1-1-1974

Buchan-type Metamorphism of the Waterville Pelite, Southcentral Maine

Osberg, Philip H.

BUCHAN-TYPE METAMORPHISM OF THE WATERVILLE PELITE, SOUTH-CENTRAL MAINE

Philip H. Osberg†
University of Maine, Orono

Introduction

This trip examines the recrystallization of the pelites of the Waterville Formation (Osberg, 1968; Heinonen, 1971) in response to a Buchan-type metamorphic event. The route parallels the regional strike of the Waterville Formation and participants may examine mineral associations from rocks of low chlorite zone through K-feldspar-sillimanite zone. Locations of stops are shown by numbers enclosed by circles in Figure 1. The area considered includes the following 15 minute U.S.G.S. Topographic maps: Pittsfield, Waterville, Vassalboro, Augusta, Gardiner, and Lewiston.

At low metamorphic grade the Waterville pelite consists of 1/4" to 1" interbeds of quartzite and quartz-mica slate. Some of the beds of quartzite contain a small amount of carbonate. In the low chlorite zone the pelite consists of quartz, plagioclase, muscovite, chlorite, $\pm$ hematite, and $\pm$ ferroan dolomite. The metamorphic grade increases southward, and isograds delineating the first appearance of biotite, garnet, andalusite-cordierite-staurolite, sillimanite, and K-feldspar-sillimanite have been mapped (Fig. 1).

Equilibrium and Phase Considerations

Equilibrium models for the Waterville pelite were discussed by Osberg (1971). K_D' values for Mg-Fe distribution between contacting cordierite and biotite are essentially identical in samples taken from compositionally different beds in a single outcrop. The proximity of the samples suggests that the external parameters (P,T, and possibly μ_j*) are essentially constant in the samples. The equality of K_D' in the samples indicates a close approach to chemical equilibrium.

Slight differences in composition of certain mineral species from grain cluster to grain cluster are interpreted as a manifestation of mosaic equilibrium, although it is not clear whether the mosaic equilibrium is a prograde process or whether it is due to retrogressive changes in external parameters or even to the effects of a later metamorphic event.

---

† Work supported by N.S.F. Grant GA-933.

* μ_j is the chemical potential of a mobile component.

