimens. Moreover, staurolite pseudomorphs never exceed 1/2 cm in length and are absent from much of the garnet zone (as recognized by Moench 1966). Probably much of this zone has never been much more highly metamorphosed than at present.

In the lower staurolite zone (Fig. 3) textures become coarser and specimens then develop a white luster. Isolated laths of chlorite and biotite are distinctly coarser than groundmass muscovite. Garnet, subhedral to euhedral is not rimmed by chlorite. Staurolite occurs as (1) subhedral, moderately to highly poikilitic megacrysts, (2) aggregates of oriented subhedra pseudomorphous after larger staurolite crystals, and (3) anhedral masses enclosed by coarse muscovite and chlorite (this mode being most common). Estimated modes are given in Table I.

S_3 is better developed than in the garnet zone, occasionally even supplanting S_2 as the most prominent foliation. In addition to the textural relationships of S_3 to pseudomorphs etc. seen in the garnet zone, fresh staurolite also truncates S_3. Curved patterns of quartz inclusions in the staurolite shows that staurolite overprints the pattern of S_3 in the groundmass. In no case does S_3 deform muscovite and chlorite partially pseudomorphing staurolite.

The upper staurolite zone (Fig. 3) is characterized by somewhat coarser grain size than the lower staurolite zone and a decrease in modal chlorite (See Table I). Most lower staurolite zone textures are repeated in the upper staurolite zone. Staurolite occurs mainly as types (1) and (2) described in the lower staurolite zone.

Also present in some specimens are large, irregular, highly poikilitic to skeletal andalusite crystals, in some cases almost forming a groundmass (similar andalusite is rare in the lower staurolite zone). The pattern of quartz inclusions reflects S_3 just as commonly seen in staurolite. In many cases the andalusite is partially replaced by coarse muscovite.

The transition zone* is marked by (see Fig. 3 and modes in Table 1):

(1) Appearance of sillimanite.

(2) Persistence of only traces of chlorite.

(3) Some replacement of staurolite by coarse muscovite alone.

(4) Some biotite epitaxial rimming of garnet.

(5) Strong development of S_3 - commonly being more prominent than S_2.

Most other textural features seen in the upper staurolite zone persist into the transition zone.

Lower sillimanite zone (Fig. 3 and modes in Table 1) rocks are similar to the transition zone but grain size coarsens and staurolite is more replaced by <u>coarse</u> muscovite. Concommittent relocation of groundmass muscovite into pseudomorphs after staurolite results in a darkening of color of the rock (Guidotti, 1968). Muscovite replacement of andalusite is complete about half way through the lower sillimanite zone. Epitaxial biotite rims on garnet are most pronounced in this grade.

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* "transition" referring to the appearance of sillimanite and persistence of chlorite in rocks apparently plotting below the staurolite-chlorite line in an AKFm diagram.

In the upper sillimanite zone (Fig. 3 and modes in Table 1) staurolite is absent (Guidotti, 1970). Textural changes worthy of note here are:

(1) Complete replacement of staurolite by muscovite.

(2) eventual coalescence of muscovite into 1 cm megacrysts.

(3) further darkening of color of hand specimens.

(4) biotite occurs as folia consisting of aggregates of plates.

(5) S_3 is almost totally destroyed by recrystallization.

In summary, an especially important point is that in the appropriate grades staurolite and andalusite have over printed S_3. In a few cases S_3 partially bends around staurolite crystals. But even then inclusion patterns inside the staurolite still reflects an over printing. This point will be considered further below.

Excluding andalusite, the mineralogy, modal changes shown in Table 1, and many of the textural features described above can be integrated into a sequence of metamorphic steps ranging from garnet to upper sillimanite zone. The mineralogy of the various grades can readily be related by means of a series of equations such as*:

Garnet Zone:
(1) Fe Chte + Musc $\rightleftharpoons$ Garn + Bio + Mg Chte + Na-richer Musc + H_2O

Garnet Staurolite Zone:
(2) Mg Chte + Garn + Musc $\rightleftharpoons$ Staur + Bio + Na richer Musc + H_2O + Qtz

Staurolite Zone:
(3) Mg Chte + Musc $\rightleftharpoons$ Staur + Bio + Na-richer musc + H_2O

Staurolite Lower Sillimanite Zone:
(4) Staur + Mg Chte + Na Musc $\rightleftharpoons$ Sill + Bio + K-richer Musc + Ab + Qtz + H_2O

Lower Sillimanite Zone:
(5) Staur + Sodic Musc + Qtz $\rightleftharpoons$ Sill + Bio + Fe-richer Staur + K-richer Musc + H_2O + Ab

Lower Sillimanite Upper Sillimanite Zone:
(6) Staur + Sodic Musc + Qtz $\rightleftharpoons$ Sill + Bio + K-richer Musc + Ab + Garn + H_2O

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* Only reactions for the lower sillimanite zone and higher have been considered in detail so far. Also Zn in staurolite is not considered here.

