

METAMORPHOSED ULTRAMAFIC ROCKS IN THE BRONSON HILL ANTICLINORIUM, CENTRAL MASSACHUSETTS

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ABSTRACT. A variety of metamorphosed ultramafic rocks ranging in age from Late Precambrian to Devonian occurs in the Bronson Hill anticlinorium, central Massachusetts. Late Precambrian occurrences in the Pelham dome include sphene hornblendite in Poplar Mountain and Dry Hill Gneisses and anthophyllite-veined harzburgite in the Mt. Mineral Formation. Fourmile Gneiss and Monson Gneiss, of uncertain age but pre-Middle Ordovician, contain miscellaneous ultramafic bodies, including hornblendite, diopside hornblendite, and olivine-orthopyroxene-clinopyroxene hornblendite variously altered to rocks containing talc, carbonate, chlorite, and serpentine. The Middle Ordovician Ammonoosuc Volcanics contain rare lenses of fairly simple hornblendite. Ultramafic bodies are much more common in the Middle Ordovician Partridge Formation which has orthopyroxene-olivine-spinel hornblendites in a narrow stratigraphic horizon along the eastern side of the main body of Monson Gneiss. Ultramafic rocks are not known in the stratified Siluro-Devonian rocks of central Massachusetts, although they do occur in some abundance in the syntectonic Acadian Belchertown Pluton.

The main focus of this paper is a discussion of the occurrence, mineralogy, bulk chemistry, and metamorphism of the ultramafic lenses in Middle Ordovician Partridge Formation. The lenses resemble boudins in which ultramafic rocks have been variably hybridized through reaction with schist or amphibolite country rock. The lenses are extraordinarily magnesian and may be the metamorphosed equivalents of ultramafic lava flows. Bulk chemistry indicates that they are not komatiitic and are unlikely to have resulted from hydrothermal seawater alteration of tholeiitic volcanics. The likeliest origin for the ultramafic lenses is as Middle Ordovician picritic lava flows that were probably not part of an ophiolite complex.

INTRODUCTION

Much attention has been paid in recent years to the presence, distribution, and composition of ultramafic bodies that occur in orogenic belts. These bodies may be parts of ophiolites or may be ultramafic pods without apparent ophiolitic affinity. Interest in these rocks centers on the assumption that ultramafic rocks originate in the mantle and that an understanding of the relations between ultramafic rocks and metamorphosed sedimentary rocks in an orogenic belt can elucidate large-scale tectonic movements involving crust and mantle in the evolution of such

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an orogenic belt (for example, Williams, 1971). Also of importance is the study of the metamorphism of orogenic ultramafic bodies (for example, Evans and Trommsdorff, 1970) because of the unusual chemistry involved, and because of the common metasomatic interaction of ultramafics with surrounding sedimentary and volcanic rocks. Studies of the "hybrid" rocks generated in such metasomatic zones have been useful in deducing the processes and scales of element migration during metamorphism (Springer, 1974; Frost, 1975; Sanford, 1982).

The ultramafic rocks of western New England and adjacent Quebec have been well known and well publicized for decades, partly as a result of the papers of Hess (1954), Phillips and Hess (1936), and Chidester (1968) and more recently as a result of regional tectonic syntheses emphasizing the significance of oceanic crust and mantle or metamorphosed fragments of the same (Bird and Dewey, 1970; Williams, 1971; Williams and St. Julien, 1982; Church, 1977; Stanley and Roy, 1982; Sanford, 1982; Hall and Robinson, 1982; Robinson and Hall, 1980; Doolan and others, 1982; Hatch, 1982). The occurrences of ultramafic rocks in central and southern New England are not so well known despite the early reports of Hitchcock (1878), Emerson (1898, 1917), Lundgren (1963, 1964), and Robinson (ms). Recently some attention has been called to these rocks and their significance in northwestern Maine (Boudette, 1982), in central and western New Hampshire (Nielson, ms; Lyons, Boudette, and Aleinikoff, 1982), and in central and western Massachusetts (Wolf and others, 1974, 1978; Ashwal and others, 1979). It is our purpose here to present a brief summary of the variety of different occurrences of ultramafic rocks in the Bronson Hill anticlinorium of central Massachusetts and then to concentrate particular attention on a group of ultramafic lenses confined to a limited stratigraphic horizon within the Middle Ordovician Partridge Formation. The ultramafic rocks of the Bronson Hill anticlinorium in Massachusetts do not seem to constitute a coherent petrologic suite, and their origins must be considered in the context of the rocks immediately enclosing each body.

Three aspects of the Partridge Formation ultramafic lenses are discussed in this paper: (1) the shape and size of mapped bodies along with the distribution of rock types and the structural relations between ultramafic, hybrid, and country rocks; (2) the petrologic and textural character of the different rock types including discussion of mineral chemistry; and (3) the correlation of bulk chemistry between the different bodies and comparison with orogenic ultramafic rocks elsewhere.

DISTRIBUTION OF ULTRAMAFIC ROCKS

The oldest rocks exposed in the Bronson Hill anticlinorium of central Massachusetts are the Dry Hill Gneiss, probably metamorphosed rhyolites, and the overlying Poplar Mountain Gneiss and Quartzite of probable sedimentary derivation (Ashenden, 1973) exposed in the core of the Pelham gneiss dome (fig. 1). Due to major recumbent folding during the Devonian Acadian orogeny, the Dry Hill Gneiss has a crudely doughnut-shaped outcrop pattern with the Poplar Mountain Gneiss over-

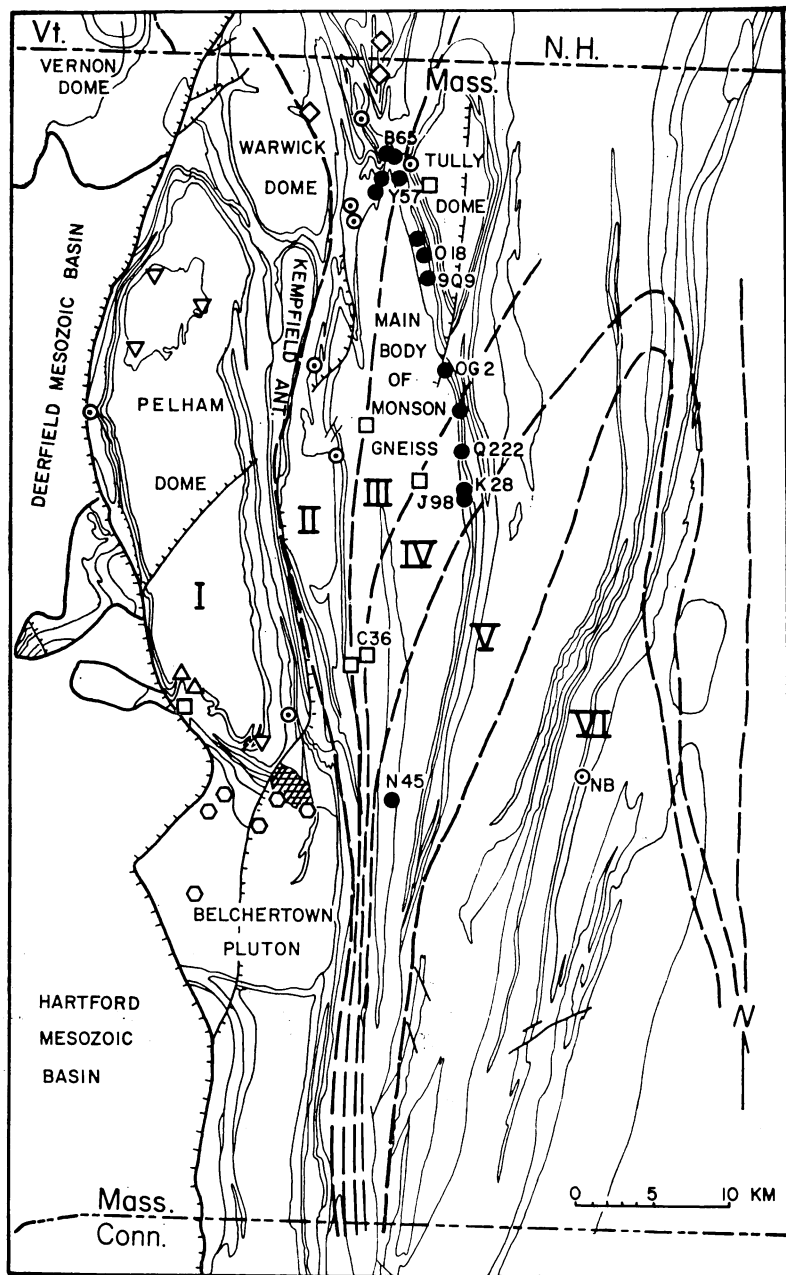


Fig. 1. Geologic map of central Massachusetts showing the distribution of ultramafic rocks in the Bronson Hill anticlinorium. Symbol explanation: hexagons—hornblende, diopside hornblende, meladiorite and olivine pyroxenite in Devonian Belchertown Pluton; crosshatch areas—intrusive breccias containing hornblende fragments; filled circles—olivine-orthopyroxene-spinel-hornblende lenses in Middle Ordovician Par-

lying it around the periphery of the dome and also structurally underlying it in an area of inverted rocks in the very center of the dome. In the southern part of the dome, the outer Poplar Mountain Gneiss grades into a more aluminous facies, the Mount Mineral Formation. All these rocks are assigned a Late Precambrian age on the basis of a $^{207}\text{Pb}/^{206}\text{Pb}$ date on zircon from the Dry Hill Gneiss of 560 my (Naylor and others, 1973; Hall and Robinson, 1982). Widely scattered through these rocks (fig. 1), but particularly concentrated within Poplar Mountain Quartzite, is a series of lenses and boudins up to 5 m in length of massive well foliated hornblende (Robinson, ms; Ashenden, 1973; Laird, 1974) locally containing euhedral sphene up to 2 cm long.

