[AMERICAN JOURNAL OF SCIENCE, VOL. 288, JUNE, 1988, P. 619–663]

STRATIGRAPHY AND GEOCHEMISTRY OF THE AMMONOOSUC VOLCANICS, CENTRAL MASSACHUSETTS AND SOUTHWESTERN NEW HAMPSHIRE

JOHN C. SCHUMACHER
Mineralogisches Institut, Universität Kiel, Olshausenstrasse 40,
D-2300 Kiel Federal Republic of Germany

ABSTRACT. The Middle Ordovician Ammonoosuc Volcanics are interpreted to be Ordovician island arc volcanics, deposited during the Taconian Orogeny and later metamorphosed during the Devonian Acadian Orogeny at amphibolite facies conditions. In Massachusetts and New Hampshire they occur above core gneisses in the gneiss domes and below the Partridge Formation and possess an internal stratigraphy of four members in ascending order: Moosehorn Conglomerate (local basal quartz-pebble conglomerate); Lower Member (amphibolites, K-poor felsic gneisses, and minor marble); garnet-amphibole-magnetite quartzite (discontinuous layer of metamorphosed chert); Upper Member (biotite-quartz-feldspar gneisses containing garnet, muscovite, and kyanite or sillimanite). The stratigraphic section ranges in thickness from 0 to 1200 m. Orthoamphibole and cummingtonite are common throughout. Major-and trace-element analyses of 64 samples indicate that most rocks retain original chemistry, but some show compositions that were apparently changed by high-and low-temperature seawater alteration, weathering, or hydrothermal alteration prior to metamorphism.

Mafic rocks from the Lower Member believed to have original compositions are chemically like low-K basalts through low-K andesites (48–58 wt percent SiO_2, <0.9 wt percent K_2O). In the Lower Member, felsic rocks believed to have original compositions are chemically like low-K dacites and low-K rhyolites (65–75 wt percent SiO_2, <0.9 wt percent K_2O), while those from the Upper Member are similar to normal dacites and rhyolites (67–77 wt percent SiO_2, 1.51 to 3.65 wt percent K_2O). Minor and trace elements in the mafic Ammonoosuc rocks are comparable with modern arc basalts. Minor and trace elements in felsic rocks (>63 wt percent SiO_2) from the Upper Member and most from the Lower Member are comparable with modern volcanic arc rocks and could have been generated by partial melting of amphibolites with trace element abundances like those of island arc basalts. Higher K, Rb, and Ba distinguish Upper Member felsic rocks from those found in the Lower Member.

INTRODUCTION

The Ammonoosuc Volcanics of central Massachusetts and western New Hampshire (Billings, 1937, 1956; Robinson, ms and 1967) along with the Middletown Formation in Connecticut (Lundgren, 1966; Lundgren, Ashmead, and Snyder, 1971) and the Post Pond Volcanics in New Hampshire and Vermont (Hadley, 1942; Rumble, ms; Thompson and others, 1968) are part of a narrow belt of mafic rocks, amphibolites, and associated felsic gneisses and granulites that run from southern

Connecticut, through Massachusetts, along the Vermont-New Hampshire border, and just into Maine. The Ammonoosuc Volcanics have been cited as evidence for an Ordovician island arc (Rodgers, 1970; Bird and Dewey, 1970; Robinson and Hall, 1980), and they play a key role in Ordovician paleogeographic reconstructions.

Several major element analyses of mafic and felsic rocks from the Ammonoosuc Volcanics were published by Billings (1937). Analyses of major elements and selected trace elements were done by Aleinikoff (1977), who believed that on this basis he could distinguish between ocean-floor and island-arc basalts. Leo, Zartman, and Brookins (1984) also report 11 analyses of felsic rocks from the Ammonoosuc Volcanics, and Leo (1985) gives analyses of 31 Ammonoosuc related rocks (mostly felsic types).

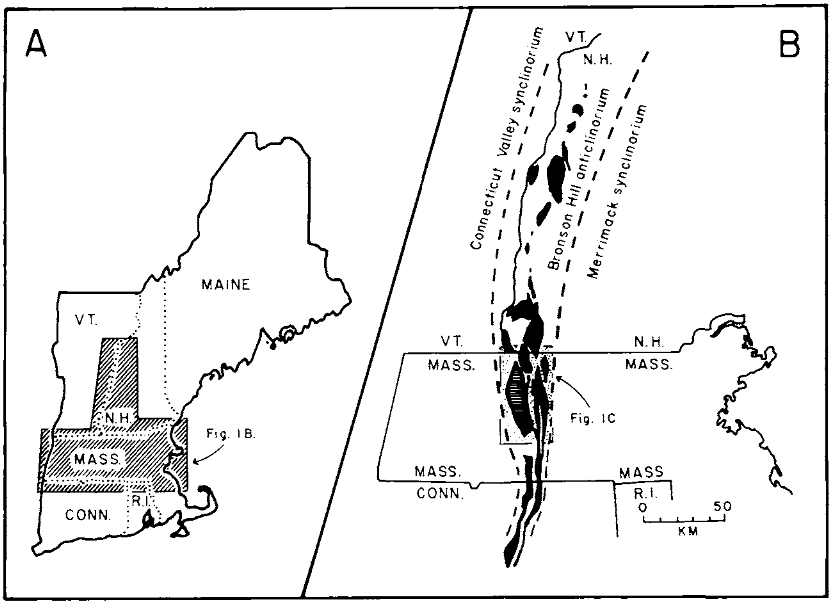
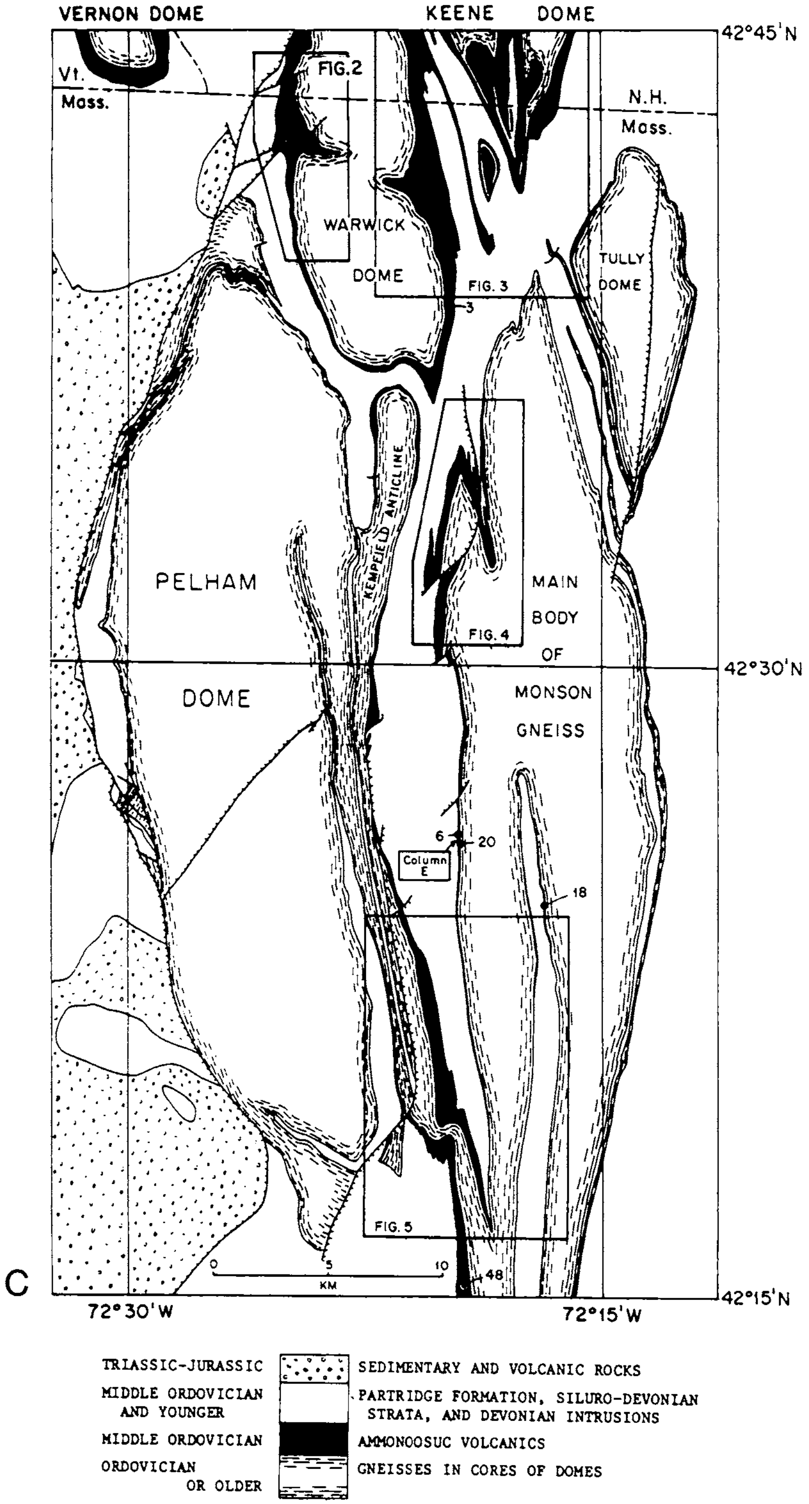


Fig. 1. Maps showing the location and distribution of the Ammonoosuc Volcanics and associated rocks. Abbreviations: CONN = Connecticut, MASS. = Massachusetts, N. H. = New Hampshire, R. I. = Rhode Island, and VT. = Vermont. (A) Map that shows the general location of (B) (*shaded area*) in New England. (B) Location map showing the distribution of gneiss domes within the Bronson Hill anticlinorium. Dashed lines depict the approximate boundaries between several tectonic subdivisions; these boundaries are not accurately located and are shown only for illustrative purposes. *Stippled area* shows the location of C. (C) Generalized geologic map showing the distribution of the Ammonoosuc Volcanics in north-central Massachusetts and adjacent New Hampshire and Vermont. Mesozoic normal faults are shown as lines with hachures on the downthrown side. Insets show locations of detailed maps. Numbers indicate locations of samples (app. and tables 1-5) not on the detailed maps. Location of column E (fig. 6) is also shown.


VERNON DOME
KEENE DOME
42°45'N
Vt.
Mass.
N.H.
Mass.
FIG. 2
WARWICK
DOME
FIG. 3
3
TULLY
DOME
KEMPFIELD ANTICLINE
PELHAM
DOME
FIG. 4
MAIN
BODY
OF
MONSON
GNEISS
42°30'N
6
20
Column
E
18
FIG. 5
0
5
10
KM
48
C
72°30'W
72°15'W
42°15'N
TRIASSIC-JURASSIC
SEDIMENTARY AND VOLCANIC ROCKS
MIDDLE ORDOVICIAN AND YOUNGER
PARTRIDGE FORMATION, SILURO-DEVONIAN STRATA, AND DEVONIAN INTRUSIONS
MIDDLE ORDOVICIAN
AMMONOOSUC VOLCANICS
ORDOVICIAN OR OLDER
GNEISSES IN CORES OF DOMES

REGIONAL SETTING

The Ammonoosuc Volcanics are part of the Bronson Hill anticlinorium, which is a stratigraphic and tectonic subdivision of western New England (Billings, 1937; Thompson and others, 1968; Robinson, 1979; Robinson and others, 1982). The Bronson Hill anticlinorium can be divided into three major stratigraphic groups: (1) gneisses and related rocks in the cores of the domes, which are Ordovician or older; (2) Middle Ordovician Ammonoosuc Volcanics and Partridge Formation; and (3) Silurian and Devonian strata and intrusive rocks.

The gneisses in the cores of the domes are of three general types. First, the Pelham dome (fig. 1C) contains a distinctive sequence of layered gneisses and minor quartzites and schists. The gneisses have been interpreted in part as metamorphosed rhyolite (Ashenden, ms; Robinson, 1979; Hodgkins, 1985), and zircon from one of them has been dated at 560 ± 30 my (Naylor and others, 1973; Zartman and Naylor, 1984). Secondly, there are stratified and layered gneisses of igneous derivation that include Monson gneiss (fig. 1). Zircon data on one specimen of the Monson gneiss gives an Ordovician age of 440 to 450 my (Zartman, personal commun., 1979, to P. Robinson; Zartman and Naylor, 1984). Thirdly, there are massive gneisses of plutonic origin that include the gneisses of the Warwick and Vernon domes (fig. 1C). Leo (1985) believes that the plutonic rocks of the Vernon gneiss dome are Ammonoosuc-related trondjhemites, which, locally, intrude the Ammonoosuc amphibolites. Zircons from the Warwick dome and from similar dome rocks in New Hampshire give a composite intercept age of 444 ± 8 my (Zartman and Leo, 1981, 1985).

The Middle Ordovician strata include the Ammonoosuc Volcanics (fig. 1) and the Partridge Formation. The Ammonoosuc Volcanics are composed of a highly varied Lower Member, which consists of interlayered amphibolites and felsic gneisses and an Upper Member, which consists chiefly of peraluminous felsic gneisses. The Partridge Formation overlies the Ammonoosuc Volcanics and is composed chiefly of metamorphosed sulfidic black shale with subordinate mafic and felsic volcanics (Hollocher, 1983 and ms) and rare ultramafic lenses (Tracy, Robinson, and Wolff, 1984). The Silurian and Devonian strata uncomformably overlie all the other rock types except the late Precambrian gneisses of the Pelham dome (fig. 1C).

The regional deformation and metamorphism affecting the area of figure 1 was Acadian (Devonian). The main phase of metamorphism was concurrent with deformation (Robinson, 1967; Field, ms; Tucker, ms; Robinson and others, 1982; Hall and Robinson, 1982). The complexity of the structural and stratigraphic relations are only briefly described but are illustrated in figures 2 to 5. Most of the Ammonoosuc Volcanics shown in figure 1C lie in the staurolite-kyanite and sillimanite-staurolite zones of metamorphosed pelitic schists (Tracy, Robinson, and Thompson, 1976; Robinson, 1979; Robinson and others, 1982), but the thin belts near sample locality 18 (fig. 1C) are in the sillimanite-muscovite-K feldspar zone.