Upper Sillimanite Zone:
(7) Na Musc + Garn $\rightleftharpoons$ Bio + Sill + Ab + K-richer Musc + H_2O

Fig. 3 includes AKFm diagrams of the mineral facies for the various grades. Clearly from Table 1 and Fig. 3, some of the zones are based upon continuous reactions, (i.e. the same mineral facies for more than one zone).

Features suggesting that the proposed sequence is real and approximates an equilibrium event are:

(1) The systematic modal, textural, and grain-size changes expected for a continuous metamorphic sequence, ranging from garnet to upper sillimanite zone, are clearly present.

(2) Systematic mineral changes can be mapped as isograds and represented by topology changes of AKFm diagrams.

(3) Systematic compositional changes occur for solid solution minerals with change in metamorphic grade. Muscovite and chlorite are especially noteable. Table 1 shows the changes in paragonite content in muscovite (including only data from the most Al-rich specimens as indicated by the assemblage present). The most sodic muscovite occurs in the upper staurolite zone (also observed by Cipriani et al, 1968) which is reasonably consistent with the experimentally determined muscovite-paragonite join of Eugster and Yoder (1955).

Chlorite exhibits changes in optical properties which indicate, (using Criteria of Albee, 1962), Fe-chlorite in the assemblage garn + bio + chlor in the lower and middle garnet zones, (Fig. 3) (this coincides approximately with rocks containing garnets rimmed by chlorite), and Mg - richer in the upper garnet zone. In staurolite grade rocks chlorite is always Mg-rich.

On Fig. 3 the staurolite and garnet zones are thus subdivided on the basis of continuous changes in the composition of muscovite and/or chlorite.

(4) The distribution of the higher grade isograds (Fig. 3) shows a distinct spatial relation to the two-mica adamellite intrusives*.

Only the andalusite does not fit into the metamorphic sequence outlined above. As will be seen below it can be considered as a relic from an earlier metamorphic event.

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* Moreover, the higher grade isogradic surfaces have low dips, thereby reflecting the low dipping sheets of two-mica adamellite.

It is of utmost importance to note that an intrinsic part of the proposed metamorphic sequence is the development of various types of pseudomorphs. They clearly relate to the proposed metamorphic sequence because the types and degrees of pseudomorphing are keyed to the metamorphic zones which in turn are based upon modal and mineralogical changes. (See Guidotti, 1968 for details of one of these pseudomorphic features). Moreover, platy minerals within the various pseudomorphs have no preferred orientation and in the appropriate grades include and are intergrown with well developed sillimanite. There can be little doubt that metamorphism producing the isograds of Fig. 3 is responsible for the numerous pseudomorphic textures. Certainly the sharpness (i.e. euhedral) of many of the pseudomorphic forms (e.g. Stop # VIII or Fig 5 in Guidotti, 1970) would be inconsistent with the pseudomorphs being relics from any earlier events.

Data for muscovite corroberates the preceding conclusion in lower grade rocks where sillimanite is absent. One might interpret the pseudomorphing there as random, late retrograde products. However, in the staurolite zone, muscovite from rocks with any staurolite present (i.e. only partial pseudomorphs) is invariably more sodic than that from specimens with staurolite totally pseudomorphed. This indicates that the pseudomorphs are not random late retrograde products, but formed during a distinct, broad-scale, coherent event. Although the pseudomorphing in the lower staurolite and garnet grades is indeed a retrograde event, it is nonetheless produced by the same metamorphic event which developed sillimanite grade rocks to the west*.

Hence, the several grades shown in Fig. 3 appear to have approached equilibrium and are thus "geared" to a single metamorphic event ranging from garnet to upper sillimanite zone--a metamorphic event commonly producing pseudomorphic textures. It is then evident that the overprint patterns of S_3 within staurolite and andalusite grains and pseudomorph development on the outer parts of these same minerals implies that most of these minerals are relics from an earlier generation. Chemical data on the staurolite (work in progress with A. L. Albee) shows that the staurolite has nonetheless readjusted compositionally to relate to the isograds of Fig. 3. With regard to the relic andalusite, its lack of any systematic distribution relative to the isograds shown in Fig. 3 suggests that it is a metastable relic. Commonly the aluminum silicates have been supposed to act in a recalcitrant fashion with regard to reactions which should destroy them. Some minor, "new" staurolite (and possibly even some andalusite) may have formed during the metamorphic event outlined above but this is difficult to prove. Possibly the staurolite occurring as euhedral swarms within larger pseudomorphs represents staurolite formed during this metamorphic event.

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* The systematic changes in the composition of muscovite from grade to grade are, of course, the best indication that the whole region has been subjected to the same final, metamorphic event.

In the light of the above picture, it is possible to suggest the following sequence of metamorphic and tectonic events in Area B.

(1) Folding along NE trending axes accompanied by the formation of an S_2 cleavage (D_1)

(2) Moderate recrystallization at low grades converting S_2 cleavage into an S_2 schistosity. (M_1).