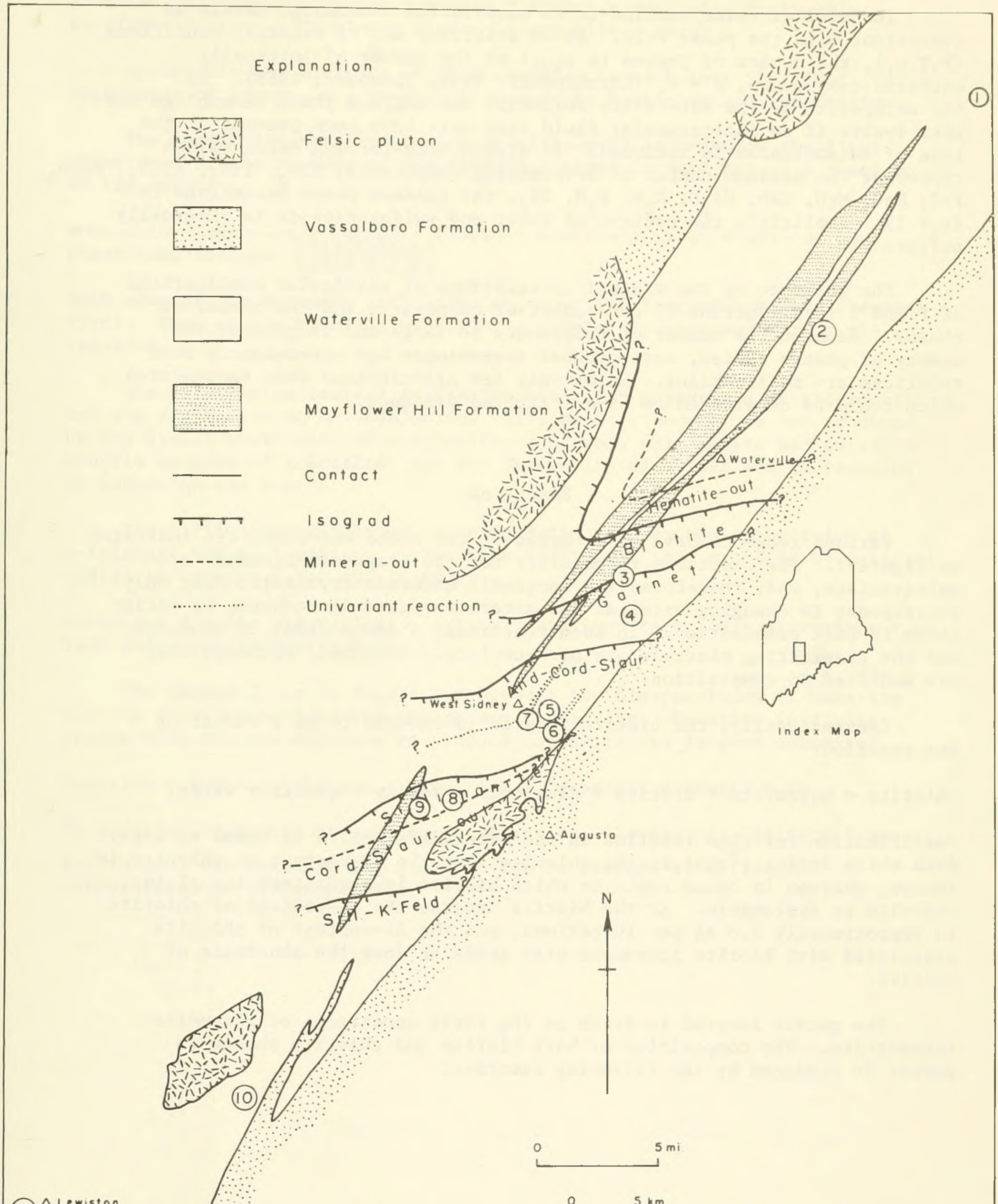

Figure 1. Metamorphic map of the Waterville Formation, central Maine.

The mineral relationships in an equilibrium assemblage should be consistent with the phase rule. At an arbitrary set of external conditions (P,T,μ_i), the number of phases is equal to the number of internally buffered components, $p = c_i$ (Korzhinskii, 1959; Thompson, 1959). In the metapelite of the Waterville Formation the maximum phase assemblage numbers twelve if an intergranular fluid that must have been present at the time of metamorphism is included. If eleven rock-forming metal oxides represent the maximum number of determining components, SiO_2, TiO_2, Al_2O_3, Fe_2O_3, FeO, MnO, MgO, CaO, Na_2O, K_2O, H_2O, SO_2, the maximum phase assemblage is (c_i+ 1). Implicitly the content of water and sulfur-dioxide is internally buffered.

The variance of the mineral associations at particular combinations of P and T is a function of the number of components and the number of phases. Because the number of components is large and in general the number of phases is few, most mineral assemblages and consequently most reactions are multivariant. Relatively few associations were encountered which could be considered to have a limited variance.

Reactions

Various isograds have been mapped in the field and these are indicated on Figure 1. The reactions responsible for the isogradic minerals are multivariate, and, therefore, the isogradic minerals crystallize not only in response to changing external parameters but also in response to variations in bulk composition. In such reactions, a new mineral is produced, and the preexisting minerals are not completely consumed, although they are modified in composition.

Conventionally, the biotite isograd is thought to be a result of the reaction:

chlorite + moscovite → biotite + aluminous chlorite + quartz + water.

Justification for this reaction in the Waterville pelite is based on x-ray data which indicate that in the chlorite zone the Al-content of chlorite is random, whereas in those rocks in which biotite is stabilized the Al in chlorite is systematic. At the biotite isograd the Al-content of chlorite is approximately 2.9 Al per 10 cations, and the Al-content of chlorite associated with biotite increases with grade as does the abundance of biotite.