STRATIGRAPHY OF THE AMMONOOSUC VOLCANICS

General Statement

The Ammonoosuc Volcanics were first described by Billings (1937) in western New Hampshire and were traced southward to Massachusetts by Billings and his students (Moore, 1949; Billings, 1956). The name was first used in Massachusetts by Hadley (1949), and its use was continued by Robinson (ms and 1967) and Peper (ms and 1967).

Hadley (1949) first made a distinction between dominantly mafic and felsic parts of the Ammonoosuc Volcanics. Robinson (ms and 1967, 1977) expanded this subdivision in north-central Massachusetts and observed that mafic rocks dominated the lower parts and felsic rocks dominated the upper parts. He also noted that the contact between the lower mafic rocks and the upper felsic rocks is sharp and that this contact is commonly the location of a thin, garnet-amphibole-magnetite quartzite (that is, coticule).

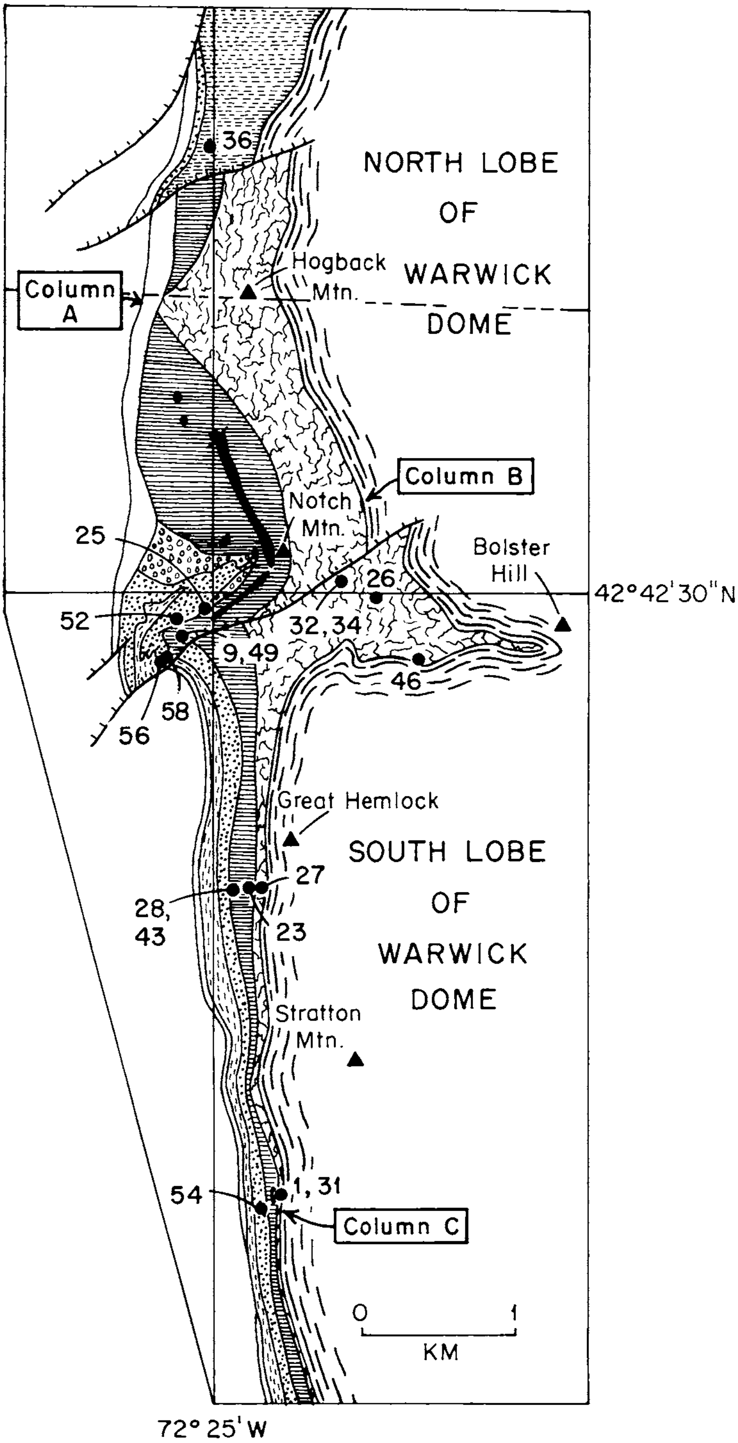
Work by Schumacher (1980a, 1981, and ms) on the west side of the Warwick gneiss dome (figs. 1 and 2) extends this subdivision of the Ammonoosuc Volcanics and has shown that, locally, felsic rocks can dominate the lower part of the Ammonoosuc section. The lower unit and the upper felsic unit are here elevated to the status of members.

Distribution and Thickness

The distribution of the Ammonoosuc Volcanics in central Massachusetts and southwestern New Hampshire is shown in figure 1C. Thickness variations of 0 to 1200 m (thickest near Mt. Grace, fig. 3) can be attributed to original variations in thickness, to unconformities beneath overlying units, or to Acadian tectonic thinning and thickening. Ignoring the extensive structural complications, the entire Ammonoosuc appears to be a linear accumulation that trends north–south and that pinches out both to the east and west. In the central part, where the accumulation is thickest, the overlying Partridge Formation is thin or even absent. Where the Ammonoosuc pinches out to the east it is overlain by much thicker Partridge Formation, which suggests the eastern thinning is a primary depositional feature. Remarkably, even where the Ammonoosuc is less than 50 m thick in the Quabbin Reservoir area, it commonly retains its rough internal stratigraphy (Peter Robinson and Kurt Hollocher, personal commun., 1981). The westward pinchout is also beneath the Partridge but in more poorly exposed, structurally complex areas.

Moosehorn Conglomerate Member

Along the west side of the main body of Monson Gneiss (fig. 1C) Robinson (1977) located a lens of quartz-pebble conglomerate and quartzite with a calcareous matrix at the Ammonoosuc-Monson contact (fig. 4). The lens is about 9 m thick and extends about 100 m along strike. The matrix is composed chiefly of finer-grained quartz and lesser amounts of hornblende, epidote, K-feldspar, and pyrite (Renate Schu-


NORTH LOBE OF WARWICK DOME
Hogback Mtn.
Column A
36
Column B
Notch Mtn.
Bolster Hill
25
26
32, 34
42°42'30"N
52
9, 49
46
58
56
Great Hemlock
SOUTH LOBE OF WARWICK DOME
27
28, 43
23
Stratton Mtn.
54
1, 31
Column C
0
1
KM
72° 25' W

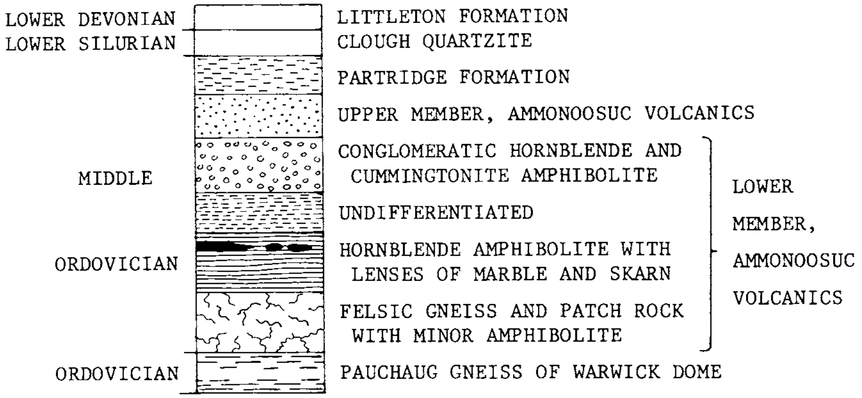


Fig. 2. Geologic map showing the detailed stratigraphy of the Ammonoosuc Volcanics on the west side of the Warwick gneiss dome. Geology by J. C. Schumacher, 1978-1980, and Peter Robinson, 1959-1980. Locations of columns A, B, and C in figure 6 and some samples (numbers) listed in the app. and tables 1 to 5 are also shown.

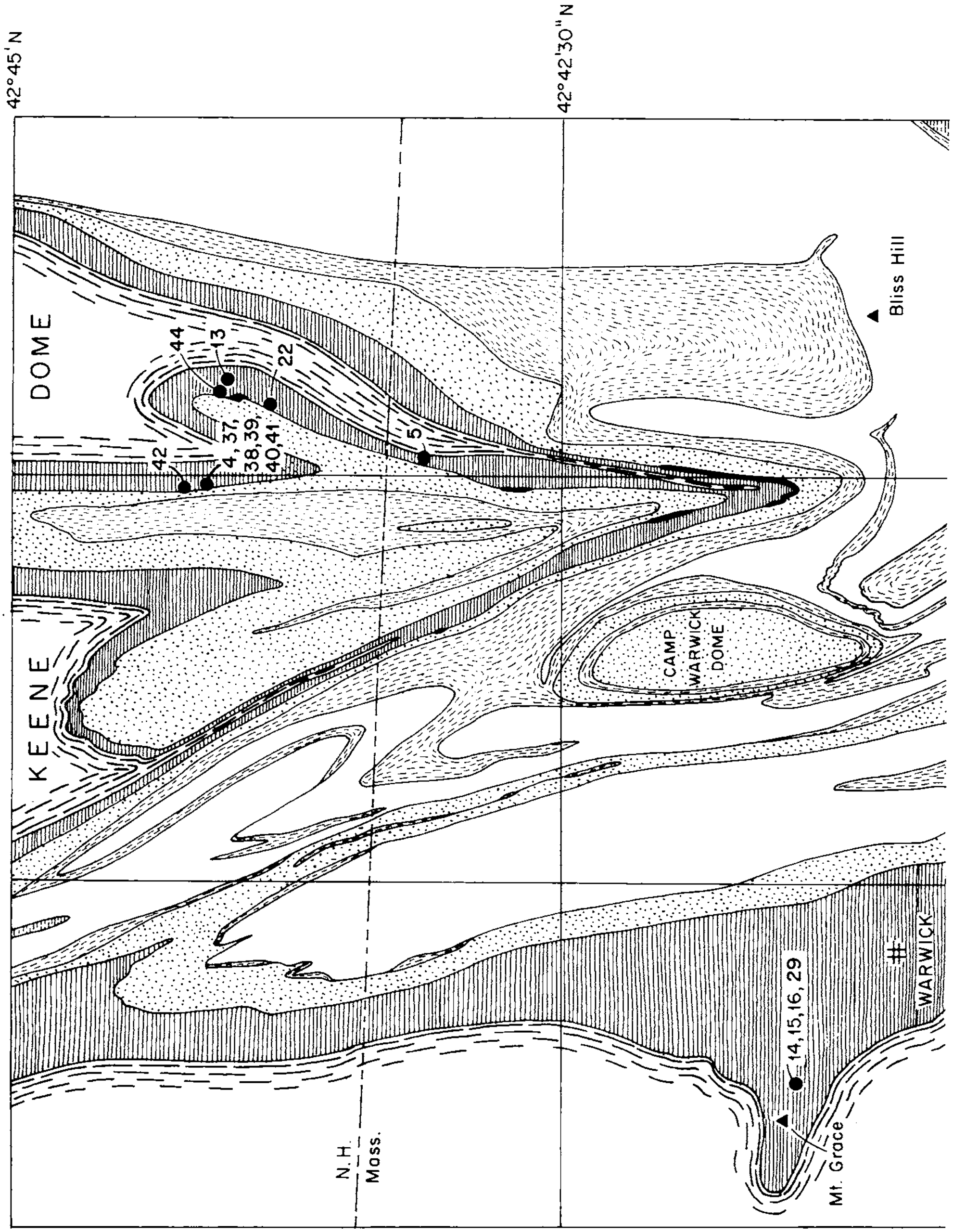
macher, personal commun., 1983) suggesting a carbonate-bearing protolith. The presence of K-feldspar suggests that the matrix may contain detritus derived from the underlying Monson gneiss. The Ca-rich matrix of the Moosehorn and the pelitic matrix of the Silurian Clough distinguish these two conglomerates. Two small lenses of quartzite, which may correlate with the Moosehorn Conglomerate Member have been found along this contact at Quabbin Reservoir (Robinson, personal commun., 1984).

Lower Member

The Lower Member, as is defined here, includes amphibolites, various felsic gneisses, rare aluminous schist, and calcareous layers. These rocks overlie the gneisses of the domes (figs. 2, 3, 4, 5) or locally the Moosehorn Conglomerate. Commonly, amphibolites and gneisses of this member contain cummingtonite, anthophyllite, or gedrite, which have been referred to as "the guide fossils of the Ammonoosuc" in Massachusetts and Connecticut.

Amphibolites.—The amphibolites from the Lower Member are composed chiefly of hornblende and plagioclase with or without cummingtonite, anthophyllite, gedrite, garnet, magnetite, biotite, and less commonly epidote, diopside, and sphene. The more feldspathic amphibolites contain minor quartz. Modes and additional rock descriptions can be found in Robinson (ms, table 3) and Robinson and Jaffe (1969b).

The generalized stratigraphic columns in figure 6 illustrate that the proportions of amphibolite to felsic rocks in the Lower Member are highly variable. In column D amphibolite makes up most of the Lower Member; whereas, in column B, it is a relatively minor part of the section.