(3) Renewed tectonic activity forming a low dipping S_3 slip cleavage and accompanied by some minor folding, (D_2). Overlapping and outlasting the tectonic activity, much of the area was metamorphosed to an assemblage of andalusite + staurolite + biotite (M_2). S_3 was recrystallized to a good schistosity.

(4) As a distinctly later event, intrusion of adamellite occurred. Intrusions were concentrated in areas where prominent development of S_3 provided easier access for the magma. The attitudes of the intrusives were controlled by the attitudes of S_3. Accompanying + outlasting the intrusives was another strong metamorphic event (M_3) having a distinct spacial relationship with the distribution of adamellites. Near the areas of abundant intrusives, sillimanite grade was reached thereby effecting a prograde metamorphism of the andalusite + staurolite grade rocks. Further from the intrusives the grade was only garnet zone, thereby retrograding the earlier andalusite + staurolite rocks.

Little evidence exists for events post-dating M_3 in Area B. Only rarely are any layer silicates cut by kink bands--(a distinct contrast with Area C). Minor chlorite after biotite in lower and upper sillimanite grade rocks is related to weathering or obvious zones of faulting.

Preceding M_3 was an event M_2 producing most of the andalusite and staurolite which was later partially pseudomorphed by M_3. Staurolite and andalusite of M_2 truncates and overprints S_2 and S_3 patterns although S_3 occasionally tends to bend around megacrysts (or pseudomorphs) of staurolite. This suggests that most of M_2 post-dates D_2 (which produced S_3) but nonetheless some S_3 shearing persisted somewhat into M_2. The chlorite and biotite plates truncating S_3 could have formed in M_2 (after all D_2 ended) but the relation of their chemistry and modal amounts to the isograds of M_3 suggests that they formed during M_3.

It appears that much of the area in Fig. 3 attained andalusite-staurolite grades (due to M_2) except for parts of Dolly Mountain as mentioned earlier. Preceding D_2 it is obvious there must have been an earlier deformation (D_1) which produced S_2.

Moench (1966, P 1450 and 1452, and pers. comm.) have postulated a significant staurolite and andalusite forming event (I have called it M_1) preceding S_3 in the central part of the Rangeley-Phillips area. Moench, on the other hand, has not distinguished two metamorphisms post-dating S_3. The writer's work in Area B neither refutes nor confirms Moench's suggestion but several facts suggest that most of the staurolite (and andalusite) in Area B post-dates S_3.

(1) Most pseudomorphs and partial pseudomorphs from garnet to lower sillimanite zone have well preserved shapes - usually being sub - to euhedral. The pseudomorphs (as well as non-pseudomorphed staurolite, garnet etc.) cross cut S_3 showing clearly that the pre-curser minerals post date S_3 also. In Area B it is difficult indeed to demonstrate any staurolite preceding S_3.

(2) Even in some lower staurolite zone specimens the pattern of quartz inclusions in staurolite remnants within partial pseudomorphs have weak patterns showing the overprinting of S_3* (these patterns being very well developed in the upper staurolite and higher grades). In a few specimens from the western slopes of Dolly Mountain (just barely above garnet grade) the S_3 overprinting is as well developed as that in any specimen from the more westerly parts of the Rangeley area. As most rocks have staurolite crystals or pseudomorphs of similar size it seems unreasonable to ascribe some staurolite to an M_1 event since most of it is clearly due to M_2.

Thus, prior to D_2, Area B may have been metamorphosed only to the extent of recrystallizing and coarsening S_2 (indicated as M_1 in our suggested sequence of metamorphic and tectonic events, P).

Still not clearly demonstrated is the implied, distinct separation of M_2 and M_3. Several points bearing on this are:

(1) Cordierite is present in several transition zone rocks and shows overprint patterns on S_3. However it is always strongly rimmed by coarse chlorite and muscovite.

(2) The isograds of M_3--especially those separating the upper staurolite, transition and lower sillimanite zone show no relation to the distribution of andalusite. The vast majority of andalusite observed shows overprint patterns on S_3 and is also significantly replaced by coarse muscovite. This holds true for rocks ranging from lower staurolite zone to well up in the lower sillimanite zone.

Absolutely no relationship exists between andalusite and the isograd which first brings in sillimanite. This isograd clearly involves the breaking of the staurolite-chlorite join on an AKFm diagram to form the sillimanite-biotite join and is associated with several systematic modal and mineralogic changes of the solid solution phases. If the reaction were really just a transition (whether stable or metastable is irrelevant) of andalusite to sillimanite, it is difficult to understand

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* Obviously the weaker development of S_3 in these lower grade rocks means that S_3 overprint patterns will also be less distinct.