The garnet isograd is drawn on the first appearance of almandine-spessartite. The composition of both biotite and chlorite change as garnet is produced by the following reaction:

biotite + aluminous chlorite + quartz → garnet + muscovite + slightly Fe-richer biotite + Mg-richer aluminous chlorite + water.

Apparently the variance of this reaction is such that the first appearance of garnet is strongly influenced by bulk chemical composition.

The andalusite-cordierite-staurolite isograd is drawn on the first appearance of one or more of the isogradic minerals produced by a reaction of the form:

muscovite + chlorite + garnet + quartz → biotite + water + one- or two-phase combinations {staurolite, cordierite, andalusite}

Bulk composition strongly influences which of the isogradic minerals appear first. None of the reacting minerals is completely consumed during the reaction.

The sillimanite isograd delineates the first appearance of sillimanite and the disappearance of andalusite. Sillimanite, however is not produced by the direct conversion of andalusite. Instead sillimanite nucleates on biotite as mats of fibrolite, and the andalusite dissolves and is replaced by muscovite and quartz.

The sillimanite-K-feldspar zone is delineated by the association of K-feldspar and sillimanite. A reaction similar to that proposed by Guidotti (1963) is suggested for this region:

muscovite + sodic plagioclase + quartz → sillimanite + sodic microcline + less sodic plagioclase + water.

The dashed lines on Figure 1 represent the disappearance of hematite and the disappearance of staurolite and cordierite. Hematite initially reacts with ferroan dolomite to produce magnetite and Fe-poor dolomite:

hematite + ferroan dolomite → magnetite + Fe-poorer dolomite + CO_2.

In addition, hematite is reduced to magnetite. Because f_{O_2} differs from bed to bed, the hematite-magnetite buffer is reached at different temperatures in different beds.

The disappearance of staurolite and cordierite is interpreted to be due to the divariant reaction:

biotite + staurolite + cordierite + plagioclase = ilmenite + garnet + sillimanite + muscovite + quartz + H_2O.

Reactions of similar form, but involving staurolite alone or cordierite alone are also responsible for the disappearance of cordierite and staurolite and are more common then the c_i-phase reaction.

The association quartz + plagioclase + muscovite + biotite + chlorite + garnet + staurolite + cordierite + andalusite is interpreted to be univariant because phase considerations indicate it to be a (c_i+ 1)-assemblage. The (c_i+ 1)-phase assemblage is represented by the reaction:

ilmenite + muscovite + chlorite + garnet + andalusite + quartz = biotite + staurolite + cordierite + plagioclase + H_2O.

The (c_i+ 1)-phase assemblage is exposed in a single outcrop and the position of the reaction on Figure 1 is based on the compatibility of chlorite + garnet as opposed to that of staurolite + cordierite. The complex geometry of the dotted line representing the reaction is due to the fact that water, as a component, is internally controlled. It is not likely that P and T could vary sufficiently in a limited volume of rock to produce the configuration shown. Because the reaction is highly dependent on the number of moles of water, the variation in water content from bed to bed explains the map pattern of the reaction.

Conditions of Metamorphism

The temperature and fugacity of oxygen were estimated from the data of Lindsley (1963) for the (c_i+ 1)-phase association at West Sidney (Stop 7 in Fig. 1) using the compositions of magnetite and ilmenite. Extrapolation of Lindsley's data gives an approximate temperature of 500°C and an oxygen fugacity of 10^{-24} bars.

The maximum possible temperature of the hematite-out line (Fig. 1) is that of the hematite-magnetite buffer. Assuming that oxygen is an inert component and that its fugacity is of the order of 10^{-24}bars, the temperature of the hematite-out line is estimated to be 370°C using the relation of Eugster and Wones (1962).

The geologic relationships at the high grade end of the metamorphic spectrum (Stop 11 in Fig. 1) suggest that temperatures are somewhat below those needed to partially melt the rock. The temperature of the minimum melting curve for granite is estimated to be 685°C, suggesting that the temperatures realized were from 600°C to 650°C.