42°45'N
42°42'30"N
KEENE
DOME
44
13
22
5
42
4, 37,
38,39,
40,41
Bliss Hill
CAMP
WARWICK
DOME
N.H.
Mass.
14,15,16,29
Mt. Grace
WARWICK

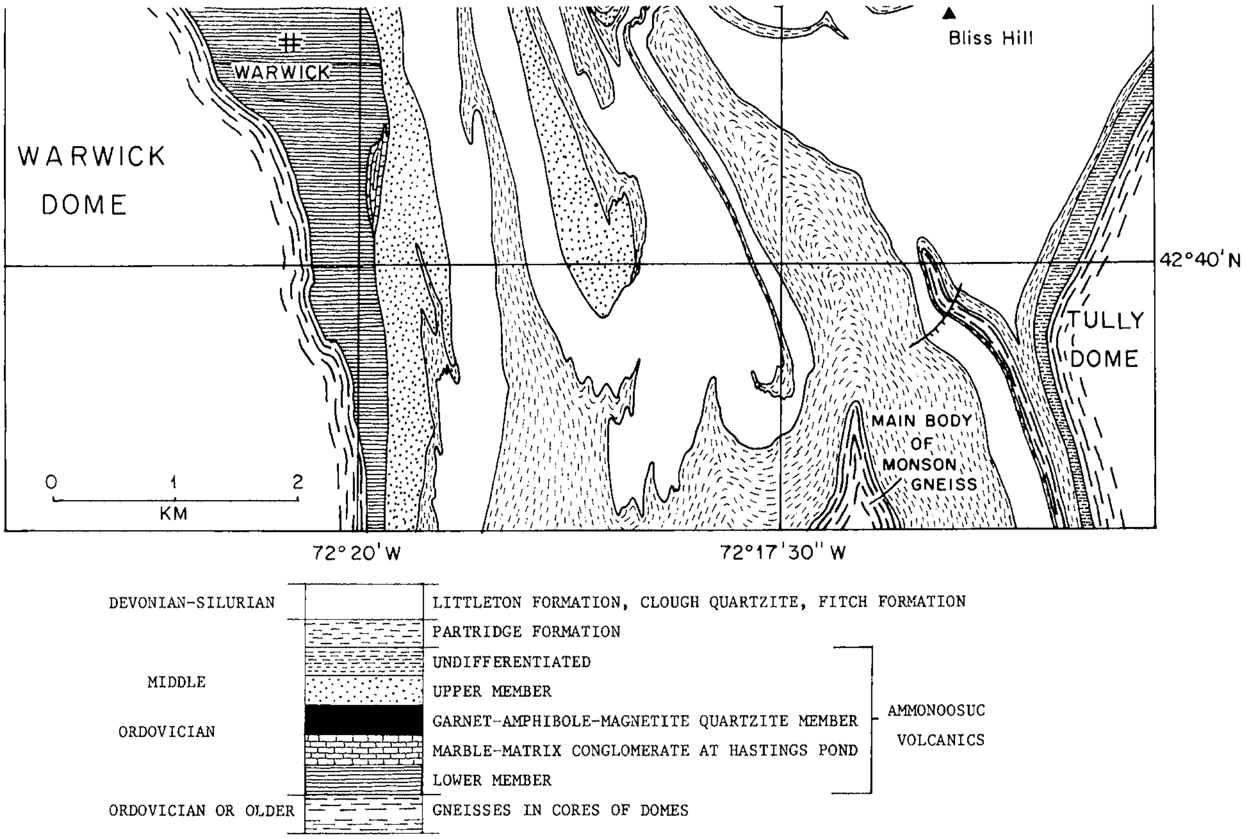
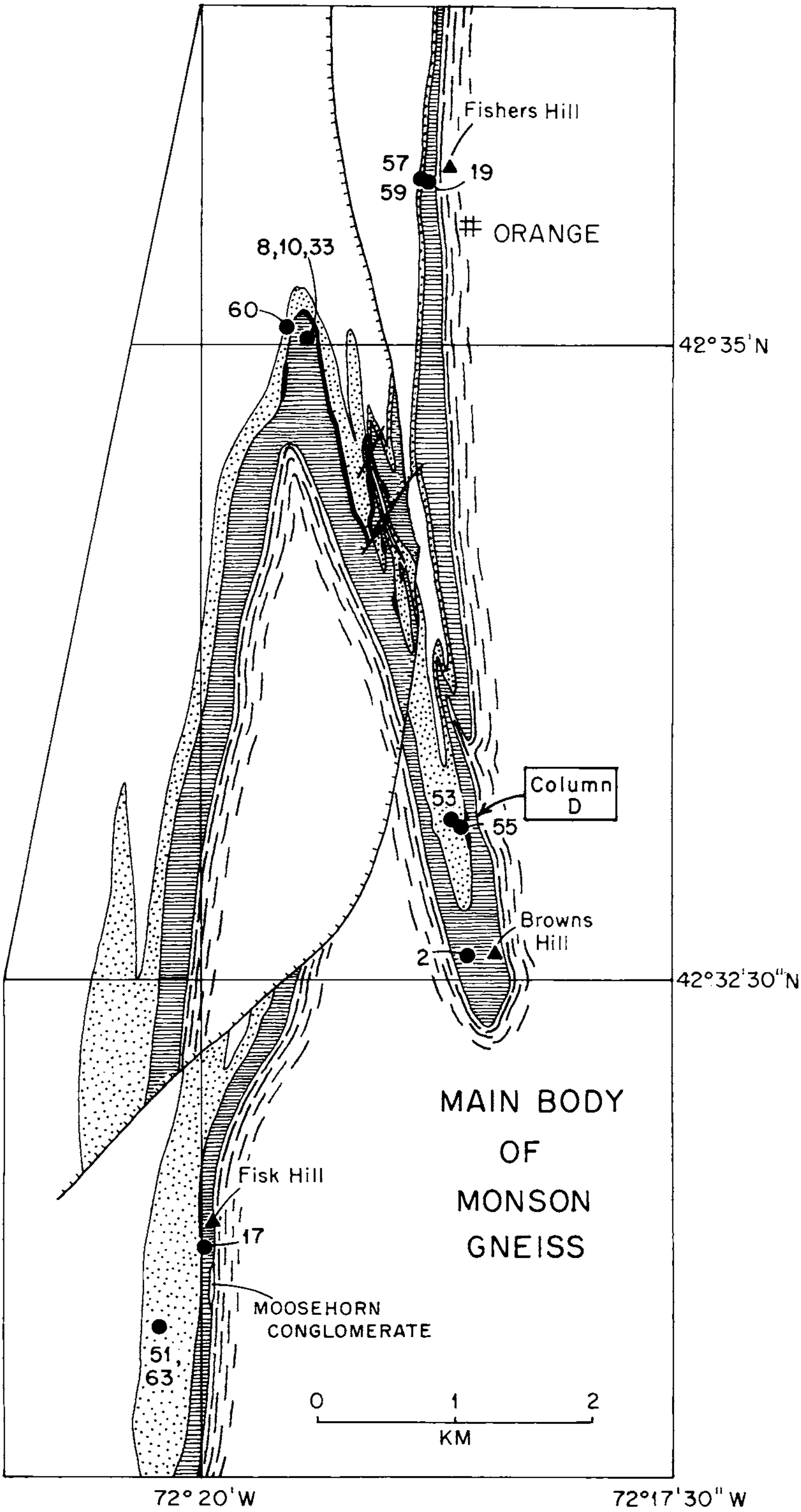


Fig. 3. G[illegible]gic map showing the stratigraphy of the Ammonoosuc Volcanics on the east limb of the Warwick gneiss dome, the [illegible] end of the Keene gneiss dome, and the Tully dome. Geology by Peter Robinson, 1959–1974. Numbers are the [illegible]ns of some samples in the app. and tables 1 to 5.


Fishers Hill
57
59
19
ORANGE
8,10,33
60
42°35'N
Column D
53
55
Browns Hill
2
42°32'30"N
MAIN BODY OF MONSON GNEISS
Fisk Hill
17
MOOSEHORN CONGLOMERATE
51, 63
0
1
2
KM
72°20'W
72°17'30" W

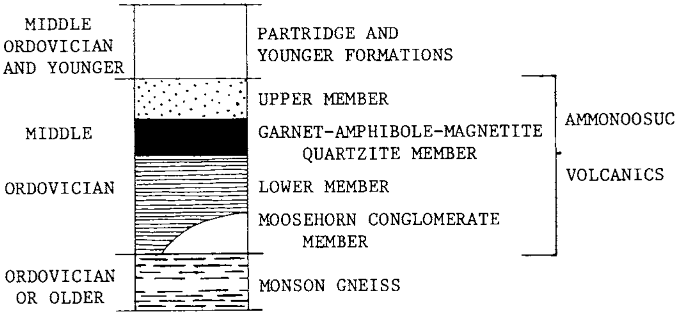
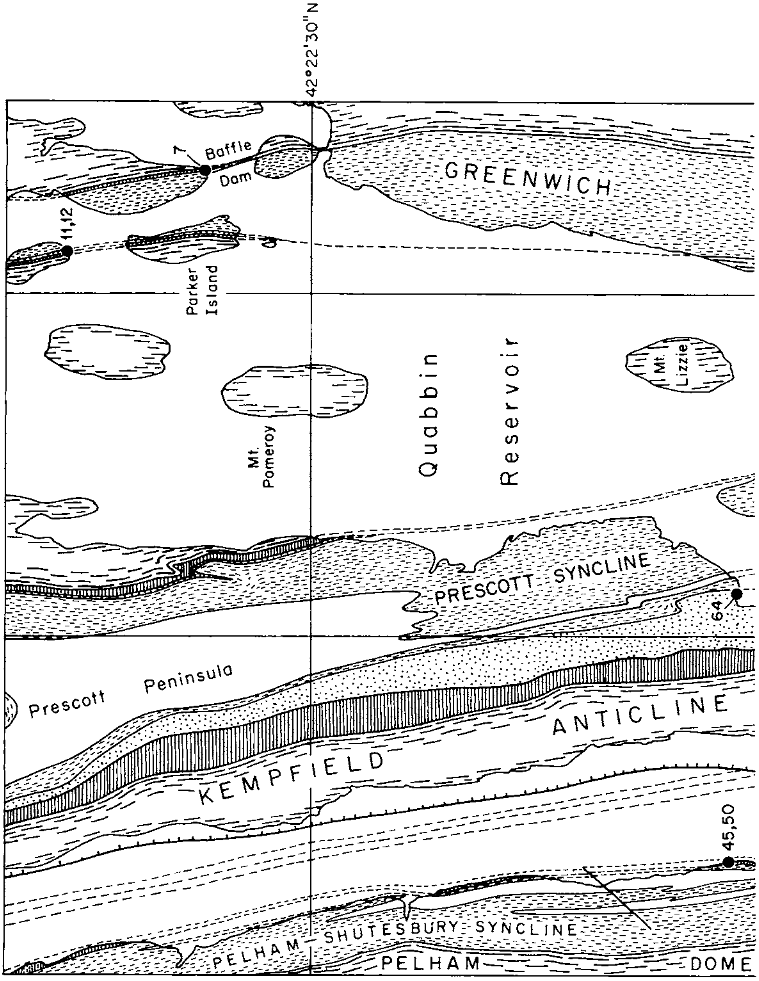


Fig. 4. Geologic map showing the stratigraphy of the Ammonoosuc Volcanics on the west side of the Main body of the Monson gneiss. Geology by Peter Robinson, 1959, 1971-1976. Locations of column D and some of the samples (numbers) in the app. and tables 1 to 5 are also shown.

A number of textures and structures seen in the amphibolites are interpreted as original volcanic features (Robinson, ms). In several localities, elongated, roughly elliptically shaped areas of amphibolite are separated from one another by thinner rims of hornblende ± garnet and are interpreted as metamorphosed pillow lavas (Robinson, ms and 1967; Schumacher, ms). Massive amphibolites may represent flows or possibly dikes and sills. Layered amphibolites with varying proportions of hornblende and plagioclase, which are on the order of centimeters thick, may represent basaltic tuffs. Coarse-grained plagioclase and plagioclase aggregates dispersed in some of the amphibolites may have been phenocrysts or amygdules in the original mafic volcanic rock. On the west side of the Warwick dome (fig. 2), amphibolite that encloses angular pieces (up to 10 cm across) of plagioclase–quartz–cummingtonite gneiss is best interpreted as a volcanic agglomerate or conglomerate of dacite pebbles and boulders in a basaltic matrix.

Gedrite gneisses.—A distinctive set of gedrite gneisses and amphibolite occurs at the top of the Lower Member at the south end of the Keene gneiss dome (fig. 3). These rocks are composed of gedrite with or without plagioclase, cordierite, hornblende, talc, garnet, staurolite, and quartz (samples 36–41 and 44 in app.; see also Robinson, ms, table 16). The gneisses are composed chiefly of gedrite and cordierite, and the cordierite itself contains enclaves of aluminous minerals such as sillimanite, kyanite, corundum, staurolite, sapphirine, spinel, and anorthite (Robinson and Jaffe, 1969a; Schumacher, 1981; Schumacher and Robinson, 1987). Robinson and Jaffe (1969a) described the detailed stratigraphic relations within these gneisses. The gedrite-rich gneisses have the chemical characterisitcs of basalts that have undergone intense, high-temperature alteration by seawater (Schumacher, 1982 and ms).

Felsic gneisses.—These rocks are composed chiefly of plagioclase and quartz with lesser amounts of hornblende, cummingtonite, gedrite


42°22'30"N
7
Baffle Dam
GREENWICH
11,12
Parker Island
Mt. Pomeroy
Quabbin Reservoir
Mt. Lizzie
PRESCOTT SYNCLINE
64
Prescott Peninsula
KEMPFIELD ANTICLINE
45,50
PELHAM-SHUTESBURY SYNCLINE
PELHAM DOME

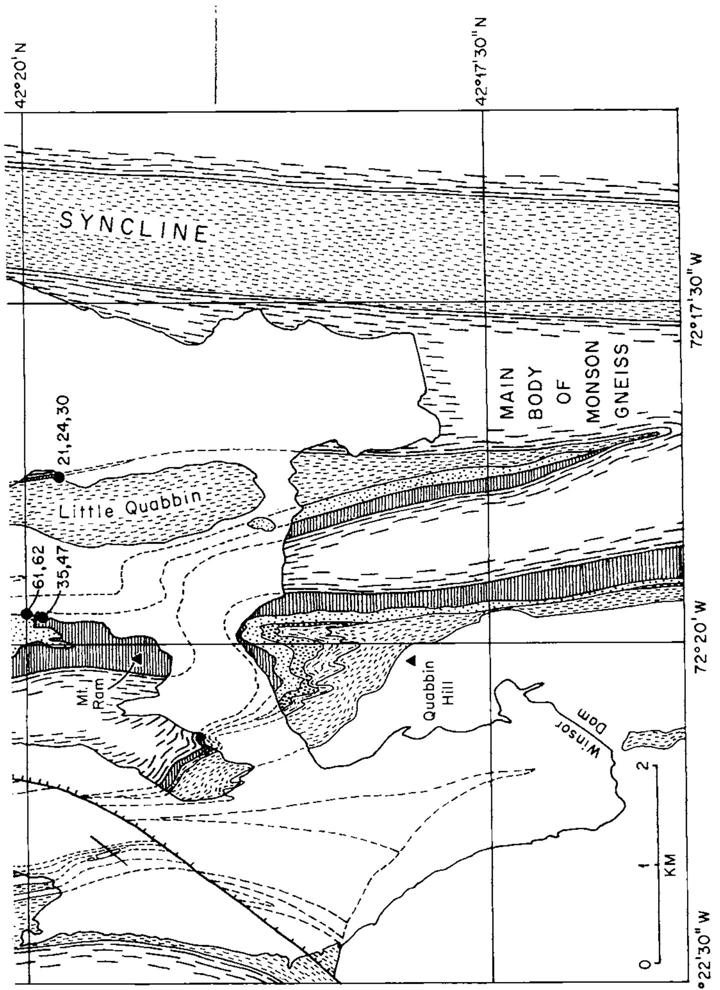


Fig. 5. Geologic map showing the stratigraphy of the Ammonoosuc Volcanics in the southern part of the Quabbin Reservoir area. Geology by Peter Robinson, 1962–1982, Stuart Michener, 1980–1981 (Pelham-Shutesbury syncline), Kurt Hollocher (Little Quabbin and Parker Island, 1981–82). Numbers indicate locations of some samples in the app. and tables 1 to 5.