FIGURE 4. PT CURVES GERMANE TO THE TRANSITION FROM STAUROLITE TO UPPER SILLIMANITE ZONE. CURVES INCLUDED ARE: **1** ALUMINUM SILICATES, NEWTON (1966), **2** BREAKDOWN OF STAUROLITE, HOSCHEK (1968), **3** BREAKDOWN OF MUSCOVITE, EVANS (1965), **4** MINIMUM MELTING OF GRANITE, TUTTLE AND BOWEN (1958), **5** BEGINNING OF ANATEXIS, WINKLER (1967), **6** UPPER STABILITY OF THE PAIR, STAUROLITE + CHLORITE

why this should coincide with the other observed modal and mineralogical changes which occur at the isograd. These several considerations are more consistent with the hypothesis that andalusite is merely a metastable relic from M_2. Clearly the production of sillimanite and the various pseudomorphs is spatially related to the plutonic rocks whereas andalusite shows no such relationship.

(3) A hinge effect is present for M_3 such that some rocks affected by M_2 have been retrograded to staurolite and garnet zones whereas others have been prograded to sillimanite zone. (A similar hinge effect was found in the Dixfield areas, (Pankiwskyj, 1964).

Points 1-3 are inconsistent with M_2 and M_3 as part of a single event such as the Mx arrow in Fig. 4. This arrow has an A and B part representing a continuous rise of temperature with time. Instead two separate events (Mx and My arrows) are necessary with My at a somewhat greater pressure (and Mx not surpassing the temperature of point A). Surely the "hinge effect" mentioned above is irreconcilable with M_2 and M_3 as part of one event because rocks in the lower staurolite zone (as an example) would have to be heated up to some temperature T_1 and recrystallized and then cooled to T_2 accompanied by further recrystallization, (all within the same event) during which time temperatures to the west (and part of the same thermal regime as in the lower staurolite zone rocks) continued rising to produce sillimanite. Clearly this is unreasonable. Two separate events M_2 and M_3 are required. Finally, even the isograds of M_3 can not be attributed merely to the late cooling history of the plutons as shown by the fact that the adamellite truncates the isograds in several places (See Fig. 3). Clearly, the isograds of M_3 are contemporaneous with the emplacement of plutons but the relations described indicate that plutons and isograds are due to a common thermal source rather than one controlling the other.

Inasmuch as M_3 and the adamellite intrusions are contemporaneous, the fact that M_3 post dates S_3 suggests that the formation of S_3 is not the result of intrusion of the adamellites*. The distribution of adamellite is related to S_3 (as pointed out by Moench also) because the intrusions commonly occur as thick, tabular bodies parallel to S_3 in the Oquossoc and S. W. Rangeley areas. But the increased intensity of S_3 near plutons noted by Moench (1966) may not result from the plutons; instead the distribution of plutons may be controlled by the degree of development of S_3.

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* Moreover, it is hard to visualize how an intruding pluton could produce the almost horizontal S_3 surfaces seen along the W. side of the Rangeley area.

Inasmuch as M_3 is related to the adamellites and the adamellites belong to the New Hampshire Plutonic series, (Green, 1964; Green and Guidotti, 1968) which is Acadian in age, then M_3 must be the same age. M_2 must also be at least Siluro-Devonian in age. Hence we have two Siluro-Devonian metamorphisms.

AREA - C: Only moderate amounts of work have been done here so far. The stratified rocks are at least partly equivalent to those in Area B. Textures, fabrics and mineralogy matching S_2, S_3, M_2, and M_3 of Area B can be recognized in the northern sections of Area C. Moreover, the approximately located isograds for staurolite and sillimanite zones are commonly almost horizontal just as in Area B. These observations suggest Areas B and C have been effected by the same events. Even the assemblages developed appear similar to those of M_2 and M_3 in Area B.

However, most striking now, in rocks of Area C is the abundant evidence for disequilibrium.

(1) Many assemblages contain excessive numbers of phases in terms of the phase rule -- e.g. Sill + Bio + Garn + Staur + Chte is common in the N and NE sections. Moreover, the anomalous blue color of chlorite suggests Fe chlorite which is unexpected in high grade pelites.

(2) Biotite is commonly replaced by chlorite and sagenitic rutile although the same rock may also contain clean megacrysts of chlorite larger than any of the biotite plates. In some cases, chlorite of two different colors is present.

(3) Sillimanite is sometimes much replaced by sericitic mica. Most commonly it is resorbed so that it now occurs mainly as inclusions in quartz, especially quartz poikilitically included in megacrysts of muscovite. Concommittent with resorption of sillimanite, muscovite megacrysts commonly fragment into sericitic aggregates. A distinct antipathy exists between sillimanite and biotite; a marked contrast with their stable textural relations at high grades.

(4) K/Na values of muscovite (using basal spacings) show little relation to assemblage present. Moreover, little or no systematic relation between isograds and K/Na values of muscovite can be discerned. The quite systematic relation of K/Na in muscovite and grade which occurred in Area B ends abruptly along an ENE trending line just south of Byron (See Fig. 3).