The aluminous rocks of the Mt. Mineral Formation contain sillimanite-orthoclase patches and pyrope-rich garnets (Robinson, Tracy, and Ashwal, 1975) which have been interpreted as relicts from an intense pre-Acadian (probably Late Precambrian) metamorphism. These relict minerals are set in a retrograde matrix of kyanite-muscovite schist produced during Acadian overprinting. Also enclosed in these schists of the Mt. Mineral Formation are four lenses of metamorphosed harzburgite less than 100 m in length (fig. 1). These were described in some detail by Emerson (1898, 1917) in connection with the occurrence of anthophyllite asbestos. The freshest harzburgites ("saxonites" to Emerson) consist of olivine and orthopyroxene crystals up to 4 cm across variably altered to chlorite, antigorite, talc, and anthophyllite. These are cut by cross-fiber veins of asbestiform anthophyllite (with serpentine, chlorite, and talc), recently described in detail by Veblen (1980). These veins attain a maximum width (and fiber length) of about 40 cm. It is suspected that the coarse olivine and orthopyroxene crystals grew during pre-Acadian metamorphism, and that the cross-cutting anthophyllite veins are a product of Acadian deformation and metamorphism under kyanite-staurolite grade conditions. These rocks come the closest of any described here to true mantle rocks, but the scenario of their emplacement is unknown.

The next level in the stratigraphy of the Bronson Hill anticlinorium is the most controversial and consists of widespread quartz-plagioclase gneisses locally with conformable layers or deformed dikes of amphibolite. Where they overlie the late Precambrian rocks of the Pelham dome, these rocks are named Fourmile Gneiss (Ashenden, 1973); elsewhere they are termed Monson Gneiss. In several areas their place in the stratigraphy is occupied by apparently plutonic massive tonalitic and granitic gneisses identical to gneisses of the Oliverian plutonic series in New Hampshire

tridge Formation; dotted circles—miscellaneous hornblendites in Middle Ordovician Ammonoosuc Volcanics; squares—miscellaneous diopside hornblendites, olivine-pyroxene hornblende and hornblende-talc-chlorite-carbonate rocks in Ordovician (?) Monson and Fourmile Gneisses; upward-pointing triangles—coarse metamorphosed harzburgites with cross-fiber anthophyllite asbestos in schist unit of Late Precambrian Mt. Mineral Formation, Pelham Dome; downward-pointing triangles—sphene hornblendites in Late Precambrian Poplar Mountain Gneiss and Quartzite, and Mt. Mineral Formation, Pelham Dome. Acadian (Devonian) metamorphic zones: I—kyanite-staurolite; II—sillimanite-staurolite; III—sillimanite-muscovite; IV—sillimanite-muscovite-Kfeldspar; V—sillimanite-Kfeldspar; VI—sillimanite-Kfeldspar-garnet-cordierite.

(Billings, 1956). Although Pb/Pb ages on zircons from a variety of these rocks (Zartman, personal commun., 1980) are around 450 my, Robinson (1979; Hall and Robinson, 1982) has argued that they are unconformably overlain by the Middle Ordovician Ammonoosuc Volcanics and Partridge Formation. Scattered throughout the layered gneisses are a variety of ultramafic pods and lenses (fig. 1), none more than 30 m long, including pure hornblende, diopside-hornblende (Mt. Pomeroy, Robinson, 1967b), olivine-orthopyroxene-talc-chlorite rock (Soapstone Hill, Emerson, 1898, 1917; Balk, ms), talc-chlorite-carbonate-amphibole rock (New Salem, Soapstone Hill, Emerson, 1898 and Balk, ms, Tully Mtn., Emerson, 1898, 1917; Robinson, ms), and hornblende-olivine-orthopyroxene-clinopyroxene rock (C36, this paper). The new locality on an island in Quabbin Reservoir (C36) consists of a concentration of glacial boulders of uniform ultramafic rock within a large outcrop area of Monson Gneiss. The rock is dominated by coarse poikilitic hornblende with subordinate biotite. Fresh olivine, a Cr-rich orthopyroxene with strange "hairy" exsolution features, and augite occur as inclusions in hornblende and biotite. The augite occurs in an intricate homoaxial intergrowth with hornblende, suggesting an origin by retrograding of a former more pigeonitic augite. Although not yet studied in detail, this and other ultramafic occurrences in the Monson and related gneisses are distinct from the well studied ultramafic rocks in the overlying Partridge Formation.

The Ammonoosuc Volcanics and Partridge Formation are assigned a Middle Ordovician age on the basis of lithologic correlation with fossiliferous areas in northwestern Maine and because they unconformably underlie the Silurian Clough Quartzite. Ultramafic rocks are not abundant in the Ammonoosuc Volcanics and consist of only a few lenses of rather monotonous hornblendites (fig. 1). Similar hornblendites with various combinations of sphene, epidote, and biotite are scattered throughout the Partridge Formation. In addition, the belt of Partridge Formation along the eastern side of the main body of Monson Gneiss (fig. 1) contains a suite of orthopyroxene-olivine-spinel-hornblendites that are the subject of more detailed discussion in this paper. These are massive to well foliated, relatively homogeneous rocks composed predominantly of magnesian hornblende with olivine, orthopyroxene, spinel, chlorite, and ilmenite. Included with these rocks are retrograded equivalents dominated by amphibole, talc, chlorite, and carbonate, and hybrid hornblende-rich rocks along the contacts between these rocks and pelitic or amphibolitic country rocks. Another type of ultramafic rock occurs in a poorly exposed lens about 40 × 600 m in the Partridge Formation at New Braintree (fig. 1, NB) (Field, 1975). The rock consists of pale brown hornblende (78 percent) and biotite (12 percent) poikilolitically enclosing olivine (7 percent), and orthopyroxene (1 percent). Although Emerson (1917) claimed to have analyzed this "wehrlite", Field (1975, see also Robinson and others, 1982) showed that the analyzed sample actually came from elsewhere.

In striking contrast to their abundance in older rocks, no ultramafic rocks have yet been identified in Siluro-Devonian stratified rocks in

central Massachusetts, although Lyons, Boudette, and Aleinikoff (1982) describe several occurrences in adjacent New Hampshire. This scarcity has figured importantly in the debate concerning the participation or non-participation of oceanic crust in tectonic processes of the Acadian orogeny (Lyons, Boudette, and Aleinikoff, 1982; Hall and Robinson, 1982; Robinson and Hall, 1980; Robinson and Tucker, 1982). Ultramafic rocks, however, do occur in some abundance in the Acadian syntectonic intrusion of the Belchertown Complex (Emerson, 1898, 1917; Guthrie, 1972; Ashwal and others, 1979). In the northern part of the intrusion, hornblendites, diopside hornblendites, and meladiorites (Guthrie, 1972) occur as five separately mapped bodies (fig. 1), as well as in countless fragments in a complex intrusive breccia at the northern border of the intrusion and as isolated small inclusions throughout the batholith. The only olivine-bearing body, described as "cortlandite" by Emerson (1917), is an elliptical mass 200 by 300 m surrounded by two-pyroxene monzodiorite in the western part of the batholith. The olivine-pyroxenite is separated from the enclosing monzodiorite by concentric zones of plagioclase pyroxenite and hornblendite (Ashwal, unpub. map, 1974; Ashwal and others, 1979). The olivine-pyroxenite rock consists of augite ($\text{Fe}/(\text{Fe} + \text{Mg}) = .13-.16$; $\text{Ca}/(\text{Ca} + \text{Mg} + \text{Fe}) = .38-.48$) (58 percent), hornblende (14 percent), biotite (12 percent), orthopyroxene ($\text{Fe}/(\text{Fe} + \text{Mg}) = .14$; $\text{Ca}/(\text{Ca} + \text{Mg} + \text{Fe}) = .02$) (8 percent), and olivine (8 percent). Fine exsolution features and electron probe analyses of coexisting pyroxenes from this rock are reported by Jaffe and others (1975). It seems possible that the hornblendites and pyroxenites of the Belchertown complex represent early samples of parental liquids or fragments of restites from which later melts of the complex were derived. The complex itself with its high temperature Mg-pyroxene and titanohematite assemblage represents a distinct anomaly in Acadian magmatism (Robinson, Shearer, and Maczuga, 1981). In any case there seems little possibility that the ultramafic fragments are pristine transported pieces of Ordovician or older ultramafics of oceanic affinity.

OLIVINE-SPINEL HORNBLENDITE LENSES IN PARTRIDGE FORMATION GEOLOGIC SETTING

Most of the olivine-spinel hornblendite lenses investigated are located within the Sulfidic Schist Member of the Middle Ordovician Partridge Formation along the eastern flank of the main body of the Monson Gneiss (fig. 1). Exceptions to this are one northern body, B65, which occurs in the Augen Gneiss Member, and the southernmost body, N45, which occurs in the same stratigraphic horizon, but in an isolated syncline surrounded by Monson Gneiss. The lenses crop out over a distance of about 40 km, from Orange, Mass. south to Quabbin Reservoir. Lundgren (1963, 1964) has reported very similar lenses at the same stratigraphic level in southern Connecticut.

The Sulfidic Schist Member of the Partridge Formation consists predominantly of sillimanite-mica-pyrrhotite-graphite schists and mica-ceous feldspathic pyrrhotite schists that may represent metamorphosed

black shales and feldspathic shales deposited in an anoxic environment. Roughly half of the exposed olivine hornblendites occur in amphibolites that probably represent metamorphosed basaltic tuffs, flows or sills, and feldspathic gneisses that represent metamorphosed rhyodacite or rhyolite tuffs or flows (Hollocher, 1983). Although a number of ultramafic bodies are in contact with amphibolites, suggesting a possible genetic relationship, others are in contact only with metamorphosed sedimentary rocks.