Total pressure is estimated to be in the range of 2.5 - 3.0 kb. The coexistence of cordierite and staurolite in middle grade associations indicates a range of pressures from 2.1 kb to 3.2 kb according to the experimental work of Hoschek (1969), Gangully (1972) and Siefert (1970). Extrapolation of the temperature from West Sideny (Stop 7 in Fig. 1) to the sillimanite isograd suggests a temperature of approximately 550°C at that isograd. Based on the work of Holdaway (1971), the total pressure is 2.8 kb.

References

Eugster, H.P. and D.R. Wones, 1962, Stability relations of the ferruginous biotite, annite: J. Pet., 3, p. 82-125.

Gangully, J., 1972, Staurolite stability and related parageneses: Theory, experiments, and applications: J. Pet., 13, p. 335-365.

Guidotti, C.V., 1963, Metamorphism of the pelitic schists in the Bryant Pond quadrangle, Maine: Am. Min., 48, p. 772-791.

Heinonen, C.E., 1971, Stratigraphy, structural geology, and metamorphism of the Tocama Lakes area, Maine: Master's Thesis, University of Maine.

Hoschek, G., 1969, The stability of staurolite and chloritoid and their significance in metamorphism of pelitic rocks: Contr. Mineral. and Petrol., 22, p. 208-232.

Holdaway, M.J., 1971, Stability of andalusite and the aluminum silicate phase diagram: Am. Jour. Sci., 271, p. 97-131.

Korzhinskii, D.S., 1959, Physiochemical basis of the analysis of the paragenesis of minerals: Consultants Bureau, New York, 142 p.

Lindsley, D.H., 1963, Fe-Ti oxides in rocks as thermometers and oxygen-barometers: In Abelson, P.H. (ed.) Annual report of the Director Geophysical Laboratory: Carnegie Institution Year Book 62, p. 60-66.

Osberg, P.H., 1968, Stratigraphy, structural geology, and metamorphism of the Waterville-Vassalboro area, Maine: Maine Geol. Survey Bull. 20, 64 p.

_____, 1971, An equilibrium model for Buchan-type metamorphic rocks, south-central Maine: Am. Min., 56, p. 569-576.

Siefert, F., 1970, Low temperature compatibility relations of corierite in haplopelites of the system K_2O-MgO-Al_2O_3-SiO_2OH_2O: Jour. Pet., 11, p. 73-100.

Thompson, J.B., Jr., 1959, Local equilibrium in metasomatic processes. In Abelson, P.H. (ed.) Researches in Geochemistry: John Wiley and Sons, New York, p. 427-457.

Itinerary

Mileage

0 Assembly point is in the parking space of the Carriage Inn and Restaurant, Somerset Avenue Exit of Route 95, Pittsfield. Starting time is 9:00 A.M. Breakfast is served in the Carriage Inn Restaurant from 6:30 A.M.

Stop 1. Leave cars in parking lot of Carriage Inn and Restaurant. Exposure is on the north bound entrance ramp to Route 95.

The outcrop contains three lithic types: black quartz-muscovite-chlorite-plagioclase-graphite-pyrite-pyrrhotite phyllite at the south end, grayish green quartz-muscovite-chlorite-plagioclase-magnetite-ferroan dolomite phyllite, and purple quartz-muscovite-chlorite-plagioclase-hematite-ferroan dolomite phyllite at the north end. The pyrrhotite in the black quartz-mica phyllite is monoclinic. The ferroan dolomite in the purple quartz-mica phyllite occurs as small porphyroblasts, as a major constituent of some quartzitic beds, and in quartz-ferroan dolomite veins.

The mineral associations are typical of the low chlorite zone. The presence of hematite-and magnetite-bearing beds in close proximity implies that f_{O_2} must have different values in different parts of the outcrop. In a gross way one might argue that the graphite-bearing assemblage is the most reduced, that the hematite-bearing assemblage is the most oxidized, and that the distribution of lithologies is a result of the mobility of oxygen, the graphite-bearing assemblage acting as an oxygen sink. The presence of interbedded purple and grayish green quartz-mica phyllite, however, argues for the differences in f_{O_2} as being related to sedimentational conditions.

You're not supposed to look at structural features on this trip, but in case you glance at them bedding and schistosity are essentially parallel and both are folded by asymmetric folds that are considered to belong to a late episode of deformation.