(5) A widely spaced but distinct slip or shear has affected many rocks appearing as sharp, angular kinks in all layer silicates (including coarse muscovite and chlorite which sometimes form partial pseudomorphs after staurolite). Kinking is most pronounced (and sometimes accompanied by mortar structure in quartz) in the area to the SE and E of Byron. In the vicinity of Thomas Farm Brook a breccia zone occurs.

(6) In the N. Central section of Area C, garnet and staurolite commonly have thin rims of fine grained, anomalous blue chlorite and sericite. The rims also follow along cracks and fractures in the garnet or

staurolite.

Hence, disequilibrium seems certain in much of the area, the evidence suggesting retrograding. Much of the area was upper sillimanite zone but some parts possibly only staurolite grade before the retrograding. The coarse, migmatitic Noisey Brook gneiss (Stop # X) may have been Ksp + Sill zone. At Stop # X, it is a coarse, swirled, "soupy" rock containing pegmatites and small adamellite bodies.

Two additional points possibly helping to relate rocks in Area C to Areas B and D are:

(1) In the N and NE sections commonly occur small, euhedral staurolite crystals (1 mm) or aggregates of crystals growing on grain boundaries of quartz and plagioclase. In some cases the euhedra occur in the same rock with larger, ragged staurolite grains which contain coarse needles of sillimanite. The euhedral staurolite "appears" fresh and as if it formed in a later event.

(2) In the S. part of the area, aggregates of fine grained euhedral sillimanite needles occur on quartz and plagioclase grain boundaries. Such aggregates are present in rocks containing coarser sillimanite which is partially resorbed. Again, it "appears" as if the euhedral needles are the result of a late event.

With these observations and impressions the writer tentatively suggests that the same events affected Parts B and C but with two additional events for the latter. These are: (in order)

(1) A metamorphic event (M_4) retrograded the northern sections to staurolite and possibly garnet zone whereas the southern sections were retrograded only to somewhat lower in the sillimanite zone. Probably equilibrium was not attained and the coarse chlorite may have formed in this event.

(2) Deformation produced the kink bands cutting the layer silicates. Possibly retrograding of biotite to chlorite + sagenitic rutile as well as the thin rims on garnet and staurolite formed in conjunction with the shearing that produced the kinks.

M_4 could be in Area C the lower grade portion of the Ksp + Sill metamorphism affecting much of the area covered in Area D.

AREA - D: This area includes much of the southern 1/3 of the Rumford quadrangle because the mineralogy of rocks there can be systematically related to the Ksp + Sill isograd. Rocks, presumably Siluro-Devonian in age, are migmatitic throughout the area. Migmatites contain Ksp only on the upgrade side of the Ksp + Sill isograd but the isograd itself is based on the association Ksp + Sill in the groundmass.

Detailed study by Evans and Guidotti (1966) suggested an approach to equilibrium and the following isogradic reaction.

(8) Musc + Qtz + Ab (from plag) $\rightleftharpoons$ K, Na spar + Sill + H_2O

The migmatites presumably formed by partial melting such as suggested by Lundgren (1966) for similar rocks in Connecticut, but no detailed work on this question has been done here. Chemical work by Fisher (1962) in the Bethel area argues against a metasomatic origin for the migmatites. Fisher favored a partial melting origin but also considered metamorphic segregation.

The possibility of getting the four phase assemblage, Sill + Ksp + Plag + Musc were clearly recognized by Thompson (1961) and (Pers. Com. 1960) due to addition of CaO to the AKNa system. Evans and Guidotti (1966) discussed this assemblage in Area D and noted that the muscovite maintained a constant composition (Pg_6) over a broad area south of the isograd. They also found that muscovite from the associated specimens containing only Musc + Sill + Plag was more sodic than muscovite from specimens with the four phase assemblage. Moreover, plagioclase in non-Ksp rocks was commonly more sodic than that in rocks with the four phase assemblage. These observations are not expected in terms of theory.* To explain these observations Evans and Guidotti suggested:

(1) Thermal gradients flattened south of the isograd such that all exposed rocks formed at the same PT.

(2) The fugacity of water was variable from specimen to specimen but internally controlled. For the four phase assemblage it was suggested that fH_2O was buffered by the assemblage.

Evans and Guidotti (1966) favored # 2 as a working model.

Although plagioclase in the four phase assemblage becomes more calcic with increased grade (see Fig. 5 of Evans and Guidotti 1966) the weak zoning present is normal instead of reverse as expected. A possible explanation is that the zoning is a late phenomenon. It may represent late recrystallization in the presence of a silicate melt (i.e. the migmatitic bands). Sodic rims would then result from simple fractional crystallization. In studies by Barker (1962) and Binns (1964) plagioclase in Ksp + Sill rocks does have reverse zoning. Possibly rates of reaction (and cooling) control the nature of zoning in plagioclase from such rocks.

Preliminary work on the Ksp in these rocks (with H. H. Herd of U. C. Davis) using Wright and Stewart (1968) to characterizing the structure state has shown:

(1) Groundmass Ksp coexisting with sillimanite is invariably close to

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*Theoretically one expects muscovite in the four phase assemblage to become K enriched with increased grade and the coexisting plagioclase to become enriched in An.

orthoclase.