The structure of the area is dominated by regional nappes, local recumbent folds, and domes, all formed during the Acadian (Devonian) orogeny. Paleozoic sedimentary and volcanic units were involved in the formation of three or more levels of fold nappes with east to west transport of up to 24 km (Thompson and others, 1968). Subsequent recumbent folding has been described as a back-folding event involving both basement (pre-middle Ordovician) and cover rocks. An early phase of gneiss dome formation can be seen in the northern end of the main body of Monson Gneiss where emplacement of a lobe of the dome caused overturning of the mantling rocks. The Clough and Littleton Formations on the upper limb of one of the nappes were refolded into an isoclinal syncline during the overturning. The axial surface of this syncline was refolded during the main phase of the gneiss dome formation.

The lenses resemble boudins, with contacts showing the effects of ductile deformation and metamorphic recrystallization. With rare exceptions, however, it is not possible to determine whether the lenses are actually tectonically separated fragments of previously more continuous layers or primary fragments themselves. Individual lenses range from 3 to 60 m in thickness and 3 to 210 m in length.

The most extensive metamorphism in the area is believed to have occurred during the Acadian orogeny and was probably synchronous with the recumbent folding and dome formation. Metamorphic grade increases from west to east, from kyanite grade in the Pelham Dome to sillimanite-K feldspar-garnet-cordierite grade at the eastern edge of the area (fig. 1). The extent of pre-Devonian metamorphism of the Middle Ordovician rocks is not known, but where Middle Ordovician strata in the Connecticut Valley are overlain by Devonian strata that are garnet grade or lower, the Ordovician rocks show no sign of an earlier higher grade metamorphism.

The primary prograde metamorphic assemblage of the predominant rock type is pargasite-orthopyroxene-olivine-spinel-chlorite with accessory ilmenite and sulfides. Various subordinate rock types which have developed as apparent metamorphic or metasomatic reaction layers contain the minerals pargasite, anthophyllite, plagioclase, phlogopite, garnet, and apatite. One of the interesting aspects of this belt of ultramafic lenses is that it passes through four distinct metamorphic zones, which permit study of metamorphic reactions in ultramafic compositions over a range of metamorphic grade. The lowest grade ultramafic body examined in this study is in metamorphic zone II (sillimanite-staurolite) where garnet-biotite thermometry of pelitic rocks gives temperatures of 600° to 625°C

(Tracy, Robinson, and Thompson, 1976). The highest grade body is in zone V (sillimanite-K feldspar) for which thermometry has yielded temperatures of about 650° to 675°C.

GEOLOGY OF THE ULTRAMAFIC LENSES

In the following section, the geology of two typical bodies is presented in order to give the reader an idea of the exposure of these bodies and of the distribution and extent of the primary and hybridized ultramafic rocks within them.

The ultramafic lens exposed at loc. 018 (fig. 1) is the largest studied in this investigation, and it occurs as four major outcrops scattered over an area 200 m long and 90 m wide about 4.5 km northeast of Orange,

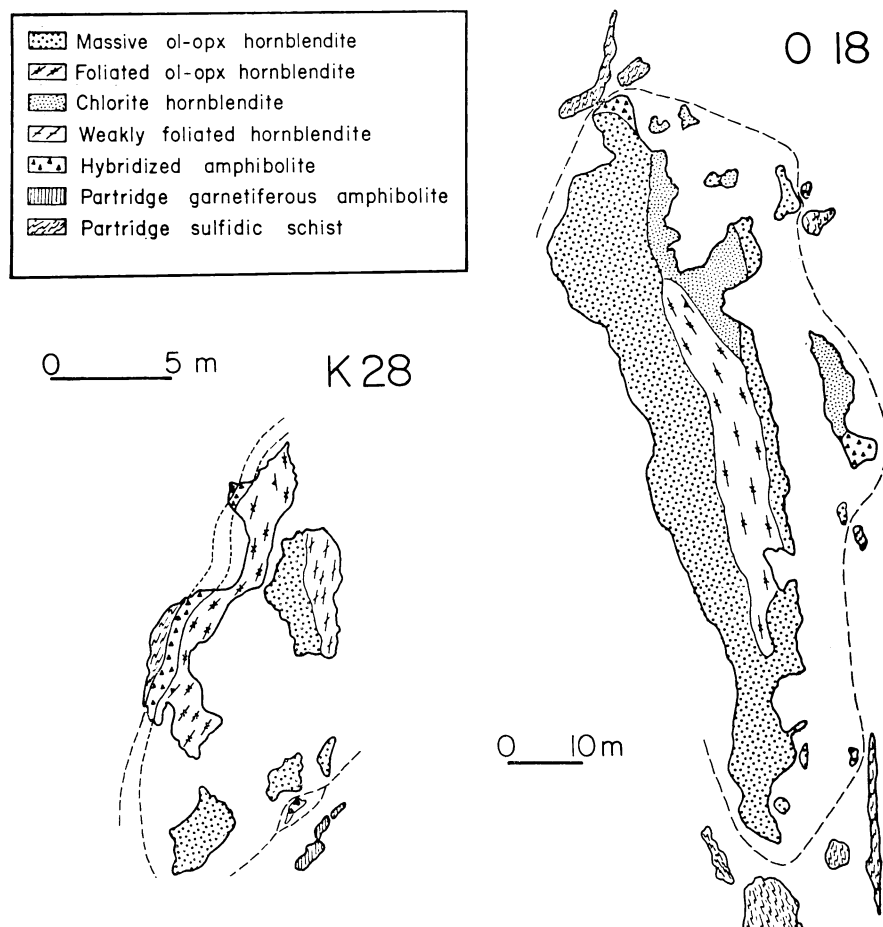


Fig. 2. Outcrop maps of ultramafic lenses at loc. O18 and K28. The body shown at O18 is one of four separate ultramafic outcrops, and the body shown at K28 is one of two. Note the development of hybridized lithologies between primary ultramafic rock and country rock, either schist or amphibolite.

Mass. (fig. 2). Contacts with country rocks are not exposed, and inferred contacts are very approximate. The general elongation of the body parallel to regional foliation and the folding within the ultramafic rock around the ends of the lens indicate that the body probably behaved as a competent boudin with respect to enclosing schist and gneiss.

A wide range of primary and hybrid ultramafic rocks with varying degrees of secondary alteration occurs at this locality. The primary ultramafic assemblage is pargasite–orthopyroxene–olivine–spinel–chlorite–ilmenite with ubiquitous accessory sulfides. Concentrations of orthopyroxene occur as coarse nodules (3 cm or larger) that form prominent bumps on a weathered surface. Pitting of these nodules is probably due to the weathering out of small interstitial olivine grains. These nodules are also found in the primary ultramafic rock in other bodies (see also Lundgren, 1963, 1964). Another unusual occurrence of orthopyroxene at loc. 018 is as large (up to 4 cm) subhedral megacrysts associated with coarse olivine grains in a fine fibrous matrix presumed to be composed of pargasite and chlorite. Alteration and replacement of ultramafic rock by such secondary minerals as chlorite, talc, and carbonate is extensive.

The primary ultramafic rock has been hybridized to varying degrees within the body as a result of reaction with the country rock. It is interesting to note that the degree of hybridization is considerably greater in the eastern outcrop (shown in fig. 2) which is in contact with the sulfidic schist member than in a western outcrop (not shown) where the country rock is augen gneiss. Prominent hybrid rock types include plagioclase amphibolite, plagioclase–biotite–hornblende–cumingtonite schist, hornblende–plagioclase–chlorite schist, hornblende–orthopyroxene–chlorite rock, and massive amphibolite. Anthophyllite does not appear to occur in hybrid rocks in this body, although it is prominent in other bodies.

The ultramafic lens at loc. K28 occurs as two 5 to 10 m outcrops, separated by about 60 m, located roughly 4 km southwest of the village of Petersham, Mass. (fig. 1). Both large outcrops contain primary ultramafic rock characterized by the assemblage pargasite–orthopyroxene–spinel–olivine–chlorite–ilmenite as well as a variety of hybrid lithologies. The distribution of rock types is illustrated in the geologic map in figure 2. In this outcrop, primary ultramafic rock is bounded on the west by hornblende–plagioclase amphibolite and foliated hornblende–anthophyllite–plagioclase rock. Outside these rocks and in contact with sulfidic schist is a garnetiferous hornblende–plagioclase amphibolite. As in most other bodies, primary olivine–orthopyroxene hornblendite is in contact with various amphibolitic hybrid rocks rather than with schistose country rock.