Return to cars. Turn left on Somerset Avenue and proceed onto southbound lane of Route 95.

11.9 Take Hinkley Road exit. Proceed across Hinkley Road and park along southbound entrance ramp.

Stop 2. The outcrop is 500 feet south on Route 95.

Greenish gray quartz-muscovite-chlorite-plagioclase-magnetite-pyrite phyllite occurs in several outcrops. The outcrop is well banded with quartzose and pelitic beds alternating. A good number of the quartzose beds contain ferroan dolomite, and ferroan dolomite also occurs in quartz-carbonate veins. The veins are crudely zoned with quartz cores and carbonate rims. The mineral assemblage is that of the chlorite zone.

The schistosity is oriented at an angle to the bedding and is parallel to the axial surfaces of moderately open folds that predate those observed at Stop 1. The quartz-carbonate veins are folded and boudinaged.

Return to cars. Proceed south on Route 95.

22.8 Turn left onto Oakland Road (Rte 11 and 137) exit. Turn right onto Oakland Road.

23.8 Turn left onto Country Club Road and proceed south.

25.4 Stop sign. Turn right and proceed west.

26.0 Stop sign. Turn left onto Middle Road and proceed south.

29.3 Turn left onto Drummond Road and proceed east to overpass for 95.

30.3 Stop 3. Park along road. Outcrops are in field to the south.

Low exposure of greenish gray quartz-muscovite-biotite-chlorite-plagioclase-pyrite-ilmenite-magnetite schist. The biotite is porphyroblastic and its orientation is crossed with respect to the schistosity. Quartz, muscovite, and chlorite are very fine grained. This outcrop lies within the garnet zone, but garnet is extremely scarce. It occurs as small euhedral dodecahedra and has the following compositions: almandine = 67%, spessartite = 20%, pyrope = 7%, grossularite = 6%. Without the garnet, the rock looks much like those in the biotite zone.

Alternate beds of pelite and quartzite are well displayed. Schistosity is essentially parallel to bedding except in the noses of isoclinal folds. A second, later cleavage is also present.

Return to cars. Proceed eastward on Road.

31.2 Stop sign. Turn right on Sidney Road (Rte. 104) and proceed south.

33.2 Turn right on Lyons Road and proceed West.

33.8 Stop 4. Park along side of road.

Greenish gray quartz-plagioclase-muscovite-biotite-chlorite-garnet-ilmenite-magnetite-sulphide schist. Biotite and garnet are porphyroblastic, whereas other minerals are fine grained. Biotite has orientation that makes an angle to schistosity, and garnet occurs as small dark translucent dodecahedra. Several quartzose beds contain limesilicates: actinolite, plagioclase, and grossularite. A couple of beds containing quartz and carbonate are in the west end of the exposure. A prominent vein of quartz and calcite cuts the schist. These assemblages are typical of the garnet zone.

Bedding and schistosity are essentially parallel. Both are cut by a younger cleavage.

Return to cars. Proceed west on Lyons Road.

34.1 Cross overpass for Rte. 95 and turn left onto southbound lane.

37.9 Turn left into rest area. Lunch. Continue south on Rte. 95.

42.5 Turn right onto Belgrade Road (Rtes. 8-11-27).

44.1 Turn right.

44.3 Continue through intersection at North Augusta onto Bog Road.

47.4 At division of Bog and Middle Roads reverse direction and retrace route along Bog Road.

48.8 Stop 5. Park along side of road. Outcrop is on east side of road.

Exposure is a greenish gray quartz-plagioclase-muscovite-biotite-chlorite-garnet-staurolite-andalusite-ilmenite-magnetite-sulphide schist. The minerals are sufficiently coarse to be identified with a lens. Garnet, staurolite, and andalusite are porphyroblastic. Garnet occurs as small translucent red dodecahedra. Staurolite is honey brown and euhedral and in the outcrop has sharply etched, positive relief. Many crystals are twinned on {232}. Andalusite is white and crystals are glomeroblastic. In the outcrop the crystals standout as rounded "hob-nails". The ratios of MgO/(FeO+MnO+MgO in the ferromagnesian minerals are: biotite = 0.448; chlorite = 0.490; garnet rim = 0.079; and staurolite = 0.149. The mineral association is consistent with the andalusite-cordierite-staurolite zone and is interpreted to be a c_i-phase assemblage representing the (cd)-reaction.