(2) Coarse grained Ksp from megacrysts and migmatitic bands is commonly more ordered -- averaging near Spencer B but ranging to Spencer U.

(3) Ksp from low alumina rocks such as calc-silicates or biotite granulites is always more ordered -- ranging from Spencer B to maximum microcline.

(4) Ksp from obviously retrograded rocks (e.g. biotite going to blue chlorite and sagenitic rutile) is usually more ordered -- ranging to maximum microcline -- regardless of what the original rock may have been.

An Acadian age is assumed for the metamorphism of Area D because many of the intrusive plutons are similar to the Concord granite, Fisher (1962), Billings (1956). The large pluton south of Area D is also shown by Doyle (1967), Page (1968), Osberg et al (1968) etc. as belonging to the New Hampshire Plutonic Series (Acadian age). Moreover, Page also ascribes the pegmatites intruding the metamorphics to the New Hampshire Plutonic Series. Hence evidence exists for a heating event at this time.

Contradictory data for an Acadian age are two Permian ages (by Rb-Sr) from micas in pegmatites (Paris Hill, S. W. corner of Buckfield area) listed in Faul et al (1963). Suggestion of a Permian metamorphism, if real, raises the possibility that M_4 in Area C represents the northern limit of such an event superimposed on M_3 which has an Acadian age. Such speculation would agree with the "Probable NE limit of Permian metamorphism" in Fig. 2 of Faul et al (1963).

Available age dating in N. W. Maine is too scanty to establish any certainty of ages of metamorphism. Presently the writer assumes an Acadian age for the Ksp + Sill isograd but allows that it could represent an event somewhat younger than M_3 in Area B.

Fig. 4 is a summary diagram indicating supposed conditions of metamorphism for M_2, M_3 and the Ksp + Sill isograd.

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Road Log for Trip B-2

Assemble in front of the Town and Lake Motel on Rte. 4, west side of Rangeley. We leave at 8:00 a.m. Head due west on Rte 4.

Mileage

6.7 Stop I in the N.E. part of the Oquossoc quad on Rte. 4 just W. of the junction with Rte. 16. Park on the wide shoulders. The rock is a typical greenstone (nearby pelites indicate biotite zone) containing actin-chlte-epid-albite and some calcite, quartz, sulfides, etc. The protolith is presumed to be basaltic flows but some pyroclasitics also are present in other outcrops. Notice the epidote-rich pods and clots in the otherwise massive to foliated volcanics. Possibly these represent volcanic bombs.

In some cases, remnant plagioclase and pyroxene grains have been found in these rocks.

Drive through Oquossoc village.

8.1 "T" in road--at Haines landing on Mooselookmeguntic. Turn left (South)

10.2 Stop II Tight parking--take care on pulling off to left! Some mud! Main stop is at Adam's Camps and just south where the best crops are. The lead cars will park 50-75 yards S. of Adam's Camps and the others as space is available.

Here we see 3 rock types--all in lower sillimanite zone or upper staurolite zone.

(1) Quartz pod pelitic schist of the Deer Mountain member of the Albee fm.

(2) Meta volcanics (amphibolites here) commonly interbedded with the pelites.

(3) Metamorphosed granite of the Highlandcroft Plutonic Series. Sometimes has Pink Ksp.

In the pelites one can find good 1/4" euhedral garnets and tourmaline; occasionally staurolite is also seen in hand specimen. Sillimanite is always microscopic. Notice some of the coarse clots of chlorite. (see text)

Continue S. on dirt road.

12.2 Turn left--still on a dirt road.

13.4 Dirt road meets Rte. 17 (Paved). Turn right (south).

18.4 Stop III--on Rte 17. Fair amount of parking on both sides of road, but use caution as there are many curves on this road. Most of this crop is cgl and grit but the more aluminous beds have 1/16 to 1/8" staurolite which is partially rimmed by muscovite. Sillimanite is present in thin section. The grade is lower sillimanite zone.

20.2 Stop IV Drill site--parking to the right, left, and just south. The Union Water Power Co. drilled and cored down to about 900 ft. at this site. They allowed me to take a sample every 20 feet or so. At the surface the grade is Transition Zone (i.e. sill + chte). With increased depth the grade rises and at about N 850 feet the hole hits adamellite (which field mapping by Moench could have predicted). About 150 feet from the granite there is an abrupt rise in muscovite and disappearance of sillimanite, suggesting K-metasomatism just as described by Green (1963) near the contacts of similar adamellites in the Errol quad.

20.8 Walk .6 mile S. on Rte 17 to Heights of Land. Crops are just about on the isograd for the lower sillimanite zone. Very good staurolite schists. In a few places, irregular, remnant andalusite weathers to form patches of higher relief.

Note Elephant Mtn. to W.S.W.--Upper sillimanite rocks lie on the west slopes.