PETROGRAPHY AND MINERAL CHEMISTRY

Three general rock types are encountered within the ultramafic lenses: primary prograde metamorphosed ultramafic rocks, hybridized rocks produced by reaction between ultramafic and country rocks, and retrograde rocks. In the following discussion, the features and mineralogy of the primary rocks will be emphasized. Table 1 gives the modes of eight representative primary rocks. Most of the primary rocks may be called

TABLE 2
Representative electron microprobe analyses of amphiboles

	Y571	9Q9A		OG2B	N45	C36
		c	r			
SiO ₂	46.95	56.95	49.53	46.20	46.17	46.42
TiO ₂	0.52	0.03	0.53	0.68	0.90	0.49
Al ₂ O ₃	11.11	1.87	9.66	12.90	12.02	11.49
Cr ₂ O ₃	0.13	0.03	0.30	—	0.23	0.98
FeO	6.98	4.62	5.90	7.74	6.71	5.80
MnO	0.14	0.08	0.04	0.11	0.06	0.16
MgO	18.18	22.49	18.25	16.50	16.96	18.24
CaO	11.96	11.92	12.03	11.50	11.89	12.37
Na ₂ O	1.52	0.16	1.02	1.62	1.42	1.73
K ₂ O	0.21	0.00	0.14	—	0.29	1.04
	97.70	98.15	97.40	97.25	96.65	98.72
Formulas based on 23 oxygens						
Basis*:	.300	15	15	.300	.300	15
Si	6.604	7.807	6.698	6.568	6.592	6.536
Al	1.396	.193	1.032	1.432	1.408	1.464
	8.000	8.000	8.000	8.000	8.000	8.000
Al	.446	.110	.571	.730	.618	.443
Ti	.055	.003	.056	.073	.097	.052
Cr	.014	.003	.033	—	.025	.109
Fe ³⁺	.440	.026	.008	.144	.167	.122
Mg	3.811	4.595	3.827	3.495	3.610	3.829
Fe ²⁺	.234	.263	.505	.558	.482	.445
	5.000	5.000	5.000	5.000	5.000	5.000
Fe ²⁺	.148	.240	.182	.218	.152	.116
Mn	.017	.009	.005	.013	.007	.019
Ca	1.803	1.751	1.813	1.752	1.820	1.865
Na	.032	0	0	0.17	.021	0
	2.000	2.000	2.000	2.000	2.000	2.000
Na	.382	.043	.278	.430	.371	.472
K	.038	0	.025	—	.052	.186
	.420	.043	.303	.430	.423	.658
fe**	.096	.099	.152	.182	.149	.128

* Ferrous iron-ferric iron calculation based upon:

.300—formula fit to ratio (A-site/Tet Al) = .300

15—normalization to 15 cations exclusive of Na and K

** fe = Fe²⁺/(Fe²⁺ + Mg).

Pale pink magnesian orthopyroxene occurs in all bodies as randomly oriented subhedral porphyroblasts uniformly distributed throughout the rock. In some primary rocks with nodular texture, orthopyroxene occurs as a major constituent of the nodules with a lesser amount of olivine. Like the larger hornblendes, large orthopyroxenes are commonly poikiloblastic with inclusions of most of the other phases in the rock. A noteworthy texture found in a sample from Y57 is the enclosure of a number of separated but optically continuous hornblende inclusions within a

TABLE 3
Representative electron microprobe analyses of pyroxenes

	Y57I	9Q9A	OG2B	N45	C36	C36 cpx
SiO ₂	54.02	54.35	53.46	53.93	55.13	54.50
TiO ₂	0.04	0.04	0.04	0.08	0.15	0.07
Al ₂ O ₃	2.27	2.19	2.17	2.25	1.40	0.45
Cr ₂ O ₃	0.00	0.06	—	0.09	0.18	0.20
FeO	15.09	13.72	16.96	14.28	9.84	2.50
MnO	0.29	0.28	0.23	0.24	0.39	0.20
MgO	28.70	29.44	27.28	28.18	31.67	17.47
CaO	0.18	0.17	0.14	0.25	0.45	23.94
Na ₂ O	0.03	0.02	0.00	0.00	0.08	0.51
	100.62	100.29	100.28	99.30	99.29	99.84
Formulas based on 6 oxygens, 4 cations						
Si	1.918	1.927	1.922	1.942	1.943	1.980
Al	.082	.073	.078	.058	.057	.020
	2.000	2.000	2.000	2.000	2.000	2.000
Al	.014	.019	.014	.036	.001	0
Ti	.001	.001	.002	.003	.004	.002
Fe ³⁺	.069	.050	.060	0	.052	.006
Cr	0	.002	—	.002	.005	.006
Mg	.916	.928	.924	.959	.938	.945
	1.000	1.000	1.000	1.000	1.000	.041
						1.000
Mg	.603	.628	.539	.553	.727	
Fe ²⁺	.379	.357	.450	.429	.239	.029
Mn	.009	.008	.007	.006	.012	.006
Ca	.007	.006	.004	.009	.017	.930
Na	.002	.001	0	0	.005	.035
	1.000	1.000	1.000	.997	1.000	1.000
fe*	.200	.187	.235	.220	.126	.069

* fe = Fe²⁺/(Fe²⁺ + Mg)

single large orthopyroxene, apparently indicating crystallization of orthopyroxene subsequent to hornblende. Compositions of orthopyroxenes from the same representative samples are given in table 3. The orthopyroxenes have slightly higher Fe/Mg than the hornblendes and have low and consistent aluminum content. The Al content of orthopyroxene in equilibrium with olivine and spinel is a function of temperature (Obata, 1976; Fujii, 1976; Danckwerth and Newton, 1978), but there appears to be no discernible change in Al content of orthopyroxenes from the lowest grade to the highest grade in the samples studied.

The third major phase of the primary rocks is olivine, which occurs both as larger porphyroblasts or aggregates of grains and as small grains in the matrix. The olivines are typically quite fresh with only minor serpentinization along fractures. Electron microprobe analyses of representative olivines are given in table 4 and show that olivines are systematically slightly higher in Fe/Mg than coexisting orthopyroxenes. Brown and Prewitt (1973) used single crystal diffraction methods to de-

termine the ordering of Fe and Mg between the sites in olivine from sample OG2B. They discovered that this olivine was disordered and suggested that the metamorphic temperatures were too low for any ordering to have occurred.

Chlorite occurs in two prominent forms in primary hornblendites. Coarse plates or flakes of colorless magnesian chlorite, commonly showing polysynthetic twinning on (001), are considered to be a primary metamorphic phase. Fine-grained pale green chlorite commonly forms pseudomorphs after orthopyroxene and is interpreted to be a retrograde mineral along with serpentine, talc and carbonate. Analyses of primary chlorites from hornblendites are given in table 5. The analyses show that chlorite is both very magnesian and very aluminous. The compositions are slightly more aluminous than the idealized formula for clinocllore, $\text{Mg}_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_8$.

The two oxide minerals observed in the hornblendite lenses are spinel and ilmenite (table 6). Spinel occurs as three major types: (1) green aluminous spinels are considered to be metamorphic; (2) brown chromite-rich spinels occur rarely as a probable result of alteration of metamorphic spinels; and (3) very minor magnetite occurs with serpentine in altered olivine. The green metamorphic spinels typically have low and relatively homogeneous chromite contents, but two localities have spinels that are slightly enriched in chromite on the rims relative to the cores. Larger spinel grains are invariably poikiloblastic, and most of the inclusions appear to be hornblende. The peculiar chromite-rich spinels of one sample

TABLE 4
Representative electron microprobe analyses of olivines

	Y571	9Q9A	OG2B	N45	C36
SiO ₂	37.59	37.80	36.18	37.95	39.57
TiO ₂	0	0.02	0.02	0	0.02
Al ₂ O ₃	0	0.01	0.05	0	0
Cr ₂ O ₃	0.06	0.01	0.02	0.12	0
FeO	26.14	22.41	26.63	23.07	14.50
MnO	0.32	0.25	0.38	0.25	0.40
NiO	0.05	0.13	—	—	—
MgO	36.04	38.93	36.96	38.67	45.30
CaO	0.02	0.01	0.01	0.02	0
	100.22	99.57	100.25	100.08	99.79
Formulas based on 4 oxygens					
Si	.993	.990	.962	.991	.994
Al	0	0	.002	0	0
Ti	0	0	0	0	0
Cr	.001	0	0	.002	0
Fe	.578	.491	.592	.504	.305
Mn	.007	.006	.009	.006	.009
Mg	1.420	1.520	1.465	1.505	1.697
Ni	.001	.002	—	—	—
Ca	.001	0	0	.001	0
fe*	.29	.24	.29	.25	.15

* fe = Fe/(Fe + Mg)

TABLE 5
Representative electron microprobe analyses of chlorites and biotite

	Y57I	9Q9A	OG2B	N45		C36
SiO ₂	29.61	30.16	28.46	28.84	SiO ₂	40.14
TiO ₂	0.02	0.02	0.07	0.29	TiO ₂	1.28
Al ₂ O ₃	21.30	20.60	21.92	20.76	Al ₂ O ₃	16.42
Cr ₂ O ₃	0.09	0.27	0.18	0.24	Cr ₂ O ₃	0.50
FeO	7.52	6.28	7.54	7.30	FeO	4.39
MnO	0.01	0.01	0.05	0	MnO	0.10
MgO	29.35	30.21	28.70	28.18	MgO	24.12
					Na ₂ O	0.38
					K ₂ O	8.95
						96.28
Formulas based on 14 oxygens					11 oxygen formula	
Si	2.818	2.865	2.743	2.808	Si	2.801
Al	1.182	1.135	1.257	1.192	Al	1.199
	4.000	4.000	4.000	4.000		4.000
Al	1.208	1.172	1.234	1.187	Al	.152
Ti	.001	.001	.005	.020	Ti	.067
Cr	.007	.020	.014	.017	Cr	.028
Fe	.598	.499	.608	.594	Fe	.256
Mn	0	.001	.004	.002	Mn	.006
Mg	4.163	4.276	4.123	4.087	Mg	2.509
	5.977	5.969	5.988	5.907		3.018
fe*	.13	.10	.13	.13		
					Na	.051
					K	.797
						.848
					fe*	0.09

* fe = Fe/(Fe + Mg)

from body Y57 seem to be related to some alteration process. They occur within a matrix of very fine-grained, apparently secondary, chlorite, and they have sharply defined rims of *ferrit chromit* which are thought to indicate alteration-oxidation (Springer, 1974). Ilmenites in the hornblendites are typically homogeneous and are quite poor in Fe₂O₃, while the MgO content is rather high for metamorphic ilmenites.

The hybridized rocks, as distinct from the primary hornblendites discussed above, are characterized by assemblages consisting of hornblende, anthophyllite, cummingtonite, plagioclase, garnet, biotite, and quartz. Edges of many larger lenses and whole smaller lenses are dominated by two-amphibole rocks with either hornblende + anthophyllite or hornblende + cummingtonite. The hybridized rocks commonly have plagioclase and, more rarely, quartz, especially in contact zone rocks. Garnet has been observed in one body in an assemblage with hornblende, anthophyllite, and plagioclase. Considerable amounts of biotite may also occur in contact zones between ultramafic lenses and country rock. A more detailed description of the hybridized rocks is given by Wolff (1978).