Bedding and schistosity are essentially parallel. Garnet, andalusite, staurolite, and chlorite grow across the schistosity, without rotational features. A later slip cleavage cuts the schistosity.

Return to cars and proceed south on Bog Road.

50.7 Turn left on Old Belgrade Road at North Augusta.

51.1 Turn left on Middle Road.

52.6 Stop 6. Turn around in small parking lot and park facing south along side of road. Exposure is 600' north on woods road.

Outcrop consists of light gray quartz-plagioclase-muscovite-biotite-chlorite-garnet-cordierite-magnetite-ilmenite schist. Garnet occurs as small, euhedral, pink crystals. Cordierite occurs as large subhedral, ameboid crystals enclosing garnet, biotite, and chlorite. Cordierite weathers readily, so is recognized in the outcrop as depressions. The association is consistent with the andalusite-cordierite-staurolite zone and is thought to represent a (c_i-2)-phase assemblage. Because of the variance of the association, the compositions of the same mineral species from similar associations show a considerable and unsystematic variation with respect to metamorphic intensity.

Bedding and schistosity are parallel. Garnet, chlorite, and cordierite cut the schistosity.

Return to cars and proceed south on Middle Road.

54.1 Stop sign. Turn right onto Old Belgrade Road.

54.4 Stop sign. Proceed through North Augusta.

54.6 Stop sign. Turn right onto Belgrade Road (Rte. 11).

56.3 Stop 7. Park along east side of road.

Outcrop contains light gray quartz-plagioclase-muscovite-biotite-chlorite-garnet-staurolite-cordierite-andalusite-ilmenite-sulphide schist. Garnet is small and euhedral. Staurolite and andalusite standout in positive relief, whereas cordierite weathers out in negative relief. (A blind person could do a fairly adequate job by a sort of brail mineralogy.) This association is interpreted as a (c_i+1)-phase assemblage marking the shift in orientation of the tie-line garnet-chlorite to staurolite-cordierite. The compositions of the ferromagnesian minerals in terms of MgO/FeO+MnO+MO) are: biotite = 0.487; chlorite = 0.521; garnet rim = 0.090; staurolite = 0.151; and cordierite = 0.639. Two thin quartz-diopside-grossulairte-actinolite granulite beds are intercalated with the pelite, and a large quartz vein cuts the outcrop.

Bedding and schistosity are parallel. Garnet, staurolite, cordierite, andalusite, and chlorite cut the schistosity and exhibit no rotational features. The bedding is folded by a large isoclinal fold. The schistosity is parallel to the axial surface of this fold. A late cleavage cuts the schistosity, and a late fold deforms bedding and schistosity. The late cleavage is parallel to the axial surface of the late fold.

Return to cars and proceed north on Rte. 11.

56.4 Reverse direction at Citgo station and proceed south on Route 11.

59.3 Turn right on Oakland Road.

60.6 Turn right onto Leighton Road.

62.2 Stop sign. Turn right onto Old Winthrop Road.

62.5 Stop sign. Turn right on Route 202 (Pine Tree Trail).

64.6 Turn right on Route 17 in village of Manchester.

65.4 Stop 8. Turn left into wood road and park. Caution of traffic.

Outcrop consists of light gray quartz-plagioclase-muscovite-biotite-garnet-sillimanite-magnetite-ilmenite-pyrrhotite schist. Garnet occurs as small euhedral pink crystals. Sillimanite occurs as small "maggot-like" mats of fibrolite. The assemblage is typical of the lower sillimanite zone. Cordierite or/and/ staurolite have been completely consumed by reaction with biotite. Several thin beds of quartz-anorthite-diopside-hornblende-garnet granulite are interbedded with the pelite, and within these beds the limesilicates have a zonal arrangement, indicating a limited mobility of components. Several small quartz veins cut the outcrop. On the south side of the road a vein containing prehnite in subhedral crystals cuts the schist (Please do not take specimens of prehnite.). Similar veins, although not common, are found througout New England, and may represent a regional zeolite facies metamorphic event (post Triassic?) that post-dates the higher grade regional metamorphism of New England.