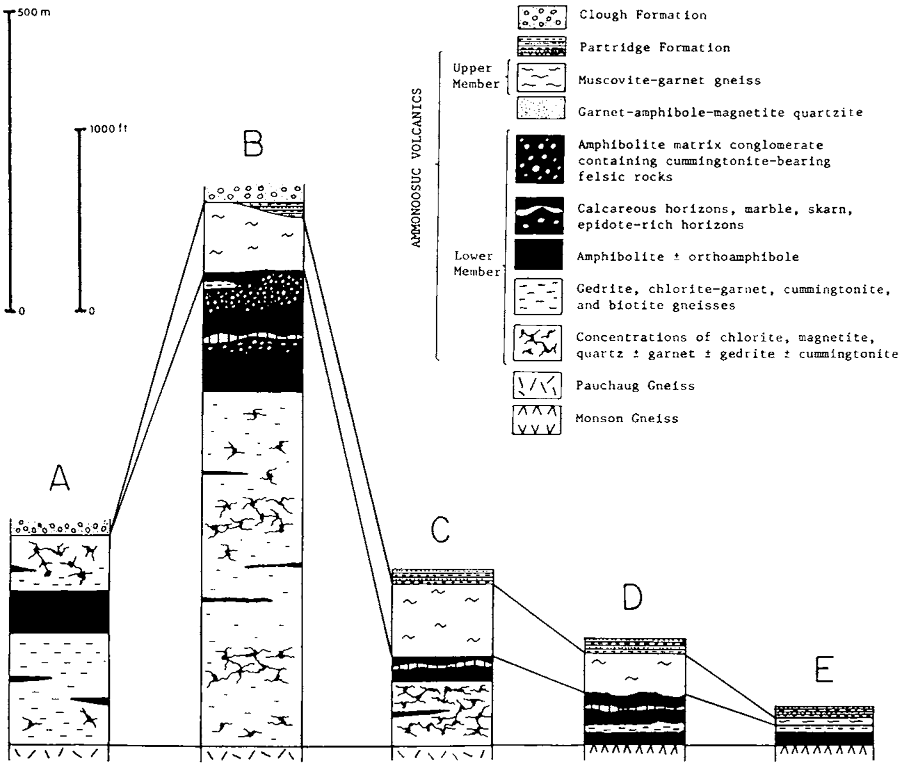


Fig. 6. Generalized stratigraphic colums that compare variations in thickness and dominant lithologic types in the Ammonoosuc Volcanics. Locations of columns A, B, and C are in figure 2; column D in figure 4; column E in figure 5.

or anthophyllite, garnet, magnetite, chlorite, staurolite, kyanite, sillimanite, or biotite. Modes and additional rock descriptions can be found in Robinson (ms, table 4). These rock types are interlayered with amphibolites in variable proportions (see fig. 6). Locally, coarse-grained, brown-weathering gedrite–quartz–plagioclase gneisses are well developed (area of fig. 4).

Concentrations and vein-like networks of chlorite or gedrite with or without garnet, quartz, euhedral magnetite, and pyrite are common textural features within the felsic gneiss. These rocks are referred to here as "patch rock." Locally, chlorite in these rocks appears as retrograde pseudomorphs of gedrite. In localities on the west side of the Warwick gneiss dome the chlorite of the "patches" is intergrown with abundant pyrite, which suggests this texture represents metamorphosed alteration zones in fractures in the original felsic volcanics.

Aluminous schist.—On the west side of the Warwick gneiss dome, near the top of the Lower Member, a unique 16 by 2 m lens of kyanite–muscovite–biotite schist (sample 49) is enclosed by garnet amphibolite. The schist also contains plagioclase, quartz, and minor tourmaline. The outcrop surface appears knobby due to resistant centimeter-sized intergrowths of kyanite and quartz and is distinct in appearance from the garnet-bearing Partridge schist. This schist may represent a metamorphosed weathering horizon or shale lens within the Ammonoosuc Volcanics.

Calcareous rocks.—Locally, around the Warwick gneiss dome (fig. 6B, C) and on the west side of the main body of the Monson Gneiss (fig. 6D) calcareous layers are found near the top of the Lower Member. On the west side of the Warwick gneiss dome a layer up to 20 m thick is traceable for nearly 2 km. Rock types include marble-matrix conglomerate that contains both amphibolite and felsic clasts, hornblende-diopside-biotite marble, idocrase–grossular–diopside–calcite skarn, massive garnet skarn, magnetite–hornblende–garnet–quartz rock, and epidote-rich amphibolite. Where the calcareous layer is thickest, the epidote-rich amphibolite underlies the marble; where thinnest (several meters), it may consist only of epidote-rich amphibolites.

On the east side of the Warwick gneiss dome at Hastings Pond, marble-matrix conglomerate that contains felsic pebbles is found (Robinson, ms). However, these are too thin to map at 1/24000.

Garnet–Amphibole–Magnetite Quartzite Member

This distinctive unit is found discontinuously along the contact between the Lower and Upper Members of the Ammonoosuc Volcanics (Robinson, ms and 1967). It may be up to 6 m thick and has been recognized as a single boudin (0.3 m thick) on Fishers Hill in Orange (fig. 4). This member is most common in the eastern exposures of the Ammonoosuc Volcanics (fig. 1C), around the south end of the Keene gneiss dome (fig. 3), and on the west side of the main body of the Monson Gneiss (fig. 4). The Garnet–Amphibole–Magnetite Quartzite Member has not been recognized on either side of the Warwick gneiss dome. This member was a key factor in interpreting the complicated refolded recumbent fold pattern at the south end of the Keene gneiss dome (fig. 3) and in the area west of the main body of the Monson Gneiss (Robinson 1977 and Robinson, 1967, figs. B-2, B-6 for explanation).

The quartzite commonly contains fine- to medium-grained magnetite and garnet and dull-white weathering apatite-rich layers. In addition cummingtonite, anthophyllite, gedrite, hornblende, epidote, Ca-pyroxene, and calcite are found in different layers. In parts of this unit cummingtonite and anthophyllite (Robinson and Jaffe, 1969b) and garnet (Schumacher, ms) are enriched in MnO. These quartz-rich rocks may be evidence of chemical sedimentation of ferruginous and locally manganiferous cherts that occurred as the chemical character of the volcanism underwent a major change.

Upper Member

The Upper Member as defined here, includes quartz–feldspar–biotite gneisses, muscovite schists and aluminous gneisses, and rare amphibolite. This group of rocks overlies the Garnet–Amphibole–Magnetite Quartzite Member and the Lower Member (figs. 2, 3, 4, and 5), and the lower contact of the Upper Member is defined at the top of the Garnet–Amphibole–Magnetite Quartzite Member where present. Where the Garnet–Amphibole–Magnetite Quartzite Member is not present, the Upper Member-Lower Member contact can be defined by (1) the abrupt change from dominantly mafic rock types to dominantly felsic rock types, or (2) the presence of abundant biotite, garnet, muscovite, sillimanite, and potassium feldspar; the latter three minerals are practically unknown from the Lower Member felsic gneisses.

Quartz-feldspar-biotite gneisses.—These gneisses consist of plagioclase, quartz, and biotite with or without muscovite, garnet, sillimanite, microcline, kyanite, and staurolite (app.). These gneisses are the dominant rock type in the Upper Member on the west side of the Warwick gneiss dome (fig. 2). Rounded quartz grains up to 1 cm in diameter or aggregates of quartz grains commonly found in these rocks may represent original quartz phenocrysts in the felsic volcanics. At Notch Mountain (fig. 2) biotite gneiss contains centimeter-sized quartz-plagioclase inclusions that may represent volcanic bombs deposited in ash. Fine layering may represent original felsic tuffs. These rocks are interpreted as peraluminous dacites and rhyolites.

Muscovite schists and aluminous gneisses.—Muscovite schists consisting chiefly of muscovite with or without quartz, plagioclase, microcline, biotite, garnet, staurolite, kyanite, and sillimanite (app., see also Robinson, ms, table 5) and aluminous gneisses consisting of plagioclase, quartz, and sillimanite with or without microcline, biotite, garnet, staurolite, and kyanite are extensively developed in the Upper Member. Along the east side of the Warwick gneiss dome, at the south end of the Keene gneiss dome (fig. 4), and the west side of the Monson Gneiss (fig. 3), Robinson (ms and 1967) has described felsic gneisses that contain quartz-sillimanite pods (± kyanite in the cores) up to 8 cm in length. These pods could represent metamorphosed concentrations of weathered glass in the original volcanics.

Amphibolites.—The Upper member contains rare amphibolite lenses and boudins that are generally less than 2 by 10 m in size. These consist chiefly of hornblende and plagioclase; locally, plagioclase is nearly lacking (app.). The Upper Member amphibolites could reflect either minor mafic volcanism that accompanied the eruption of the rhyolites and dacites of the Upper Member, or they could represent pieces of Lower Member rocks incorporated in the Upper Member during explosive phases of felsic volcanism.

Contacts with Underlying Formations

The Lower Member overlies both layered gneisses such as the Monson Gneiss of the main and Tully bodies, the Swanzey Gneiss of the Keene dome (fig. 1C), and the Fourmile Gneiss of the Pelham dome and the Kempfield anticline (fig. 5); and massive gneisses such as the Pauchaug Gneiss of the Warwick and Vernon domes (figs. 1C and 2).

The Pauchaug Gneiss of the Warwick dome is poorly foliated, coarse-grained, quartz–plagioclase–biotite gneiss with or without microcline (Robinson, ms and 1967). Part of the weakly-foliated, quartz–plagioclase–biotite gneiss, assigned to the "border facies" of the dome rocks by Hadley (1949) and Balk (1956) on the west side of the Warwick dome, has been reassigned to the Lower Member of the Ammonoosuc Volcanics (fig. 2). Here, some felsic rocks of the Lower Member show a textural resemblance to the Pauchaug Gneiss, but they are assigned to the Ammonoosuc based on the presence of "patch rock" (see discussion of gneisses from the Lower Member) and the occurrence of abundant cummingtonite, garnet, and magnetite. These garnet- and magnetite-rich rocks may represent fossil soil or weathering horizons.

The Monson Gneiss includes (1) interlayered quartz–plagioclase–microcline–biotite gneiss and plagioclase–hornblende–biotite amphibolite, (2) quartz-feldspar gneiss with minor vairation between layers, and (3) weakly foliated quartz-feldspar gneisses of probable intrusive origin (Robinson, ms) (figs. 1C, 4, and 5). The distinction between amphibolite-bearing Monson Gneiss and the Lower Member of the Ammonoosuc can be made through the presence of orthoamphibole, cummingtonite, and chlorite, and large garnets in the Ammonoosuc rock types. In addition, the overall heterogeneity of the Ammonoosuc rock types presents a strong contrast to the mineralgoic monotony of the Monson biotite-feldspar gneiss and hornblende amphibolite.

The nature of the lower contact of the Ammonoosuc Volcanics with the dome rocks is a point of some controversy. Leo (1980, 1985) and Leo, Zartman, and Brookins (1984) have argued that at least some of the contact between the dome gneisses and the Ammonoosuc is a metamorphosed intrusive contact, and this interpretation is largely based on localities showing felsic rocks cross cutting amphibolites and localities showing amphibolites as rafts in felsic gneisses. However, at most of these localities the Ammonoosuc Volcanics have not been mapped in detail and the possible significance of this can be seen in light of recent work. Several kilometers of the Monson-Ammonoosuc contact have been mapped in detail at Quabbin Reservoir (figs. 1C, 4, and 5); this work indicates the contact is sharp, and the Monson rocks do not cut the Ammonoosuc Volcanics (Advanced Mapping Classes, Univ. Massachusetts 1981–1983). Within the Monson Gneiss, Hollocher (1987) describes intrusive relationships involving rock types similar to those cited by Leo (1980, 1985) and Leo, Zartman, and Brookins (1984). These recent developments plus the similarity between some Ammonoosuc and dome rock types suggest that some localities where intrusive relations are reported may warrant reexamination.

Other observations also favor an unconformity at the base of the Ammonoosuc Volcanics. Fe-Mg amphibole-bearing rocks, which are exceedingly common in the Ammonoosuc throughout New England, have not been found as inclusions in any of the gneisses thought to represent intrusive rocks. In addition, Robinson (ms and 1967) noted that the same coherent sequence of Middle Ordovician rocks including the Partridge Formation overlies varied dome rocks rather than homogeneous intrusive units, and he located a basal conglomerate (Moosehorn Conglomerate Member, see above).

The interpretation favored here is that there is an unconformity at the base of the Ammonoosuc Volcanics. In Massachusetts, detailed mapping proved to be a useful and, in places, an indispensable aid to locating the lower contact. Additional mapping, in light of the Ammonoosuc stratigraphy discussed above, is needed and in fact may be crucial to define correctly the lower Ammonoosuc contact in Massachusetts and elsewhere.