CHEMICAL COMPOSITIONS

Bulk rock analyses for eight ultramafic bodies in central Massachusetts are reported in table 7. The first five analyses are for the Partridge Formation ultramafic lenses; sample C36 is a geologically distinct body in the Monson Gneiss. The final two analyses are taken from Ashwal and others (1979) and are of ultramafic rocks from the Devonian Belchertown Batholith. The six new analyses were done by plasma spectroscopy at Technical Service Laboratories, Mississauga, Ontario; ferric iron-ferrous iron ratios were determined at the University of Massachusetts using wet chemical techniques.

Arndt, Naldrett, and Pyke (1977) have suggested the use of a diagram in which wt percent Al_2O_3 is plotted against the weight ratio $\text{FeO}^*/(\text{FeO}^* + \text{MgO})$ (where FeO^* is total iron oxide) as a discriminant between mafic and ultramafic volcanic rocks. Figure 3A shows the compositional data for the Massachusetts rocks with data for other Phanerozoic ultramafic rocks, both volcanic and plutonic, and some Archean komatiites. The diagonal line in this diagram was proposed by Arndt, Naldrett, and Pyke (1977) as separating tholeiitic (right) from ultramafic (left) rocks, but this generally applies only to the Fe-enriched tholeiites associated with Archean komatiites. For example, typical picritic basalts plot well to the left of the line in figure 3A and could therefore be confused with komatiites on this plot.

TABLE 6
Representative electron microprobe analyses of spinels and ilmenites

	Y57I	9Q9A	Spinel OG2B	N45	C36		Y57I	9Q9A	Ilmenite OG2B	N45
TiO ₂	0.06	0.01	0.01	0	2.02	52.69	52.71	54.10	53.27	
Al ₂ O ₃	58.98	60.79	62.80	62.25	6.19	0.12	0.07	0	0.05	
Fe ₂ O ₃	4.03	0	1.27	0	34.47	2.70	2.61	0	0.53	
Cr ₂ O ₃	2.78	4.66	1.69	3.25	24.66	0.16	0.24	0.07	0.32	
FeO	18.53	20.14	23.86	21.95	28.86	40.01	40.00	43.00	42.18	
MnO	0.21	0.70	0	0.10	1.04	0.80	0.80	0.63	0.77	
MgO	14.68	14.22	12.20	12.73	2.97	3.08	3.21	2.80	2.55	
	99.27	100.52	101.83	100.28	100.21	99.56	99.64	100.60	99.67	
Formulas based on 3 cations, 4 oxygens						Formulas based on 2 cations, 3 oxygens				
Ti	.001	0	0	0	.055	.976	.970	.999	.988	
Al	1.856	1.887	1.940	1.938	.261	.003	.001	0	.001	
Cr	.059	.097	.035	.068	.699	.003	.004	.001	.006	
Fe ³⁺	.081	0	.025	0	.930	.050	.048	0	.010	
	1.997	1.984	2.000	2.006	1.945	1.032	.983	1.000	1.005	
Mg	.584	.558	.476	.501	.158	.114	.117	.102	.094	
Fe ²⁺	.414	.443	.523	.485	.865	.823	.817	.883	.880	
Mn	.005	.003	0	.002	.031	.017	.017	.013	.016	
	1.003	1.004	.999	.988	1.054	.954	.951	.998	.990	
fe*	.41	.44	.52	.49	.85					

* $\text{fe} = \text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg})$

TABLE 7
Chemical analyses of Massachusetts ultramafic rocks

	Y57I	O 18	9Q9A	J98	N45	C36	B11*	B12*
SiO ₂	42.83	43.52	42.74	44.30	47.50	49.09	49.0	53.72
TiO ₂	0.52	1.26	0.79	0.68	0.65	0.30	0.39	0.77
Al ₂ O ₃	12.06	10.07	10.34	13.39	8.11	5.40	4.9	5.64
Cr ₂ O ₃	0.16	0.15	0.29	0.16	0.23	0.66	—	0.29
Fe ₂ O ₃ **	1.38	2.18	1.16	2.74	1.60	0.98	1.7	1.03
FeO**	11.37	10.74	9.88	9.40	10.43	5.61	5.2	4.87
MnO	0.20	0.21	0.19	0.20	0.20	0.13	0	0.12
MgO	22.03	20.76	23.20	17.97	20.25	20.73	22.4	17.03
CaO	7.26	7.80	7.31	9.66	8.74	15.61	13.5	13.41
Na ₂ O	0.66	0.36	0.46	0.73	0.75	0.59	0.89	0.91
K ₂ O	0.39	0.27	0.17	0.23	0.16	0.68	0.38	1.07
P ₂ O ₅	0.20	0.26	0.25	0.19	0.16	0.14	0.25	0.03
ZrO ₂	0.01	0.01	0.01	0.01	0	0	—	—
CuO	0.01	0.01	0.01	0.01	0.01	0.01	—	—
LOI	0.95	1.39	1.75	0.07	0	0.37	—	—
	100.03	98.99	98.55	99.74	98.79	100.30	98.61	98.89

Analyst: P. E. Burgener, Technical Service Laboratories, Mississauga, Ontario.

* Analyses of ultramafic rocks from the Belchertown Batholith (Ashwal and others, 1979, p. 945)

** Done by wet chemical analysis. Analyst: K. T. Hollocher, University of Massachusetts, Amherst.

An alternative method for plotting the chemical data for these ultramafic rocks is shown in figure 3B, a ternary representation of weight proportions of MgO, CaO, and Al₂O₃ as used by Arndt, Naldrett, and Pyke (1977) and Echeverria (1980). The Massachusetts ultramafic lenses cluster with the Newfoundland ultramafic flows (Upadhyay, 1978) and the Gorgona Island flows (Echeverria, 1980). Plutonic ultramafic rocks from the Cortlandt Complex (cortlandtite and clinopyroxenite) (Bender, Hanson, and Bence, 1983) plot quite distinctly from the ultramafic volcanics and the Massachusetts lenses on figure 3, A and B. Interestingly, C36 and the ultramafic rocks from the Belchertown Batholith (Ashwal and others, 1979) show an affinity to the Cortlandt Complex rocks; the potential significance of this will be noted in the next section.

In figure 4, the compositions of the ultramafic lenses are compared with all the other compositions from figure 3 on two projections within the olivine-plagioclase-silica-wollastonite tetrahedron (see Walker and others, 1973). The dashed lines on figure 4 are the approximate low-pressure liquidus boundaries in this system. Figure 4A indicates that, as expected, all the plotted compositions are strongly olivine normative. Only the ultramafic flows from Newfoundland appear to bear significant similarity to the compositional trends of Archean komatiites. The ultramafic lenses from Massachusetts and the Gorgona Island ultramafic flows show distinct basaltic affinity, supporting the idea that they are, in fact, picrites or very mafic basalts. Figure 4 shows the strong similarity between the Cortlandt Complex rocks and the anomalous rocks from Massachusetts, C36 and the Belchertown samples, which also appeared in figure 3.