Bedding and schistosity are essentially parallel and steeply dipping. A late cleavage cuts both bedding and cleavage.

Return to cars and proceed south on Route 17.

66.4 Stop sign. Turn right onto Route 202 (Pine Tree Trail).

68.2 Turn right onto "old" road through East Winthrop.

68.3 Turn right onto Case Road.

68.8 Stop 9. Turn around in driveway. Reverse direction and park on road.

Outcrop consists of light gray quartz-plagioclase-muscovite-biotite-garnet-sillimanite-staurolite-cordierite-ilmenite-magnetite schist. Sillimanite occurs as mats of fibrolite. Garnet occurs as small, red subhedral crystals. Staurolite occurs as small reticulated, yellow-brown grains set in large plates of muscovite, a relation similar to that described by Guidotti (1968). Cordierite can be seen only under a microscope. It occurs as small ameboid grains that include quartz and biotite. This association is regarded as a c_i-phase assemblage and represents the (Chl)-reaction. Several thin beds of quartz-plagioclase-hornblende-diopside-grossularite granulite are present. Again these beds show crude zoning due to the limited mobility of the chemical components. A pegmatite intrudes the pelite.

Bedding and schistosity are parallel and steeply dipping. Small asymmetrical folds belonging to the late episode of deformation deform both bedding and schistosity. A poorly expressed cleavage is parallel to the axial surfaces of the folds.

Return to cars and proceed south on Case Road.

69.2 Stop sign. Turn left.

69.3 Stop sign. Turn left onto Route 11 (Pine Tree Trail).

71.1 Turn right at Manchester onto Pond Road.

79.6 Stop sign. Turn right.

79.7 Bare left at fork at Litchfield Corner.

81.7 Stop sign. Turn right onto Routes 9 and 126.

89.1 Stop 10. Park along road. Outcrop is on east side of road. Caution of traffic.

Exposure consists of light gray quartz-microline-plagioclase-muscovite-biotite-sillimanite-garnet-magnetite-ilmenite schist. Sillimanite occurs as mats of fibrolite. Garnet occurs as small, subhedral grains. Microcline occurs as "chalky" white, irregular crystals. Chlorite is retrograde. Many veins of quartz and a few small pegmatites cut the schist.

Bedding and schistosity are parallel and steeply dipping.

Return to cars and proceed southwest on Routes 9 and 26.

92.6 Continue straight ahead on Route 126. Do not turn with Route 9.

97.1 Crossing light. Continue straight on.

97.5 Stop light. Continue on Route 126.

97.7 Stop light. Continue on Route 126.

98.1 Stop light. Continue on Route 126.

98.4 Stop light. Continue on Route 126.

98.6 Rotary. Turn left on Routes 202 and 11 through center of Lewiston and to Auburn.

99.0 Bridge over Androscoggin.

99.2 Stop light. Continue west through center of Auburn on Routes 202, 4 and 100.

99.4 Stop light. Continue west on Routes 202, 4 and 100.

99.5 Stop light. Turn left with Routes 202, 4 and 100 toward Maine Turnpike.

100.0 Large (not obvious) rotary. Follow signs for Routes 202, 4 and 100 toward Maine Turnpike.

101.2 Stop 11. Park along road. Caution of busy traffic.

Large outcrop containing light gray quartz-microline-plagioclase-biotite-sillimanite-garnet-muscovite-magnetite-ilmenite gneiss. Microcline is abundant and muscovite is relatively scarce. Garnet occurs as large subhedral crystals. Sillimanite occurs as abundant filrolite. Chlorite is retrograde. Two types of pegmatite are present: one has "fuzzy" boundaries with the gneiss, and the other has sharp boundaries. A thin basaltic dike, much younger than the metamorphism, also cuts the gneiss.

Layering and schistosity are parallel and gently dipping.

Return to cars. End of trip.