Contacts with Overlying Formations

The Ammonoosuc Volcanics are overlain by the Middle Ordovician Partridge Formation and, in places, unconformably overlain by the Silurian Clough Quartzite and the Devonian Littleton Formation. In the area of figure 2 both the Partridge Formation and the Upper Member are cut out by the unconformity at the base of the Clough Quartzite, which cuts as low as the lowest unit of the Lower Member. Robinson (ms) defined the contact of the Partridge Formation as the first occur-

TABLE 1

Major- and trace-element analyses from the Lower Member of the Ammonoosuc Volcanics of mafic rocks believed to have original compositions. Oxides in wt percent and trace elements in ppm

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	46.51	47.07	48.02	48.17	48.38	48.94	49.46	49.47	49.55	49.83	49.84	49.95
TiO_2	1.10	0.75	0.41	1.32	0.86	1.20	0.63	1.61	0.36	1.16	1.44	1.38
Al_2O_3	14.29	15.98	14.70	15.51	16.91	15.26	15.40	17.35	15.97	15.91	17.11	15.56
Fe_2O_3	4.99	10.88	10.31	5.10	3.71	12.53	1.63	10.51	3.31	11.95	10.05	2.01
FeO	8.41			7.31	8.38		8.56		8.03			7.22
MnO	0.34	0.22	0.34	0.21	0.25	0.25	0.18	0.19	0.20	0.24	0.17	0.26
MgO	9.99	7.17	10.59	8.83	10.19	8.98	9.01	6.57	8.98	9.52	6.33	9.33
CaO	12.20	13.53	12.99	9.37	8.27	8.62	12.61	11.79	11.05	8.45	11.41	8.17
Na_2O	1.63	3.38	1.01	3.79	2.39	3.63	1.66	2.29	1.72	3.06	3.19	3.41
K_2O	0.65	0.40	0.18	0.14	0.20	0.18	0.38	0.34	0.15	0.11	0.39	0.17
P_2O_5	0.15	0.11	0.04	0.10	0.08	0.10	0.09	0.20	0.06	0.15	0.16	0.13
Total	99.74	99.49	98.59	99.34	99.25	99.69	99.61	100.30	99.05	100.37	99.68	99.01
Y	19	12	6.3	28	17	22	12	29	7.7	19	28	26
Sr	45	168	97	166	124	153	251	261	153	101	253	100
Rb	7.2	8.3	9.0	1.0	2.8	2.4	5.4	5.2	1.5	0.4	2.9	1.5
Th	2	1	1	0	0	1	1	1	1	1	1	0
Pb	27	29	50	13	6	14	7	6	2	16	6	26
Ga	15	15	14	19	16	17	14	18	15	16	18	16
Nb	2.1	1.4	1.5	10	1.5	1.6	0.7	4.1	0.7	3.0	2.8	3.2
Zr	63	29	22	67	41	63	28	130	12	49	120	80
Zn	482	91	309	99	90	109	78	83	100	100	79	87
Ni	186	46	148	105	98	145	142	50	92	113	43	89
Cr	434	286	790	308	275	365	438	247	418	321	240	278
V	270	352	277	331	252	274	284	232	264	288	222	307
Ba	73	4	27	6	15	18	34	125	0	14	72	17

rence of sulfidic mica schist and noted that the metamorphosed volcanics below this horizon are dominantly felsic, whereas the metamorphosed volcanics of the Partridge include interbedded mafic and felsic types (see Hollocher, 1983 and ms).

In most localities the Clough Quartzite, composed of quartzite and quartz-pebble conglomerate, is easily distinguished from the Ammonoosuc rock types. However, on the east side of the Warwick gneiss dome, Clough Formation rocks can be confused with aluminous gneisses from the Upper Member, which contain quartz-sillimanite pods.

GEOCHEMISTRY

Sixty-four major and trace element analyses of specimens from the Ammonoosuc Volcanics are shown in tables 1 to 5. The collected samples were generally between 1 and 10 kg. Seven of these were supplied by K. T. Hollocher from newly recognized Ammonoosuc localities in the Quabbin Reservoir area. Sample distribution (figs. 1–5) is partly controlled by efforts to obtain fresh and non-retrograded samples. Amphibolites composed of hornblende + plagioclase ± orthoamphibole are the most common mafic rock types and were

TABLE 1

(Continued)

13	14	15	16	17	18	19	20	21	22	23	24
50.36	50.71	50.90	51.70	51.73	51.82	52.61	54.04	55.27	56.04	56.40	58.84
0.60	2.16	2.16	0.37	1.18	0.76	0.80	0.97	1.17	1.18	0.84	0.94
16.43	14.66	14.75	14.86	17.00	15.84	15.99	14.65	13.98	13.58	14.67	14.97
3.26	4.99	8.83	4.08	7.22	2.62	2.33	14.64	4.05	3.87	3.96	4.49
8.05	8.70	5.35	5.89	6.68	7.07	7.11		10.68	9.06	7.03	7.66
0.32	0.38	0.39	0.36	0.36	0.18	0.16	0.22	0.27	0.16	0.34	0.24
9.70	5.33	5.72	9.74	5.85	7.43	5.92	5.38	4.10	4.04	5.92	3.49
8.02	6.56	6.69	7.81	7.41	9.79	8.64	5.59	8.32	6.13	6.99	4.45
2.62	3.60	3.14	3.39	2.98	3.67	3.51	4.07	1.52	4.50	4.31	4.67
0.39	0.13	0.21	0.19	0.12	0.25	0.19	0.09	0.23	0.15	0.34	0.09
0.08	0.19	0.25	0.04	0.05	0.12	0.11	0.09	0.11	0.16	0.19	0.13
99.50	97.41	98.66	96.63	99.86	99.55	97.37	99.72	99.70	98.87	100.99	99.98
13	34	32	7.8	17	15	20	20	20	15	20	27
82	154	140	116	89	236	233	69	267	86	74	101
4.8	1.8	4.3	5.2	2.5	1.3	2.2	0.5	3.3	1.1	18	1.1
2	2	2	2	2	1	2	3	1	2	2	3
14	3	14	13	129	8	12	2	7	12	37	1
21	21	16	20	17	17	16	18	18	18	16	16
1.9	1.7	2.5	1.0	1.2	1.7	0.4	0.5	1.2	2.0	2.9	1.3
28	93	90	19	35	49	46	34	35	38	53	44
415	135	131	246	246	90	34	115	75	122	109	95
60	26	21	7	49	88	32	8	6	10	18	5
200	26	35	260	260	250	55	7	4	17	62	4
312	358	364	256	387	239	216	333	389	535	209	146
20	7	8	7	0	99	76	20	15	1	16	17

TABLE 2

Major- and trace-element analyses of felsic rocks from the Lower Member of the Ammonoosuc Volcanics that are believed to have original compositions. Oxides in wt percent and trace elements in ppm

	25	26	27	28	29	30	31	32	33	34	35	36
SiO_2	65.38	65.66	65.94	66.47	66.87	71.68	73.65	74.29	74.46	74.95	76.85	77.38
TiO_2	0.62	0.50	0.80	0.59	0.64	0.42	0.30	0.31	0.25	0.25	0.23	0.17
Al_2O_3	17.71	14.46	13.64	14.01	12.78	13.01	11.98	11.30	10.56	12.12	11.70	12.44
Fe_2O_3	3.36	6.35	3.92	2.56	6.42	2.13	5.68	5.17	5.22	2.47	2.46	1.95
FeO			6.86	5.12	4.32	3.98		2.07				
MnO	0.01	0.10	0.87	0.27	0.09	0.11	0.07	0.05	0.18	0.11	0.03	0.06
MgO	2.18	3.58	1.31	1.25	1.48	1.06	1.16	1.04	3.24	1.21	1.97	0.50
CaO	4.18	2.34	2.91	5.78	2.54	4.84	1.04	2.42	3.60	1.07	0.41	2.94
Na_2O	4.86	6.40	3.73	3.30	4.92	2.70	5.57	3.79	2.11	4.50	4.32	3.21
K_2O	0.78	0.05	0.35	0.40	0.10	0.07	0.81	0.03	0.05	0.41	1.30	0.89
P_2O_5	0.13	0.11	0.31	0.18	0.23	0.11	0.05	0.07	0.09	0.03	0.06	0.04
Total	99.21	99.55	100.25	99.67	99.75	100.11	100.31	98.47	99.77	99.19	99.33	99.59
Y	12	45	40	47	40	31	31	28	21	36	9.5	13
Sr	192	98	99	52	127	285	73	156	21	57	37	79
Rb	22	0.6	28	9.1	4.0	0.4	44	0.2	1.1	25	38	35
Th	2	3	3	2	2	4	2	3	5	2	2	9
Pb	8	5	5	10	16	5	7	5	5	5	8	20
Ga	16	14	15	19	16	9.7	13	15	14	13	12	12
Nb	2.4	2.5	2.3	3.5	2.3	2.2	2.7	2.3	2.8	2.6	3.1	15
Zr	72	143	107	96	92	82	106	104	115	99	85	68
Zn	60	65	160	121	78	27	29	25	84	18	10	122
Ni	8	17	3	2	3	2	1	3	4	3	4	0
Cr	2	3	1	3	15	2	0	1	0	0	5	3
V	52	17	2.5	27	12	19	10	24	17	9.3	4.6	18
Ba	199	27	67	127	25	14	129	13	20	66	96	249

TABLE 3

Major- and trace-element analyses of mafic rocks (left) and felsic rocks (right) from the Lower Member of the Ammonoosuc Volcanics that are believed to have modified compositions. Oxides in wt percent and trace elements in ppm

	37	38	39	40	41	42	43	44	45	46	47	48	49	50
SiO_2	45.50	47.05	47.79	47.83	48.10	48.25	48.46	55.67	57.06	58.05	65.24	69.84	72.21	81.29
TiO_2	1.38	1.18	0.98	0.97	0.97	1.38	0.58	0.87	0.76	0.50	0.34	0.50	0.14	0.10
Al_2O_3	18.74	15.42	13.60	13.70	15.83	17.52	15.22	17.44	15.93	21.28	16.83	13.91	17.41	11.63
Fe_2O_3	13.71	14.35	13.24	13.11	11.34	12.13	2.29	2.83	2.85	6.30	5.70	5.82	2.72	1.10
FeO							5.74	9.57	10.19			5.97		
MnO	0.31	0.33	0.34	0.25	0.23	0.19	0.26	0.08	0.25	0.18	0.08	0.14	0.03	0.00
MgO	17.43	18.87	18.59	18.88	15.16	18.54	10.69	8.70	8.12	1.93	5.03	3.61	3.75	0.69
CaO	0.80	0.84	3.65	2.56	5.81	0.56	16.59	0.88	2.13	3.33	0.30	0.22	0.64	1.86
Na_2O	1.42	1.13	0.68	0.63	0.91	0.42	0.29	1.12	2.64	7.81	3.41	0.41	0.56	3.63
K_2O	0.14	0.10	0.32	0.12	0.14	0.07	0.20	1.40	0.05	0.41	2.39	0.11	2.04	0.34
P_2O_5	0.07	0.05	0.09	0.09	0.09	0.07	0.12	0.08	0.10	0.09	0.06	0.09	0.03	0.02
Total	99.50	99.32	99.28	98.14	98.28	99.13	100.21	98.64	99.69	99.88	99.38	100.62	99.33	100.66
Y	19	20	16	23	17	39	12	11	18	52	29	34	28	12
Sr	10	11	2.9	13	36	25	140	28	106	176	29	7.6	51	119
Rb	6.6	5.0	9.8	4.5	3.9	4.0	8.6	26	1.4	23	45	4.7	71	13
Th	0	1	0	2	2	1	2	1	3	5	4	3	6	9
Pb	27	23	27	25	57	11	25	45	6	12	9	5	21	11
Ga	21	19	20	16	15	18	15	17	17	21	19	16	22	8.9
Nb	2.0	2.1	1.4	2.2	1.1	3.5	2.1	2.2	2.1	3.9	3.4	3.3	7.3	2.3
Zr	66	58	49	50	41	89	29	37	35	162	114	74	226	127
Zn	928	723	302	185	159	139	158	159	188	86	129	74	130	23
Ni	89	70	476	354	113	47	46	15	15	3	4	4	8	3
Cr	268	215	1073	761	390	203	157	41	63	1.4	1	17	16	2
V	336	328	249	252	198	295	244	315	259	9.0	2	65	18	21
Ba	49	11	197	61	57	0	69	1575	17	69	242	21	210	213

TABLE 4

Major- and trace-element analyses of mafic rocks (left) and felsic rocks (right) from the Upper Member of the Ammonoosuc Volcanics that are believed to have original compositions. Oxides in wt percent and trace elements in ppm

	51	52	53	54	55	56	57	58	59
SiO_2	47.85	67.41	69.29	73.56	73.59	73.80	76.85	76.96	77.30
TiO_2	2.59	0.53	0.34	0.16	0.30	0.27	0.19	0.11	0.19
Al_2O_3	16.53	15.63	15.85	14.93	14.20	13.23	12.55	12.90	12.70
Fe_2O_3	12.74	0.90	1.05	0.22	0.79	0.52	0.38	1.58	0.28
FeO		4.98	2.48	1.50	2.67	2.90	1.51		1.36
MnO	0.27	0.11	0.06	0.06	0.11	0.08	0.04	0.05	0.03
MgO	6.71	1.99	1.12	0.49	0.86	2.69	0.16	0.72	0.10
CaO	11.96	3.53	3.07	2.77	2.41	1.31	1.70	2.11	1.32
Na_2O	1.29	3.03	4.19	2.89	3.62	4.03	4.53	3.44	3.82
K_2O	0.26	1.97	1.53	3.65	1.51	1.64	2.07	1.89	3.37
P_2O_5	0.52	0.12	0.09	0.04	0.10	0.06	0.05	0.03	0.05
Total	100.72	100.07	99.07	100.24	100.08	100.41	99.94	99.79	100.48
Y	34	24	22	15	24	21	10	19	11
Sr	213	79	113	130	100	59	68	73	74
Rb	5.3	50	48	96	42	48	54	60	65
Th	2	4	3	8	4	3	5	8	6
Pb	12	13	2	21	5	10	18	16	26
Ga	25	16	16	12	14	12	11	10	9.7
Nb	2.5	3.9	4.4	5.4	3.1	2.7	3.6	5.3	3.9
Zr	260	90	89	132	81	81	100	85	98
Zn	145	128	29	34	30	54	23	33	41
Ni	71	2	2	5	3	5	2	2	1
Cr	74	14	3	1	14	3	2	2	18
V	257	27	39	7.5	38	21	4.3	3.6	6.3
Ba	18	283	556	546	365	207	478	454	698

considered the most likely to represent original compositions. Rocks composed largely of more exotic minerals, such as gedrite and cordierite, were not extensively sampled. Felsic rocks were collected on the basis of their stratigraphic position. Felsic rocks with large modal proportions of Al-silicates, muscovite, and garnet represent various rock types believed to have non-igneous compositions. Analyses of all trace elements and all major elements (total Fe as Fe_2O_3) except Na_2O and FeO were done by X-ray fluorescence at the Ronald B. Gilmore X-ray Laboratory at the University of Massachusetts. Na_2O was determined both by flame photometry and by XRF. FeO was determined by titration, and Fe_2O_3 was obtained by difference from total ferric iron. Analyses of all trace elements were done on pressed powder pellets, and major elements were done on fused glass discs using procedures modified from those of Norrish and Chappell (1967) and Norrish and Hutton (1969).