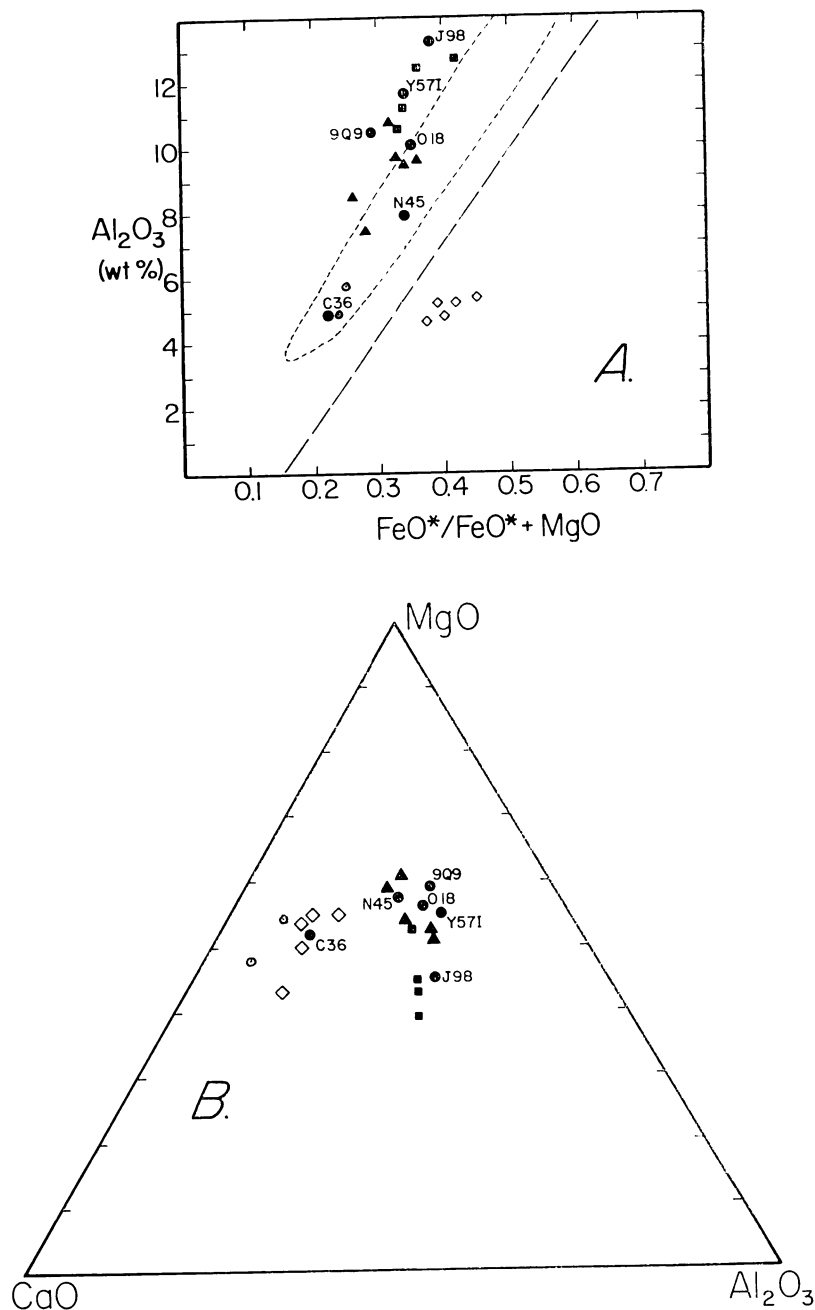


Fig. 3 (A) Plot of Al_2O_3 (wt percent) against $\text{FeO}^*/(\text{FeO}^* + \text{MgO})$ where FeO^* is total iron as FeO . The dashed area outlines the field of Archean komatiites (Arndt, Naldrett, and Pyke, 1977). Other symbols: filled circles—Massachusetts ultramafic rocks; circles with dots—Belchertown ultramafic rocks (Ashwal and others, 1979); filled squares—Gorgona Island ultramafic flows (Echeverria, 1980); filled triangles—Betts Cove, Newfoundland ultramafic flows (Upadhyay, 1978); diamonds—Cortlandt Complex, New York, plutonic ultramafic rocks (Bender, Hanson, and Bence, 1984). (B) Ternary plot of weight proportions of CaO , Al_2O_3 and MgO ; symbols are the same as in (A).

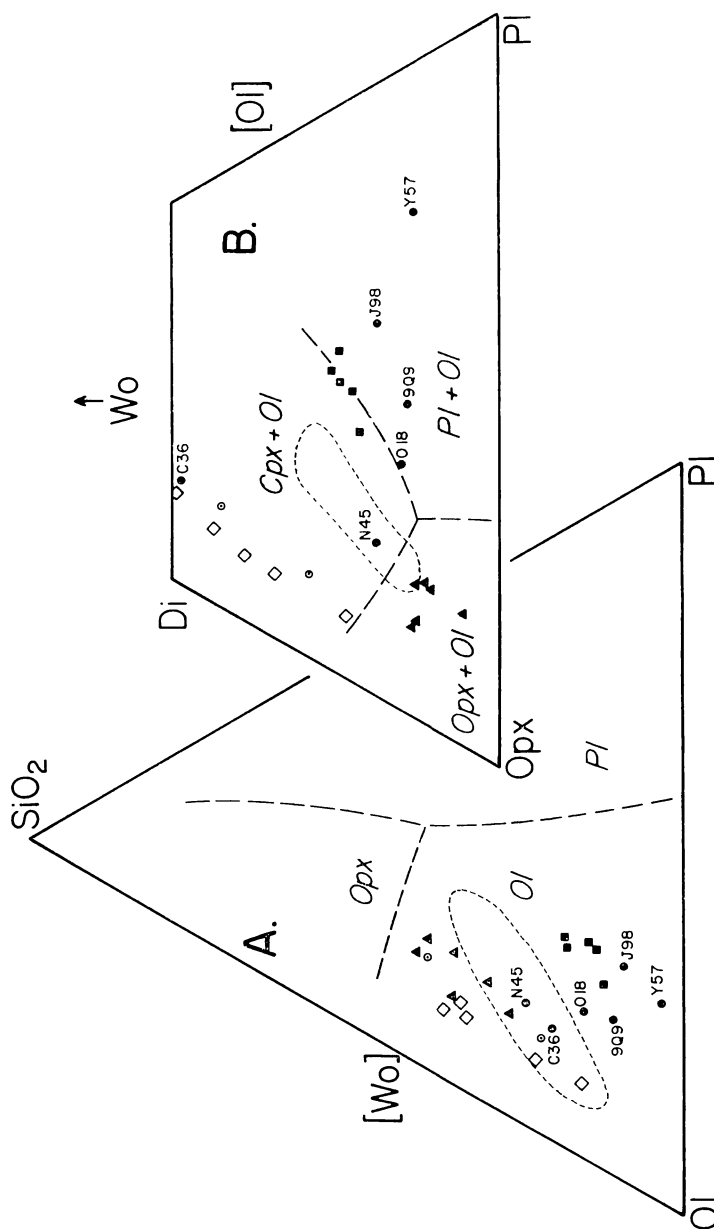


Fig. 4. Two projections within the tetrahedron olivine-wollastonite-plagioclase-SiO₂, based upon normative compositions. The left projection is from wollastonite, and the right one is from olivine. Field boundaries shown are the approximate low-pressure liquidus boundaries — note that the boundaries in the right-hand figure are the intersections with the olivine saturation surface. Symbols are the same as in figure 3.

These compositions are the lowest in normative plagioclase and therefore the most ultramafic.

Figure 5 shows the ultramafic compositions on a plot of $\text{CaO}/\text{Al}_2\text{O}_3$ (molar) against MgO (wt percent) as suggested by Schumacher (1981). The diagram shows the fields of Archean komatiites and central Massachusetts tholeiitic-composition amphibolites, as well as the CaO -depleted compositions formed by seawater alteration of tholeiites. The ultramafic lenses clearly have affinities with documented ultramafic lava flows and do not appear to be simply related to more typical amphibolites. The more calcic Massachusetts ultramafics (C36 and Belchertown) are quite unlike either the ultramafic lenses or the ultramafic flows but do bear a similarity to the Cortlandt Complex intrusive rocks.

Obviously it is hazardous to infer protolith compositions for rocks that might have undergone significant pre-metamorphic hydrothermal alteration with accompanying metasomatism. But assuming that major compositional changes did not occur, it seems reasonable to infer that the Massachusetts ultramafic lenses were originally ultramafic igneous rocks. Their similarity in composition to apparently unaltered volcanics like the spinifex-textured flows from Newfoundland and Gorgona Island supports the notion that they may have been ultramafic flows. Certain aspects of the chemistry of the lenses are clearly not compatible with komatiites, for example the low Ca/Al ratios and the high TiO_2 contents. On the other hand, the compositions are quite consistent with picritic basalts (see Carmichael, Turner, and Verhoogen, 1974, p. 414, 432, 444, 544, and 547), which are reasonable volcanic rocks and do not necessarily imply an ophiolite association.

METAMORPHISM

The presently observed mineral assemblages in all bodies are presumed to be metamorphic assemblages formed during the Devonian (Acadian) metamorphism. We have no knowledge of the assemblages that existed in the bodies at the time of their origin or emplacement, and it is therefore not possible to trace the series of metamorphic reactions leading from the original to the present mineralogy. However, if it is assumed that the interiors of the bodies remained fixed in composition with respect to all non-volatile components following any metasomatism accompanying the presumed Ordovician emplacement, then certain isochemical reactions may be proposed to relate mineralogy to bulk chemistry.

Evans and Trommsdorff (1970) and Evans (1977) have discussed in detail the progressive metamorphism of alpine ultramafic bodies, which are compositionally similar to the ultramafic lenses in the Bronson Hill anticlinorium. A likely low-grade (less than 300°C) metamorphic assemblage appropriate to the bulk compositions of the ultramafic lenses would have been diopside-serpentine-chlorite \pm brucite (Evans, 1977). The presence of small amounts of Na_2O in the bulk compositions (see table 7) suggests that minor sodic or intermediate plagioclase may have been present as well. For the metamorphic conditions represented by figure 6,

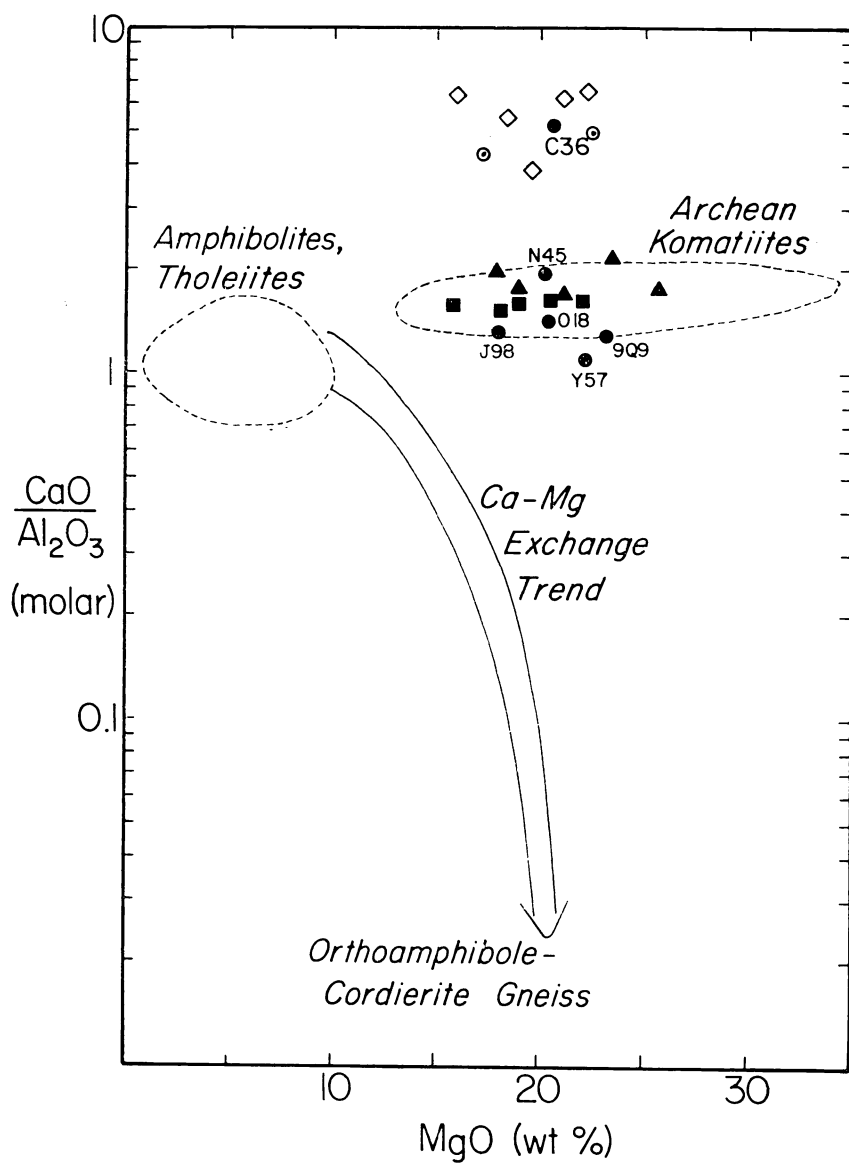
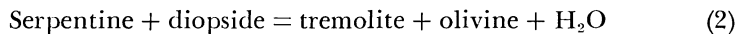
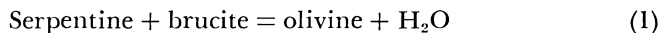