22.8 Stop V--Optional--if only a few cars present! Very difficult parking, narrow shoulders. Rocks are merely an example of the dull mineralogy that occurs in low alumina rocks--Only biotite granulites and grits are present although the crops are in the lower sillimanite zone.

23.4 Middle of Beaver Pond.

23.8 Stop VI Just over the crest of the hill east of Beaver Pond. Park on the right side of road-wide shoulders. Walk back to see the interbedded biotite granulites and calc silicates. Rocks at this stop are in the Transition Zone. .2 miles down hill are good dense, white schists. Sillimanite is present in thin section. Some staurolite is totally pseudomorphed by coarse muscovite but some is only rimmed by the muscovite (N. most crop).

25.2 Stop VII Park on the left side of highway--wide shoulders. Rocks are in the upper staurolite zone. Notice the pseudomorphs which now consist of aggregates of euhedra in a matrix of muscovite and quartz.

26.9 Stop VIII Just across the bridge over the Swift River. Plenty of parking but watch embankments on entering parking area. Rocks are low to upper staurolite zone. Follow trail down stream on S. side of River. About 1/8 to 1/4 mile down stream are large slabby crops with very good pseudomorphs (similar to VII) which clearly indicate two periods of staurolite formation.

32.3 Stop IX--at Byron picnic area--in the Rumford quadrangle. Rocks are staurolite grade. Very good development of staurolite! Also notice on some slab surfaces the "turkey track" pseudomorphs after andalusite--again suggesting polymetamorphism. In some specimens andalusite is still present but rimmed by muscovite. It is interesting that here and elsewhere in the Rangeley area andalusite seems best preserved in rocks rich in sulfides and graphite. One can speculate that the fluid in such rocks had a lower % of H_2O and thus reactions removing metastable andalusite (especially by forming hydrous minerals like muscovite) may have been inhibited. Some workers have appealed to dissolved Fe_2O_3 in the andalusite acting as a stabilizer.

The other common site for relic andalusite is in quartz veins. This may result from relative inaccessibility to solutions bearing K_2O.

LUNCH STOP

33.2 Stop IX[1] Optional for later trips using this guide book. To the east in the woods about 1/4 mile can be found good crops of the very sulfitic Smalls Falls formation. Biotite in pelitic specimens is nearly colorless, suggesting phlogopite. It is the only unit that seems to have cordierite fairly commonly.

38.8 Stop X Roxbury Picnic area--Noisey Brook gneiss. Rocks here are superb examples of swirled up "soup". Bedding seems to have been obliterated. Rocks were originally upper sillimanite zone but have now been significantly retrograded. Sillimanite shows many signs of resorption. Crops a little S. of here show some signs of regeneration of sillimanite.

Continue S. on Rte. 17 to the center of Mexico.

Junction of Rte. 17 and Rte. 2 at stop sign in Mexico. Turn right on Rte. 2 and continue across bridge over Swift River.

46.1 Rte. 2 bears left by the stop sign at the State Armory. Follow Route 2 through Rumford.

47.7 --at the pull out beside the Androscoggin River, just west of town. Re-group here. Then proceed W. on Rte. 2.

50.7 Stop XI --big crops in back of Mammoth Mart. Upper sillimanite zone, coarse schists. Notice the clots or eyes of muscovite which are probably pseudomorphous after staurolite. In rocks of higher grade, the muscovite in the pseudomorphs re-crystallizes to single large megacrysts much like occurred at Stop X.

56.5 Junction with Rte 232. Turn S. on Rte 232 across the Androscoggin River.

59.5 Stop XI -- Optional stop for people using this field guide at a later time. Rocks on Barker's High Ledge are Ksp + Sill grade. Here one finds some of the best development of single, subhedral Ksp megacrysts up to 2 inches in good sillimanite-bearing schists.

64.2 Stop XII at N. Woodstock. Turn left on small paved road and park near the end of the paved section (about 1/4 mile). Walk 250 yards up the dirt road beside Billings Hill brook. Then go into the stream bed to see the large crops of migmatites and biotite schists. Most crops of this unit (Billings Hill fm) are fairly rich in sulfides. Try to find some of the more aluminous beds. Some of them are as much as 30% sillimanite which is intergrown with fairly coarse, translucent Ksp. Be careful here, the rocks are very slippery! -- Back to Rte 232 and turn left, to the south and resume mileage clocking.

65.9 -- Intersection with Rte 26 -- turn left and then stop in the big rest area.

Stop XII^1 -- Walk back to granodiorite crop on Rte 232. Different from most of the big Sebago pluton in that it is not per-aluminous. In places it has small amounts of hornblende. Some jointing surfaces have thin seams of epidote. The feldspar to the sides of the seams has commonly become pink in color.

Head S. on Rte 26.

66.3 more of the granodiorite

69.7 Stop XIII at S. Woodstock -- Big crops of Sill + Ksp rocks. Sillimanite is very abundant and megacrysts of Ksp are common. Some of the megacrysts contain subhedral to euhedral, bipyramidal quartz.