The "immobile elements" (Ridley and others, 1974; Pearce and Cann, 1973; Floyd and Winchester, 1978; and Pearce and Norry, 1979) have been widely used in attempts to identify the tectonic setting of metamorphosed volcanic rocks. If metamorphism is isochemical, or, in

TABLE 5

Major- and trace-element analyses of mafic rocks (left) and felsic rocks (right) from the Upper Member of the Ammonoosuc Volcanics that are believed to have modified compositions. Oxides in wt percent and trace elements in ppm

	60	61	62	63	64
SiO_2	71.64	75.72	76.30	78.97	81.71
TiO_2	0.26	0.06	0.06	0.21	0.14
Al_2O_3	16.82	13.68	14.59	12.16	10.43
Fe_2O_3	2.66	1.16	1.11	1.35	1.29
FeO				2.40	
MnO	0.04	0.01	0.01	0.03	0.02
MgO	0.79	2.84	2.26	1.97	0.19
CaO	1.07	0.58	0.39	0.56	2.70
Na_2O	0.82	1.75	0.77	1.43	2.40
K_2O	5.53	3.31	4.07	1.08	1.12
P_2O_5	0.06	0.01	0.01	0.04	0.02
Total	99.67	99.12	99.57	100.07	100.02
Y	22	51	28	14	27
Sr	56	62	44	76	89
Rb	112	86	102	29	32
Th	4	10	9	3	4
Pb	14	13	11	4	7
Ga	17	13	13	11	11
Nb	4.7	7.1	7.8	4.0	4.2
Zr	103	80	98	93	102
Zn	57	32	31	27	90
Ni	5	4	2	0	0
Cr	1	1	1	4	4
V	3.9	1.9	1.3	5.6	0
Ba	1144	817	896	282	176

other words, the proportions of all components except H_2O remain constant, then original and altered igneous rocks ought to be identifiable, even after metamorphism. This is the working assumption in this study. In the Ammonoosuc Volcanics the best evidence for isochemical metamorphism is the preserved chemical heterogeneity. Contacts of layers with highly contrasting composition (amphibolite and quartz-feldspar gneiss) show little or no mineralogical evidence of chemical exchange. Potassium, commonly cited as an extremely mobile element, is highly variable within quartz-feldspar gneisses from essentially the same metamorphic conditions, rather than homogenized, as would be expected, if metamorphism, per se, is affecting the element mobility (see also, Leo, 1985, fig. 10).

The remaining discussion involves: (1) the general geochemical criteria that reinforce the stratigraphic distinction between the Upper Member and the Lower Member, particularly with respect to the felsic rocks, (2) major element variations that can be explained by premetamorphic alteration, and (3) comparison of Ammonoosuc compositions with volcanic rocks from modern tectonic settings.

Original versus Modified Igneous Compositions

General geochemical characteristics.—The processes most likely to have modified the Ammonoosuc Volcanic rocks are: (1) mixing of water-laid volcanic material (ash) with sedimentary material, (2) weathering, (3) low temperature hydrothermal alteration, and (4) high-temperature hydrothermal alteration. Since the only equivalents of chemical and particulate sediments are the carbonate horizons, the garnet quartzite, and the unique schist lens, and these horizons occupy special stratigraphic positions and are either absent or minor constituents of the total section, mixing of volcanic ash and sediments (clay and carbonate) is not likely to have been extensive. Weathering, high- and low-temperature alteration seem to be the most likely processes.

Mafic rocks.—A summary of low-temperature seawater alteration of basaltic rocks (Scott and Hajash, 1976) and an additional study by Andrews (1977) indicate Ca, Mg, and Na are lost by mafic rocks, and K is gained. Several studies of surface weathering of basalt cited by Loughnan (1969) indicate that Ca, Mg, and Na are lost from the rocks, an effect similar to that of low-temperature seawater alteration.

Experimental studies of seawater-basalt interactions at high-temperatures (Bischoff and Dickson, 1975; Mottl, ms; Seyfried and Bischoff, 1981; Seyfried and Mottl, 1982) and studies of ocean floor basalts (Humphris and Thompson, 1978; Mottl, 1983) indicate Ca and K are lost from basalt while Mg is gained. Mottl (1983) states that Ca-Mg exchange is on a mole-for-mole basis. In addition Na can be gained by basalt undergoing high-temperature seawater alteration at water-to-rock ratios less than 10 (see Mottl, 1983, for discussion).

Humphris and Thompson (1978) and Mottl (1983) have used plots of CaO versus MgO (wt percent) to distinguish fresh from high-temperature, hydrothermally-altered basalts. These same oxides, both lost from basalt during weathering and low-temperature seawater alteration, can also be used to identify the effects of these processes.

The behavior of Mg and Ca in the Ammonoosuc Volcanics is shown on a plot (fig. 7) of the atomic proportions of Ca/(1/2 Al-1/2 Na-1/2 K) versus Mg/(1/2 Al-1/2 Na-1/2 K) for analyses with less than 63 wt percent SiO_2 (tables 1, 3, and 5). These analyses are compared with representative ocean-floor and island-arc rocks (Basaltic Volcanism Study Project, 1981) and hydrothermally-altered rocks from the Mid-Atlantic Ridge (Mottl, 1983). This comparison shows only that modern mafic volcanics exist that have similar CaO and MgO contents to the Ammonoosuc Volcanics (filled circles) and that these rocks fall in a region on the diagram described by plagioclase, diopside, orthopyroxene, and olivine. The MgO-rich and CaO-poor Ammonoosuc compositions (filled squares) are like those of hydrothermally altered basalts from the Mid-Atlantic Ridge, and these rocks plot below the plagioclase–(olivine–orthopyroxene) line. These compositions could have been derived by high-temperature seawater alteration that involves one-to-one exchange of Mg in seawater for Ca in basalt.

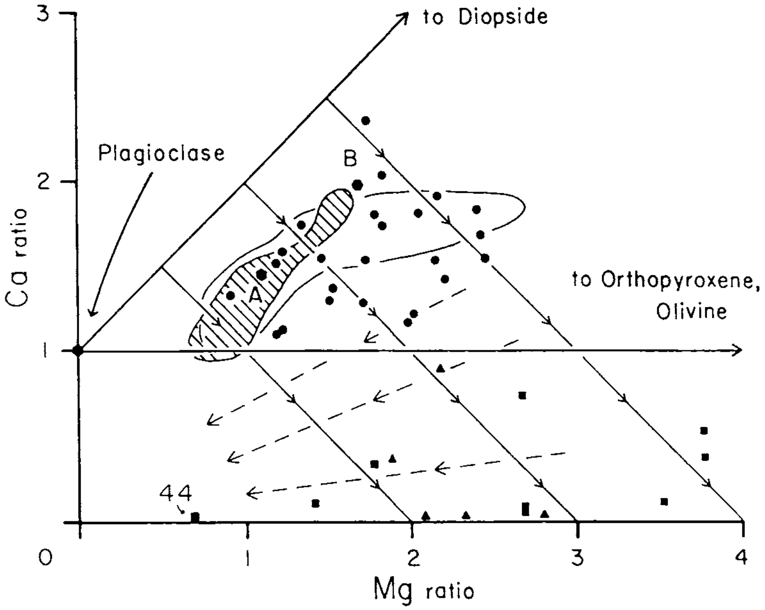


Fig. 7. Plot of the atomic proportions of Ca/((Al-Na-K)/2) (Ca ratio) versus Mg/((Al-Na-K)/2) (Mg ratio). Key: *filled hexagons,* average basalt (B) and andesite (A) (Nockolds, 1954); *filled triangles,* hydrothermally altered ocean ridge material (Mottl, 1983); *area of the closed line,* island arc basalt reference suite and *ruled area,* ocean floor basalt reference suite (Basaltic Volcanism Study Project, 1981); *filled circles,* Ammonoosuc analyses with less than 63 wt percent SiO_2 believed to represent original compositions; *filled squares,* Ammonoosuc samples with less than 63 wt percent SiO_2 believed to be hydrothermally altered. Solid lines with multiple arrowheads show changes in composition due to one-to-one exchange of Mg in seawater for Ca in basalt. Dashed lines show the composition changes due to low-temperature hydrothermal alteration and weathering.

Sample 44 (fig. 7, table 3) is a cordierite-gedrite rock with significant garnet and is an example of the kind of rock whose analysis has characteristics that suggest high-temperature followed by low-temperature seawater alteration. This sample contains low CaO (0.88 wt percent) and relatively high MgO (8.7 wt percent), which is the evidence for the high-temperature hydrothermal alteration. However, other altered rocks with comparable Ca contents have about twice the Mg of sample 44. This lower Mg can be explained by subsequent low-temperature hydrothermal alteration. This is supported by other chemical criteria such as anomalously high K_2O (1.4 wt percent), high Rb (26 ppm), and Pb (45 ppm), which are elements found to increase during low-temperature hydrothermal alteration (Hart, 1969; Thompson, 1973; Scott and Hajash, 1976). The best explanation for the chemistry of sample 44 is that it underwent high-T followed by low-T hydrothermal seawater alteration.

The geochemistry of the hydrothermally-altered and essentially original mafic compositions (fig. 7) is reflected in the upper-amphibolite facies mineralogy, which is directly applicable to field studies. The rocks with unaltered compositions are chiefly hornblende-plagioclase amphibolites. Those that are more Mg-rich also contain subordinate amounts of orthoamphibole or cummingtonite in addition to the plagioclase and hornblende. Rocks with altered compositions all have orthoamphibole (± cordierite) as the dominant mafic phase.

Felsic rocks.—Assessing pre-metamorphic alteration in felsic rocks ($SiO_2 > 63$ wt percent) is more difficult because lower Ca- and Mg-contents make recognition of Mg-Ca exchange harder to detect, although it does occur (Hajash and Chandler, 1981). The generally higher K-contents in felsic rocks reduce the usefulness of this element as an indicator of possible low temperature seawater alteration.

Feldspars plus quartz and/or glass of the same composition are the principal constituents of felsic rocks, and hydrothermal alteration and weathering will act on these components. Alteration processes produce chiefly clay minerals such as illite, kaolinite, and montmorillonite. Illite contains significant K as interlayer cations, kaolinite contains no interlayer cations, and montmorillonite has only minor K, Na, and Ca as interlayer cations. As a consequence, production of clay minerals concentrates Al and decreases Na and Ca in the rock. If illite is produced, K would also increase relative to Ca and Na. Addition of significant amounts of pelitic material would also concentrate Al, which would cause them to plot nearer the origin of figure 8.

The behavior of Na and Ca relative to Al in felsic rocks from the Ammonoosuc Volcanics with SiO_2 greater than 63 wt percent is shown in a plot of 2Ca/(Al-K) versus Na/(Al-K) (fig. 8). Analyses of two felsic rocks and the weathered horizons developed on them (after Goldich, 1938, *in* Loughnan, 1969; after Wahlstrom, 1948, *in* Blatt, Middleton, and Murray, 1972) illustrate the effects of weathering. Rocks that contain only plagioclase-potassium feldspar-quartz plot along the line between anorthite and albite (fig. 8) at the composition of the plagioclase. Analyses with normative corundum (peraluminous) plot to the left of the An-Ab line, and those with normative diopside plot to the right of the line. Most felsic rocks from the Upper and Lower Members are slightly peraluminous and plot near the An-Ab line (fig. 8), which suggests they are almost unaffected by pre-metamorphic weathering or hydrothermal alteration. On the other hand, seven analyses, four from the Upper Member (open squares) and three from the Lower Member (filled squares), plot relatively near the origin of figure 8. Although modification processes cannot be distinguished here, all these samples probably represent modified compositions. In addition two samples, 64 (Upper Member) and 50 (Lower Member), contain more than 80 wt percent SiO_2 and are probably not igneous compositions.