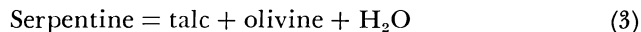
Fig. 5. Semi-log plot of $\text{CaO}/\text{Al}_2\text{O}_3$ molar ratio against wt percent MgO, as suggested by Schumacher (1981). Labelled dashed areas indicate fields of tholeiitic basalts and metamorphosed equivalents (amphibolites) and Archean komatiites. Symbols are the same as in figure 3.

the initial reactions upon progressive metamorphism would have produced olivine and/or tremolite:



Evans (1977) emphasizes that the calcic phase is diopside only at lowest and highest grades in ultramafic compositions (that is, below about 400°C and above about 800°C at intermediate pressures).

At about 500°C (fig. 6), any remaining serpentine should break down:



After an interval of almost 200°C in which no reaction occurs, the next reactions occur between 650° and 700°C:

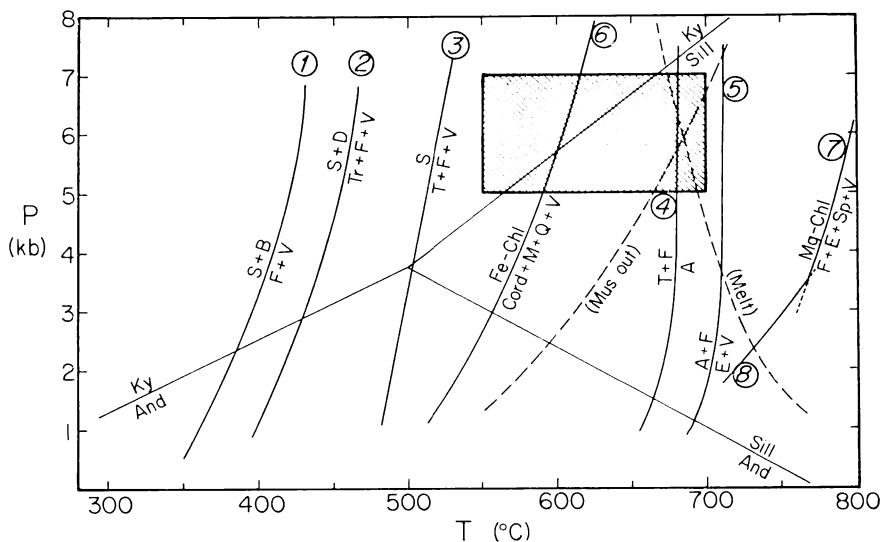
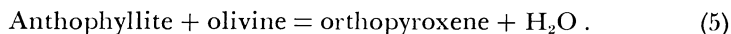
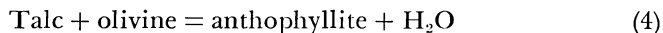


Fig. 6. P_{H_2O} - T diagram showing a number of experimentally determined or calculated equilibria in an ultramafic system that are relevant to the metamorphism of the Massachusetts ultramafic lenses. The aluminum silicate triple point (Holdaway, 1971) and the muscovite dehydration (Mus out) and granite solidus (Melt) curves (Thompson and Tracy, 1979) are shown for reference. The ruled box outlines the limits of metamorphic conditions estimated for the outcrop area in which the ultramafic lenses occur (Tracy, Robinson, and Thompson, 1976). Data sources for the curves: (1) serpentine + brucite = forsterite + vapor — Johannes (1968); (2) serpentine + diopside = tremolite + forsterite + vapor — Evans and Trommsdorff (1970); (3) serpentine = talc + forsterite + vapor — Yoder (1966); (4) talc + forsterite = anthophyllite + vapor — Greenwood (1963); (5) anthophyllite + forsterite = enstatite + vapor — Greenwood (1971); (6) Fe-chlorite = cordierite + magnetite + quartz + vapor — Turnock (1960); (7) Mg-chlorite = forsterite + enstatite + spinel + vapor — Chernosky (1974); (8) Mg-chlorite = forsterite + spinel + cordierite + vapor — Chernosky (1974).

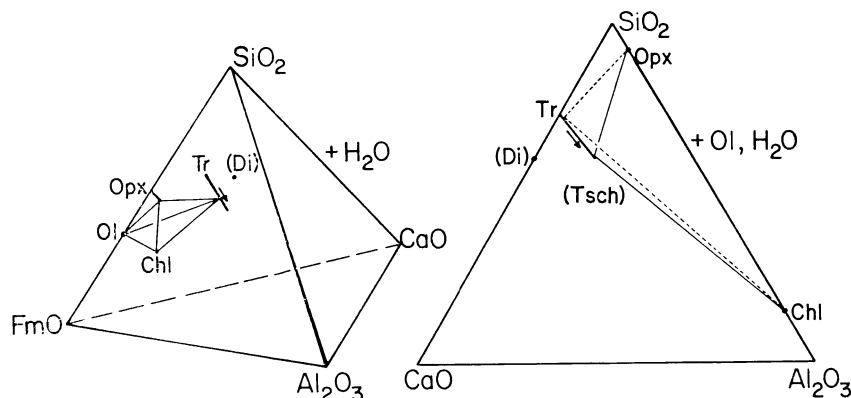
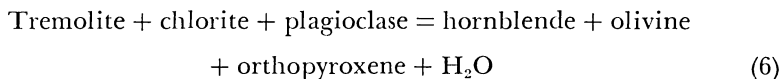


Fig. 7 (A) Tetrahedron showing the condensed quaternary system (Fe,Mg)O-Al₂O₃-CaO-SiO₂ with compositions of olivine, orthopyroxene, Ca-amphibole, diopside, and chlorite illustrated. The schematic four phase volume shows the postulated reaction assemblage in which low-Al amphibole reacts to form pargasite. (B) Projection from olivine onto the CaO-Al₂O₃-SiO₂ face. The movement of the amphibole apex of the projected four-phase volume is shown by the arrow, and progressive positions of the volume are shown: dashed (early) and solid (late). Compositions of aluminous amphibole, chlorite, and orthopyroxene are based upon the analytical data in the tables.

At this point, the assemblage would be tremolite-chlorite-olivine-orthopyroxene-(plagioclase), and this is the assemblage that most likely immediately preceded the one that is observed in the ultramafic lenses.

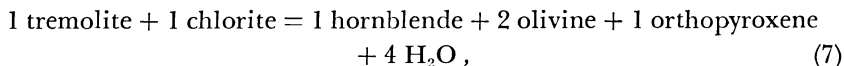
In order to get from the assemblage tremolite-chlorite-olivine-orthopyroxene to the observed assemblages (see table 1), it is necessary to accomplish two things: (1) to begin the breakdown of chlorite, producing spinel and (2) to convert tremolite into pargasitic hornblende. The preservation of zoned amphibole crystals in sample 9Q9A (as described in an earlier section) provides very useful evidence that there was indeed a conversion of tremolite to hornblende and that it occurred at high enough grade (about 600°C) to be preserved. A possible generalized multivariant reaction for the conversion is:



This reaction may be conceptualized either graphically or through treatment of the exchange and net transfer equilibria relating the participating phases.

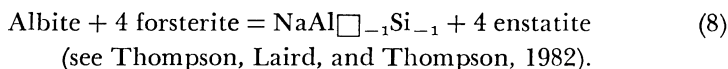
Reaction (6) is difficult to illustrate graphically, but because olivine is always present, an olivine projection in the idealized system CaO-(FeMg)O-Al₂O₃-SiO₂-H₂O may be used. As shown in figure 7, the projection from olivine is within the condensed tetrahedron CaO-(FeMg)O-Al₂O₃-SiO₂ onto the CaO-Al₂O₃-SiO₂ face. Amphibole, chlorite, and orthopyroxene all have variable plotting positions within the projection, because all three are variably aluminous (fig. 7B). The positions at which these minerals are plotted in figure 7B are based, however, upon actual

average compositions. The postulated reaction by which amphibole becomes progressively more aluminous is reflected by movement of the four-phase volume (fig. 7A) or the projected three-phase triangle (fig. 7B). The reaction topologies are based on an idealized form of reaction (6):

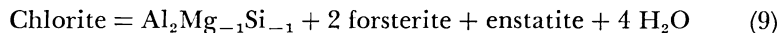


which is coupled with the tschermak exchange in amphibole, $\text{Al}^{\text{VI}} + \text{Al}^{\text{IV}} = (\text{FeMg})^{\text{VI}} + \text{Si}^{\text{IV}}$ (chlorite is clinocllore, and hornblende is $\text{Ca}_2(\text{FeMg})_4\text{AlSi}_7\text{AlO}_{22}(\text{OH})_2$ in reaction 7). In actuality, the reaction is more complex, because the presence of Na in hornblende indicates the participation of plagioclase; this more complicated reaction cannot conveniently be shown graphically.