If many cars present, some can park .3 miles down the road.

73.9 Stop XIII[1] Auxilliary Stop -- at Snow's Falls picnic area. Good Ksp + Sill migmatites.

Return to Trapp Corner (i.e. N. on Rte 26)

76.1 -- Trapp Corner, turn left (W) on Rte 219 and go through West Paris.

77.5 -- On west side of W. Paris across RR tracks and bridge, Rte 219 bears right -- do not follow it. Head up the hill.

77.8 Stop XIV -- Take a sharp right into the Bell Mineral Quarry and park. Only about 6 cars can fit in here so the others will have to park to the S. on the paved Road. Walk for .6 miles on dirt road to the quarry. THIS IS AN ACTIVE FELDSPAR QUARRY. THE MANAGEMENT ALLOWS PEOPLE IN HERE AT THEIR OWN RISK. PLEASE NOTE: YOU ENTER THIS QUARRY PROPERTY AT YOUR RISK AND THE BELL MINERALS CO. CAN NOT BE HELD LIABLE. PLEASE STAY OUT OF THE "CAVERNS".

Here we can see some spectacular inclusions of calc-silicates "floating" in pegmatite. The diopside has about 30-40% of the hedenbergite end member. Quartz + calcite are common in many specimens. No wollastomite has been found. On some of the loose blocks at the mouth of the quarry look for evidence of migration of components.

Head back toward West Paris.

78.1 Junction with Rte 219 -- Turn left on Rte 219.

82.5 Greenwood Village -- end of Rte 219 -- Turn left by the N. end of Hicks Pond. Head S. along the ponds.

83.3 Stop XV on W. shore of Hicks Pond. Nicely exposed recumbent fold in migmatites. Provides some of the evidence of strongly overturned folding in this region.

Continue S. past Mud Pond etc.

87.1 at Nobles Corner turn left and follow winding dirt and paved road.

90.5 Turn right (South) at the 600' Corner

91.8 Stop XVI -- Park on the right -- Follow small dirt road on left side of road into Crockett Ridge quarry. We are now in the Norway quadrangle. The calc-silicates here show rather strong evidence of element exchange between carbonate beds and biotite granulite with good bands of diopside developing at the interfaces. Some of the bands are 1/4 to 1/2 inch thick.

Table I Mineral Data* for Area B

Assemblages are those with Max #'s of Phases. Metamorphic Zones keyed to Fig 3.	Muscovite			Chlorite⁽⁴⁾			Biotite				Staurolite		Sill.	Plag.	Garn.
	d(002)Å	%Pg.	Modal %	Color (4) X'd Nicols	Mg/Fe	Modal %	B	Color	Mg/Fe (3)	Modal %	Mg/Fe	Modal %	Modal %	An%	Modal %
Zn.1: Gn+Bio+Chte	9.977	9	29	blue	Fe-rich	12	N.D.(5)	orange brown	N.D.	5	X	X	X	ND	Tr
Zn.2: Gn+Bio+Chte	9.970	12	27	blue	Fe-rich	12	N.D.	orange brown	N.D.	8	X	X	X	ND	1
Zn.3: Gn+Bio+Chte	9.954	17	30	blue + brown	Fe+Mg	7	N.D.	orange brown	N.D.	10	X	X	X	ND	1
Zn.4: Staur+Bio+ Chte±Gn	9.945	20	27	brown	Mg-rich	5	N.D.	orange brown	N.D.	20	N.D.	3	X	ND	1.5
Zn.5: Staur+Bio+ Chte±Gn	9.933	24	26	greenish brown	.9816	2	1.635	orange brown	.8704	20	.1798	4	X	17.5	2
Zn.6: Sill+Staur+ Bio±Gn± Tr.Chte	9.943	21	22	greenish grey	X	.2	1.638	moderately dark orange brown	.9005	22	.1875	6	.4	18	1.5
Zn.7: (Rangeley) Sill+Staur+ Bio±Garn	9.951	18	22	X	X	X	1.638	dark orange brown	.8763	24	.1845	4	2	20.5	1
Zn.7: (Oquossoc) Sill+Staur+ Bio±Garn	9.951	18	20-25	X	X	X	1.642	dark orange brown	.7040	25	.1518	4	5-8	20	1
Zn.8: Sill+Bio +Garn	9.963	14	10-15	X	X	X	1.648	dark reddish brown	.7311	25-30	X	X	10-15	25	1

*(1) Modes are averaged visual estimates.

(2) Compositions etc. are averaged values and thus of only limited use. Detailed values for specific specimens will be published elsewhere.

(3) Mg/Fe, biotite based only on probe data; zones 5, 6, 7 by A. L. Albee, zones 7 and 8 by B.W. Evans.

(4) Data on chlorite from zones 1-4 are based only on optical parameters. Thus Mg/Fe is not designated specifically.

(5) N.D. = No data