Chemical classification.—Ammonoosuc analyses believed to have original chemistry are classified (fig. 9) according to the K_2O-SiO_2 (wt percent) scheme in the Basaltic Volcanism Study Project (1981) which is

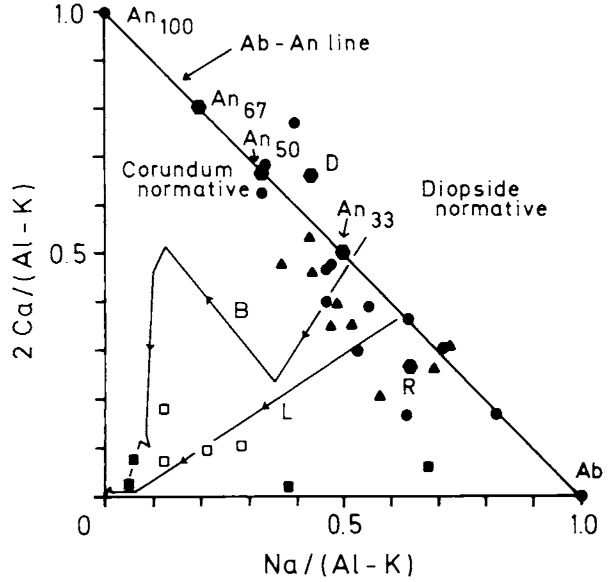


Fig. 8. Plot of 2 Ca/(Al-K) versus Na/(Al-K) (atomic proportions) for analyses of all felsic rocks (greater than 63 wt percent SiO_2) from the Ammonoosuc Volcanics. Key: *filled hexagons with letters*, average dacite (D) and rhyolite (R) (Nockolds, 1954); *filled circles*, Ammonoosuc felsic rocks not believed to be chemically altered; *open squares*, Upper Member felsic rocks believed to be modified; *filled square*, Lower Member felsic rock believed to be modified; *filled triangles*, Upper Member compositions believed to be original; *filled circles*, Lower Member compositions believed to be original. Two lines with multiple arrowheads show compositional changes in weathering profiles developed on granitic rocks from Loughnan (1969) (L) and Blatt, Middleton, and Murry (1972) (B). The Ab-An line represents plagioclase compositions and *filled hexagons with numbers* denote specific plagioclase compositions.

similar to that of Ewart (1979). Analyses of the Lower Member belong to the low-K group of basalts, basaltic andesites, andesites, dacites, and rhyolites. The felsic rocks of the Upper Member are a dacite and rhyolites of normal-K content. In classifications based on alkali and SiO_2 content (for example, Carmichael, Turner, and Verhoogen, 1974, fig. 11-6) the Ammonoosuc analyses skirt the border of tholeiitic/high-alumina field but lie mostly in the tholeiitic field. Analyses of the Lower Member rock types are similar to basalts and dacites reported from the Tonga island arc (Bryan, Stice, and Ewart, 1972; Ewart and Bryan, 1972). The Upper Member felsic rocks resemble some rhyodacites and rhyolites from the Bismarck Archipelago, Papua, New Guinea (Smith and Johnson, 1981).

Chemical Distinction of Lower- and Upper-Member Felsic Rocks

In general, felsic rocks (>63 wt percent SiO_2) of the Upper Member (tables 4 and 5) contain larger amounts of K_2O and Rb than those of the Lower Member (tables 2 and 3). The Upper-Member K_2O

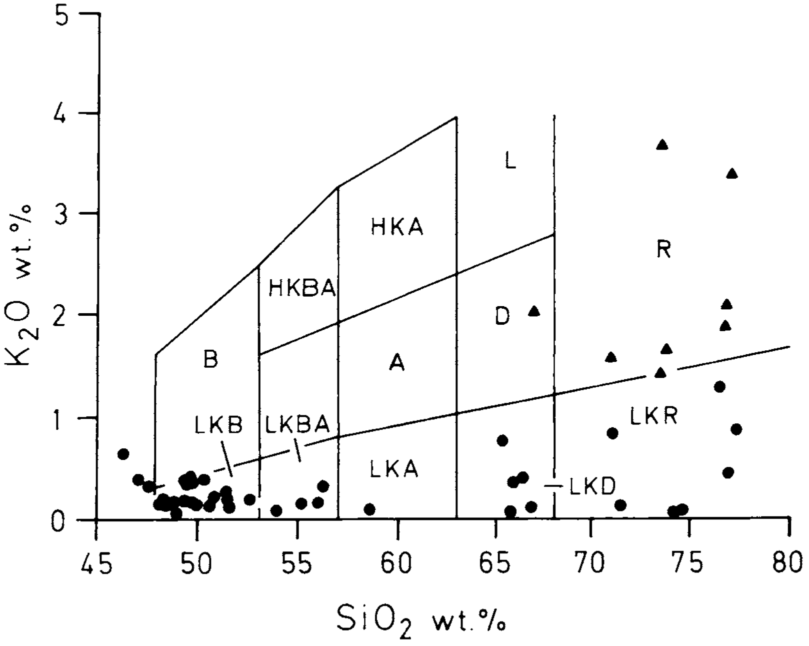


Fig. 9. Plot of K_2O versus SiO_2 for all analyses of the Ammonoosuc Volcanics believed to have original compositions. Key: *filled circles,* mafic rocks and Lower Member felsic rocks; *filled triangles,* Upper Member felsic rocks. Chemical classification scheme is from the Basaltic Volcanism Study Project (1981): LKB = low-K basalt, LKBA = low-K basaltic andesite, LKA = low-K andesite, LKD = low-K dacite, LKR = low-K rhyolite, B = basalt, BA = basaltic andesite, A = andesite, D = dacite, R = rhyolite, HKBA = high-K basaltic andesite, HKA = high-K andesite, L = latite.

contents are greater than 1 wt percent, and only three samples from the Lower Member have values in this range. Two of these high-K_2O rocks (samples 49 and 35) are atypical of the Lower Member. One is from a unique lens of kyanite schist in amphibolite, and the other is a felsic clast formed in a chlorite-rich matrix from near the top of the Lower Member, which may represent a piece of Upper Member rock. In addition the felsic rocks from the Upper Member have a more restricted range of K/Rb ratios (260–440) than felsic rocks of the Lower Member and mafic rocks from both members (200–2280) (fig. 10).

Chemical Comparisons and Genesis

The rest of the discussion relies mostly on the elements believed to be immobile through most non-igneous geological processes. Nevertheless, only those analyses believed to retain original chemistry are used in the subsequent discussion.

Mafic rocks.—Multiple element comparison of the Ammonoosuc basaltic rocks (48–52 wt percent SiO_2) with modern basalts from various

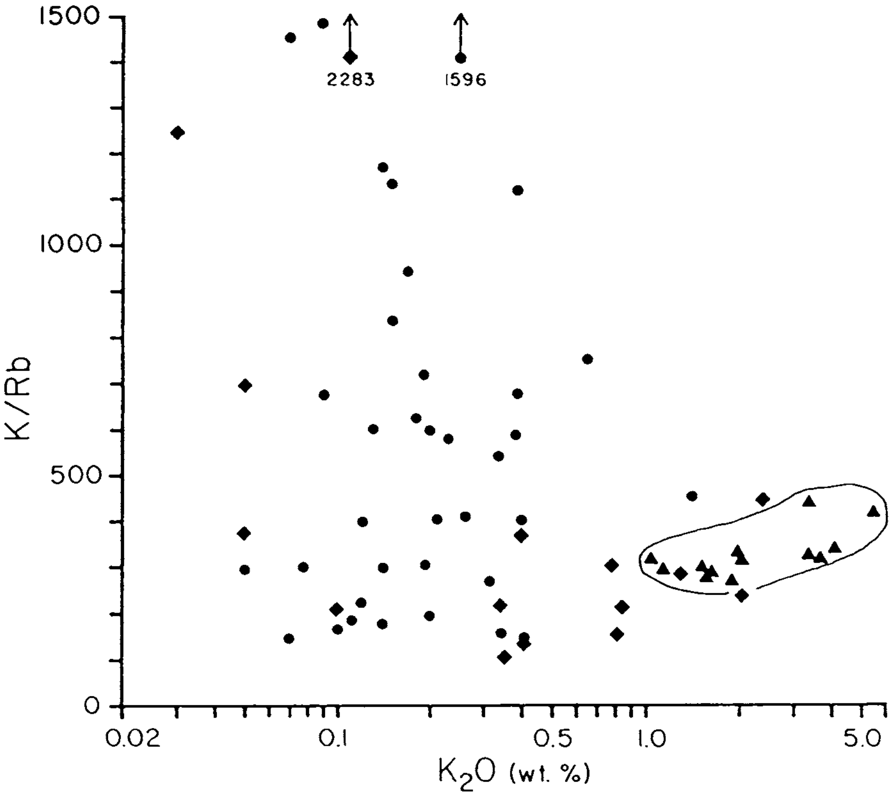


Fig. 10. Plot of K/Rb ratio versus K_2O for all analyses from the Ammonoosuc Volcanics. Key: *filled circles,* mafic rocks from the Upper and Lower Members; *filled diamonds,* felsic rocks from the Lower Member; *filled triangles enclosed by a line,* felsic rocks from the Upper Member.

tectonic settings can be done by using the approach of Sun (1980), in which minor and trace elements are normalized to mantle abundances. Figure 11A gives the range of values and averages of elements (Rb, Ba, Nb, K, Sr, P, Zr, Ti, and Y) in Ammonoosuc rocks (table 1). In figure 11B the average Ammonoosuc values are compared with average enriched (e-MORB) and depleted (d-MORB) mid-ocean ridge basalts (Sun, 1980) and average Hawaiian tholeiite (Basaltic Volcanism Study Project, 1981); in figure 11C the average Ammonoosuc values are compared with average island arc tholeiite (IAT) and averaged high-Al, alkaline, and calc-alkaline basalts from island arcs (Sun, 1980), and average basalt from the New Britain island arc (Basaltic Volcanism Study Project, 1981). The Ammonoosuc samples display the same low trace-element contents and significant depletion of Nb relative to K and other incompatible elements, which are common in the island arc

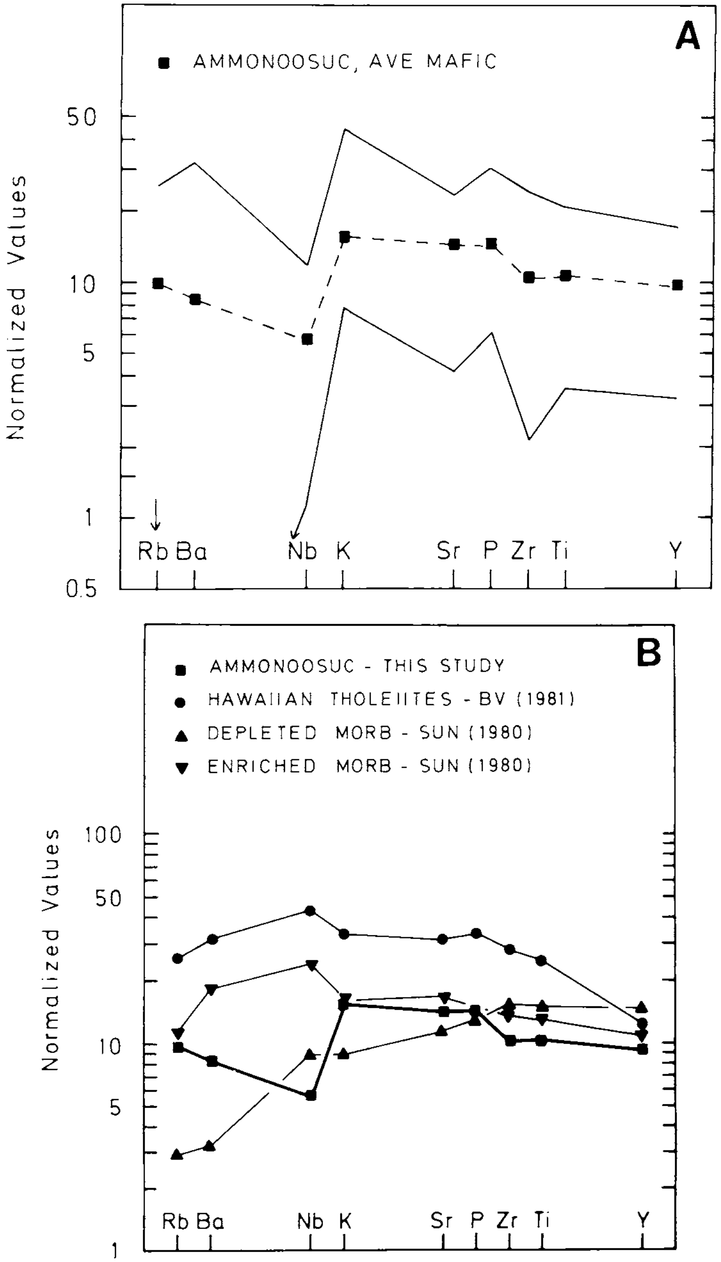


Fig. 11. Mantle normalized element abundances of Rb, Ba, Nb, K, Sr, P, Zr, Ti, and Y. Normalizing factors from Sun (1980). (A) Range (solid lines) and average values (*filled squares*) of basaltic Ammonoosuc rocks (SiO_2 48–52 wt percent) from table 1. (B) Comparison of average Ammonoosuc values with enriched mid-ocean ridge basalt (MORB), depleted MORB (values from Sun, 1980), and average Hawaiian tholeiites (Basaltic Volcanism Study Project, 1981).

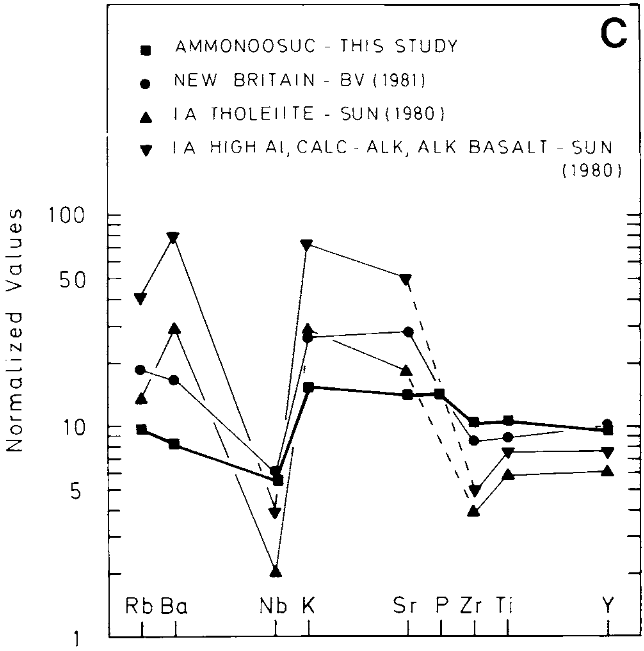


Fig. 11. (continued)
(C) Comparison of average Ammonoosuc values with average island arc tholeiite and the average of combined high-Al, calc-alkaline, and alkali basalts from island arcs (values from Sun, 1980), and average basalt from the New Britain island arc (Basaltic Volcanism Study Project, 1981).

samples (see Thirlwall and Bluck, 1984, fig. 2), but absent in the other basalt types.