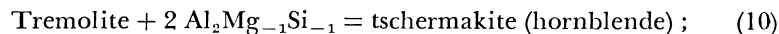
An alternative method of treating the conversion of tremolite to hornblende is to identify the relevant exchange and net transfer equilibria that relate hornblende to tremolite, chlorite, orthopyroxene, plagioclase, and olivine. This method has been developed in considerable detail by Thompson (1982) and Thompson, Laird, and Thompson (1982). For example, increase of the tschermakite component in amphibole (tschermakite endmember taken to be $\text{Ca}_2\text{Mg}_3\text{Al}_2\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$) may be expressed through the operation of an exchange vector $\text{Al}_2\text{Mg}_{-1}\text{Si}_{-1}$ on tremolite. Similarly, edenite ($\text{NaCa}_2\text{Mg}_5\text{Si}_7\text{AlO}_{22}(\text{OH})_2$) may be expressed as the operation of $\text{NaAl}\square_{-1}\text{Si}_{-1}$ on tremolite. These exchange components such as $\text{Al}_2\text{Mg}_{-1}\text{Si}_{-1}$ can be considered to have been produced in net transfer reactions such as



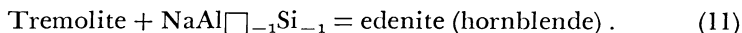
For the specific case of conversion of tremolite to pargasitic hornblende in 9Q9A (see data in table 2), a number of net-transfer and exchange reactions may be proposed. The major change in composition, the increase in tschermakite component, is expressed as a combination of a net-transfer reaction and an exchange:



and



the reader should note that these two reactions add up to the more traditionally expressed reaction (7). In addition, the tremolite–hornblende conversion involves an edenite substitution that combines the net transfer (reaction 8) with the exchange



Any increase in solid solution of calcic amphibole toward cummingtonite (that is, a decrease of Ca in M4) that might be expected with increasing temperature (Robinson and others 1982a) would be controlled by a possible net transfer reaction that produced the exchange component

MgCa₋₁. Such a net transfer does not appear likely, given the observed assemblage, and the analytical data do not show any particular trend toward greater cumingtonite component in hornblende.

The highest grade metamorphic feature observed in the lenses is the breakdown of magnesian chlorite to olivine + orthopyroxene + spinel. This reaction has been observed in other localities, notably by Springer (1974) and Frost (1975), and has been extensively studied experimentally (Turnock, 1960; Fawcett and Yoder, 1966; Chernosky, 1974; Staudigel and Schreyer, 1977). Experimentally determined or calculated positions of chlorite breakdown reactions in the system FeO-MgO-Al₂O₃-SiO₂-H₂O are shown in figure 6, which indicates that the predicted breakdown of a magnesium-rich aluminous chlorite at pressures above about 5 kb should occur in the stability field of the assemblage olivine + orthopyroxene. This prediction is consistent with the observed ultramafic assemblages for peak metamorphic temperatures.

Figure 6 indicates that aluminous chlorites such as those in the ultramafic lenses should break down in the presence of olivine and orthopyroxene at a temperature of about 700°C (see also Frost, 1975, fig. 12). However, regional temperature estimates based on pelites (Tracy, Robinson, and Thompson, 1976) suggest a range of temperatures from about 600°C for the lowest grade bodies to about 675°C for the highest grade one, all of which seem to display chlorite breakdown. Frost's calculation of chlorite stability, as well as the experimental data, are based on assumed or controlled $P_{H_2O} = P_{total}$. The lower apparent temperatures of chlorite breakdown in Massachusetts probably reflect decreased aH₂O in any fluid in the bodies or perhaps the absence altogether of any ambient metamorphic fluid.

MODELS FOR ORIGIN AND EMPLACEMENT

The hornblendites of the Partridge Formation discussed in this paper (excluding C36) lie within a rather narrow stratigraphic and structural domain and are therefore considered to be of common origin. There are three likely origins for the bodies: (1) they were tectonized ophiolite fragments, tectonically emplaced; (2) they were the result of profound hydrothermal seawater alteration of tholeiitic volcanics; and (3) they were once continuous or nearly continuous horizons of ultramafic lava flows. All three models involve mechanisms of origin during the Middle Ordovician, because all involve contemporaneity with the deposition of the Partridge Formation late in the Taconian orogeny. It has been assumed that all subsequent metamorphism and deformation was during the Devonian (Acadian). The considerable tectonic and metamorphic modification of the lenses makes it difficult to demonstrate their origin unequivocally, but certain aspects of their occurrence and chemistry are suggestive.

The present exposure of the lenses as structural boudins does not necessarily preclude their origin as intrusive bodies, later metamorphosed and deformed. However, their rather strict confinement to a relatively thin zone for a considerable distance along strike (see fig. 1) makes such an origin unlikely. Some of the other types of central Massachusetts

ultramafic bodies are better candidates to be intrusive, for example, the various bodies (including C36) in the Monson Gneiss and the ultramafic rocks of the Belchertown Complex. Bender, Hanson, and Bence (1984) suggested that many of the Ordovician ultramafic bodies across central New England might have had a common parentage with the magma that formed the Cortlandt Complex in southeastern New York. The apparent chemical affinity of C36 and the Belchertown rocks to the Cortlandt rocks (figs. 3 and 4) may support this genetic connection for C36, but the Belchertown bodies are probably of Middle Devonian rather than Ordovician age.

While it is impossible to rule out the hypothesis that the ultramafic lenses were once serpentinites that were parts of an ophiolite or ultramafic complex, this model is difficult to reconcile with the absence of other parts of such an ophiolite, since no harzburgitic rocks of Ordovician age have been found nearby. It is unlikely that high grade metamorphism and intense deformation could have obliterated most traces of an ophiolite assemblage, and there do not appear to be enough mafic and ultramafic rocks to indicate the former presence of an ophiolite of the magnitude and composition of the Lower Paleozoic ophiolites of Newfoundland (Williams, 1971) or Quebec (St. Julien and Hubert, 1975).

The second model proposes that the present ultramafic compositions of the lenses could have been produced by hydrothermal alteration or low grade metamorphism of tholeiitic basalts in the presence of seawater. While it is true that the MgO content of altered basalts may be greatly enhanced during alteration (Bischoff and Dickson, 1975), there are accompanying chemical changes, notably significant loss of Fe oxides and CaO and increases in TiO_2 and Na_2O . The Massachusetts ultramafic lenses do not seem to show these other chemical changes, at least in comparison with common tholeiite compositions (Carmichael, Turner, and Verhoogen, 1974). Model two is therefore considered to be unlikely. In fact, the Ca-Mg exchange trend that characterizes hydrothermal seawater alteration results in bulk compositions so depleted in CaO that the resultant metamorphic equivalents are kyanite-chlorite-albite schist (at about 500°C in a Barrovian sequence) and orthoamphibole-cordierite gneiss (at about 600°C) (Schumacher, 1981). The path of hydrothermal seawater alteration shown on figure 8 illustrates graphically why Ca-Mg exchange is not a viable method for producing the observed compositions of the ultramafic lenses.

The third model, the one we prefer, proposes that the ultramafic lenses are fragments of horizons representing particularly mafic to ultramafic extrusive activity in the Ordovician. The Middle Ordovician Ammonoosuc Volcanics and Partridge Formation contain dominant proportions of marine basinal rocks including variably altered (Ca-Mg exchanged) basalts and sulfidic pelitic schists likely derived from marine pelagic muds. This apparently restricted marine environment with considerable mafic volcanic activity may be a reasonable site for especially mafic or picritic basaltic flows. The chemical similarity of the ultramafic

lenses to unmetamorphosed Phanerozoic ultramafic lava flows (for example, Upadhyay, 1978; Echeverria, 1980) supports this model, although in Massachusetts there appears to have been a considerably smaller volume of ultramafic magma.

Petrogenetic links between the igneous precursors of the different lower to middle Paleozoic ultramafics from Massachusetts are unlikely. While a Middle Ordovician age for the postulated ultramafic flows is fairly well constrained, the ages of the other bodies are more ambiguous. They are certainly Devonian or older, and it is at least possible that C36, which is contained within the Monson Gneiss, is also Ordovician. The Belchertown bodies are contained within a well dated Devonian pluton (Ashwal and others, 1979) with which they have reacted; they are therefore Devonian or older. It has been argued by Ashwal and others that they are comagmatic with the Belchertown monzodiorite, but if they are older than Devonian, they may represent xenoliths of late Precambrian or Ordovician rock. It is certainly premature at this point to relate any of the Massachusetts ultramafics to Cortlandt Complex-type magmatism occurring to the west in the Ordovician.

In summary, the olivine-orthopyroxene-spinel hornblendites of the Partridge Formation could represent metamorphosed fragments of dismembered ophiolite, but if so, the dismemberment process was highly selective in including only extremely mafic gabbros or gabbroic cumulates and no peridotites and harzburgites. An origin by hydrothermal alteration of mafic basalts seems improbable because of the limited bulk compositional variation and because the compositional trends are not in the right direction. The possibility of derivation from ultramafic flows or shallow intrusions, of probable late Taconian age, needs to be explored further.

ACKNOWLEDGMENTS

Financial support for this research was provided by the National Science Foundation through grants GA-33857 and GA-31989 (to P.R.) and EAR 78-19901 and EAR 81-20670 (to R.J.T.), and by a Sigma Xi Grant-in-Aid to R.A.W. Very helpful reviews by R. N. Abbott, Jr. and Jo Laird resulted in significant improvement of the paper. We also acknowledge Kurt Hollocher for his help with the chemical analyses.

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