Pearce and Norry (1979) used a plot of Zr/Y versus Zr to distinguish "within plate basalts" (WP, that is, ocean island basalts), ocean ridge basalts (ORB), and island arc basalts (IAB) (fig. 12). The Ammonoosuc basalt compositions fall largely within the islant arc field. Taken together, the major, minor, and trace elements are most like island arc basalts, in agreement with reconstruction of their Middle Ordovician tectonic setting (Robinson, 1979; Robinson and Hall, 1980).

The model of island-arc basalt formation suggested by Nicolls and Ringwood (1972), Ringwood (1974, 1975), Green (1980), and Arculus (1981) implies that the Ammonoosuc basaltic rocks would have been generated in the mantle wedge that overlies the subducted plate. The melting is initiated when water is released from the subducted amphibolite (hydrated ocean crust) as it undergoes the transition to eclogite at a depth of about 80 to 100 km.

Pearce and Norry (1979) suggested that variable Zr and Y abundances in island arc basalts can be explained by partial melting of mantle

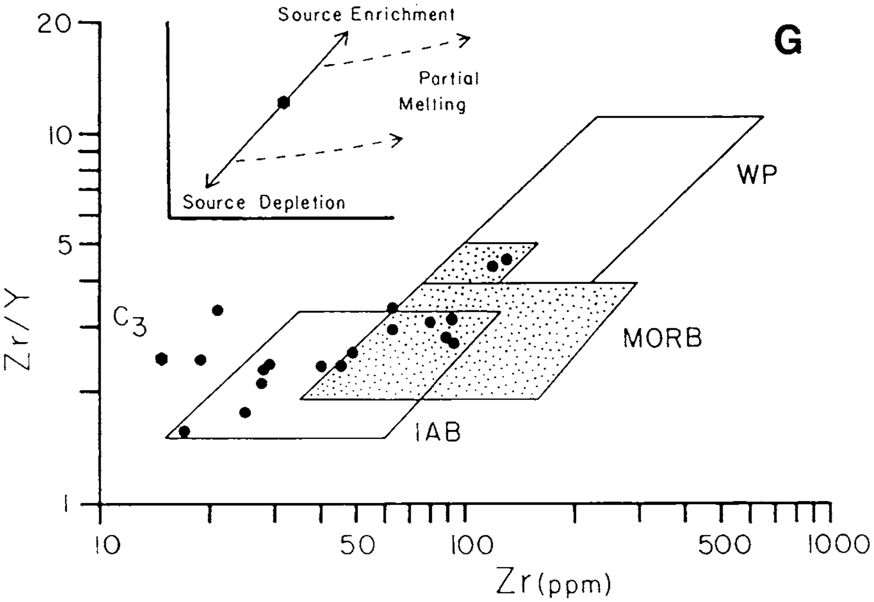


Fig. 12. Zr/Y versus Zr (ppm) diagram that shows composition fields of "within plate basalts" (WP), mid-ocean ridge basalts (MORB), and island arc basalts (IAB) (Pearce and Norry, 1979). Key: *filled circles,* analyses of Lower Member mafic rocks; *filled hexagon,* C3 chondrite composition. Inset shows the effects of source enrichment and depletion and partial melting (see Pearce and Norry, 1979).

which is either depleted or enriched relative to C3 chondrites, followed by fractional crystallization of olivine, clinopyroxene, orthopyroxene, or plagioclase. The Zr and Y values for the Ammonoosuc Volcanics are consistent with melts generated by 20 to 30 percent partial melting of a mantle source nearly as depleted as the source rocks postulated for the Tonga island arc (see Pearce and Norry, 1979, for discussion), which underwent varying degrees of fractional crystallization prior to their emplacement.

Felsic rocks.—Multiple element comparisons for the felsic Ammonoosuc rocks can also be done using the normalization factors of Sun (1980). The range and average values for elements (Rb, Ba, Th, Nb, K, Sr, P, Zr, Ti, and Y) in Ammonoosuc rocks believed to have original compositions are shown for the Upper Member and the Lower Member in figure 13A, B, and C. In the Upper Member rocks the Rb, Ba, Th, and K values are roughly equal and significantly higher than the Nb (fig. 13A). The Lower Member rocks are shown in two groups: (1) type A rocks show a pattern similar to the Upper Member rocks, but with consistently lower values of Rb, Ba, Th, and K, (fig. 13B) and (2) type B rocks have Rb, Ba, and K values roughly equivalent to Nb, while the Th is higher (fig. 13C).

Partial melting of mafic island arc material is one way to generate the element patterns of the rhyolites and dacites of the Ammonoosuc Volcanics. Ryolites from the Bismarck Archipelago, Papua New Guinea, which are considered by Smith and Johnson (1981) to be derived from partial melting of island arc material (fig. 13D) have patterns similar to the Upper Member and type-A Lower Member felsic rocks (fig. 13A and B). In addition experimental melting of basalts at $P_{H_2O} = 5$ kb and T° C = 700 to 1000 by Helz (1976) indicates it is possible to derive liquids with K_2O contents that are very similar to the New Guinea examples and the felsic rocks from the Upper Member of the Ammonoosuc Volcanics.

As a further test of the partial melting hypothesis, calculated element patterns can be compared with the average Ammonoosuc values. The amount of melt and restite mineralogy needed for the calculation is based on the work of Helz (1976). At the conditions of melting the basalts had been converted to amphibolite mineralogy. The partial melts of 18 to 6 percent produced 1.2 to 3.5 wt percent K_2O, respectively, and have variable proportions of hornblende and plagioclase in the residua. For a 6 percent partial melt, hornblende is about 70 percent and plagioclase about 30 percent of the residuum, and for a 18 percent partial melt, hornblende is 95 percent and plagioclase 5 percent of the residuum.

Using the above information two simple batch melting calculations were done. In the first calculation the source was assumed to have the element concentrations given by Sun (1980) for average IAT, and the second used the average element concentrations of the Ammonoosuc basaltic compositions. The 6 and 18 percent partial melts calculated for both sources give good approximations of the observed patterns in the Upper Member (fig. 14A and B). The process of partial melting tends to amplify the relatively high K to low Nb values present in the source. Sr values are quite variable and are highly dependent on the initial Sr content of the source and the amount of plagioclase in the residuum. Neither the Ammonoosuc nor the IAT abundances are perfect source values for the felsic rocks. The most notable deviation is the predicted Ti content, which is much higher than the observed one; however, this discrepancy can be explained, if minor amounts of ilmenite or rutile, which were not considered in the model, were present in the source. Given the uncertainty of source composition, mineralogy and proportions of residuum minerals, mineral-melt partition coefficients, and percentages of partial melt that is generated, as well as possible effects of other processes not considered, the above modeling cannot be expected to explain all element variations. Nevertheless, this simple explanation accounts reasonably well for the element patterns shown by Upper Member felsic rocks and Lower Member type-A rocks (fig. 13A and B).

Despite the similarity in element patterns, differences that argue against a common source for the Upper Member and type-A Lower Member exist. The Upper Member has generally higher values of K, Ba, and Rb than those of the Lower Member, which, if they had a common

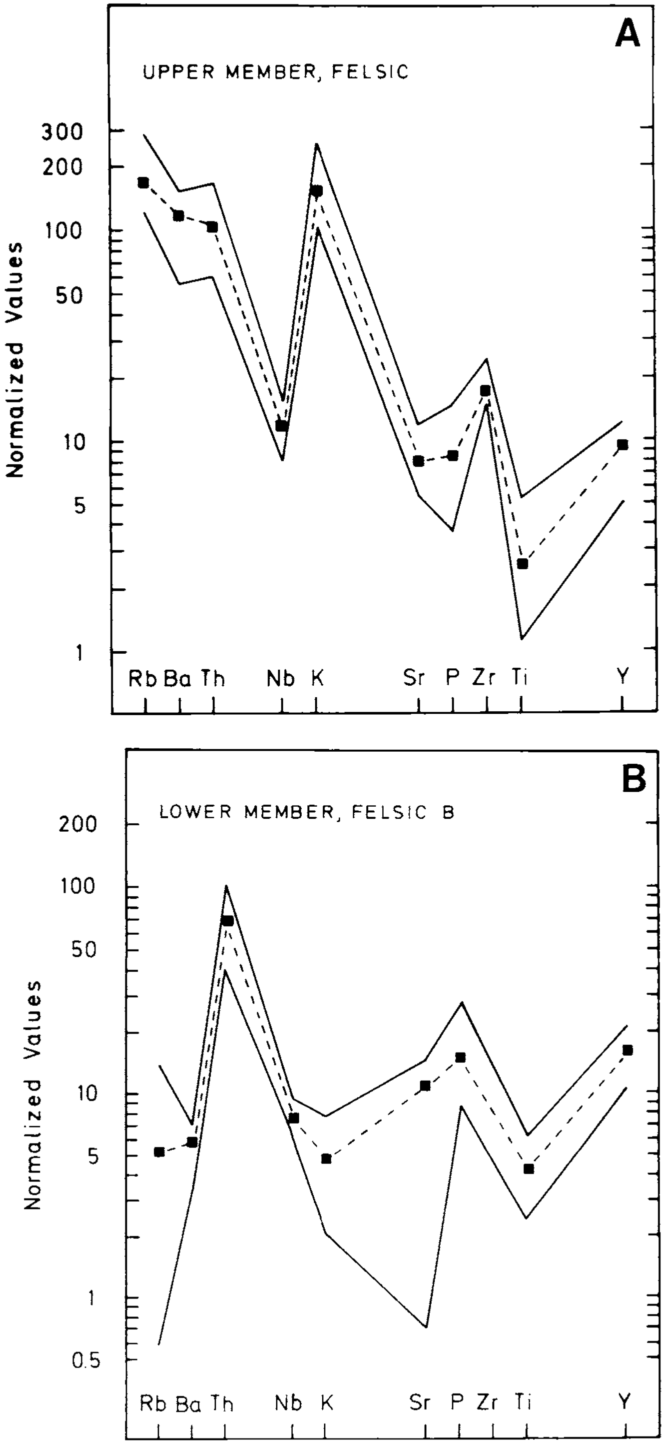


Fig. 13. Mantle normalized element abundances of Rb, Ba, Th, Nb, K, Sr, P, Zr, Ti, and Y. Normalizing factors from Sun (1980). (A) Range (solid lines) and average values (*filled squares*) of Upper Member felsic Ammonoosuc rocks from table 4, nos. 46–53). (B) Range (lighter lines) and average values (*filled squares*) of Type-A Lower Member felsic Ammonoosuc rocks (table 2, nos. 24, 26, 27, 30, 33, 35).

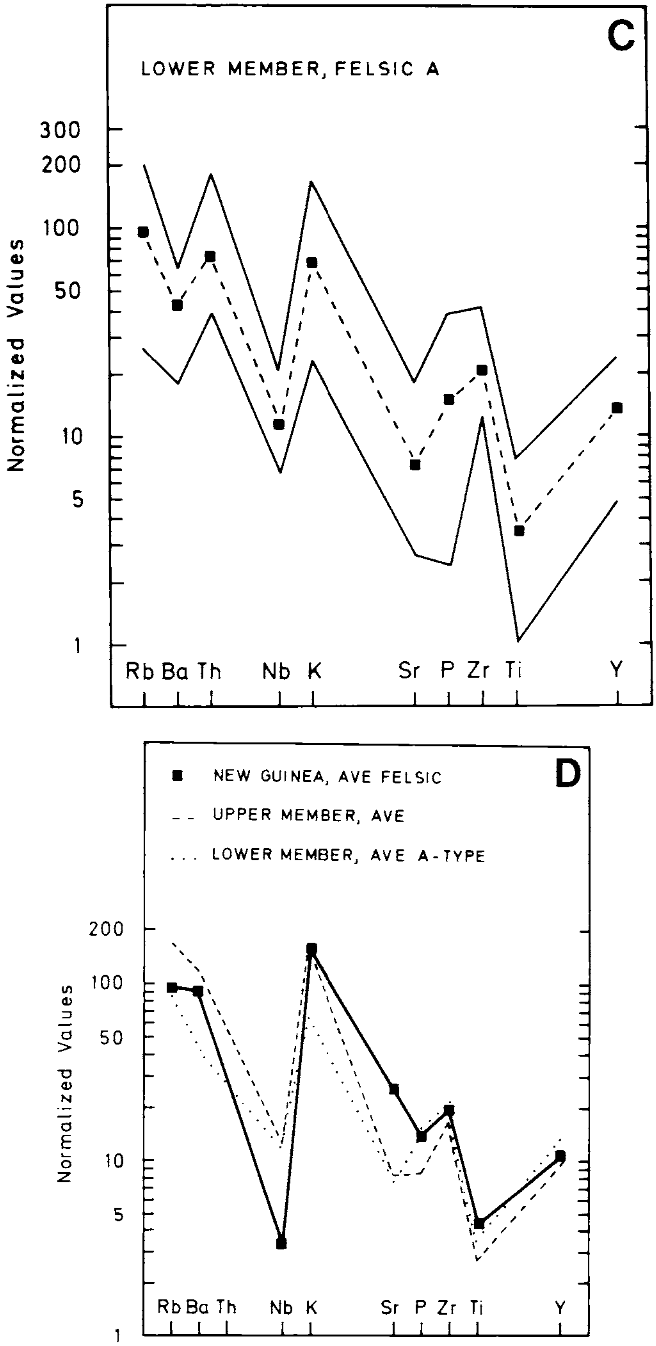


Fig. 13. (continued)
(C) Range (lighter lines) and average values (*filled squares*) of Type-B Lower Member felsic Ammonoosuc rocks (table 2, nos. 25, 28, 29, 31, 32, 34). (D) Range (lighter lines) and average values (*filled squares*) of rhyolites and dacites from the Bismarck Archipelago, Papua, New Guinea (Smith and Johnson, 1981, their table 1, nos. E2/10, F6/3, F7/14, Gs1/7, Gs1/8, Gs3/4.

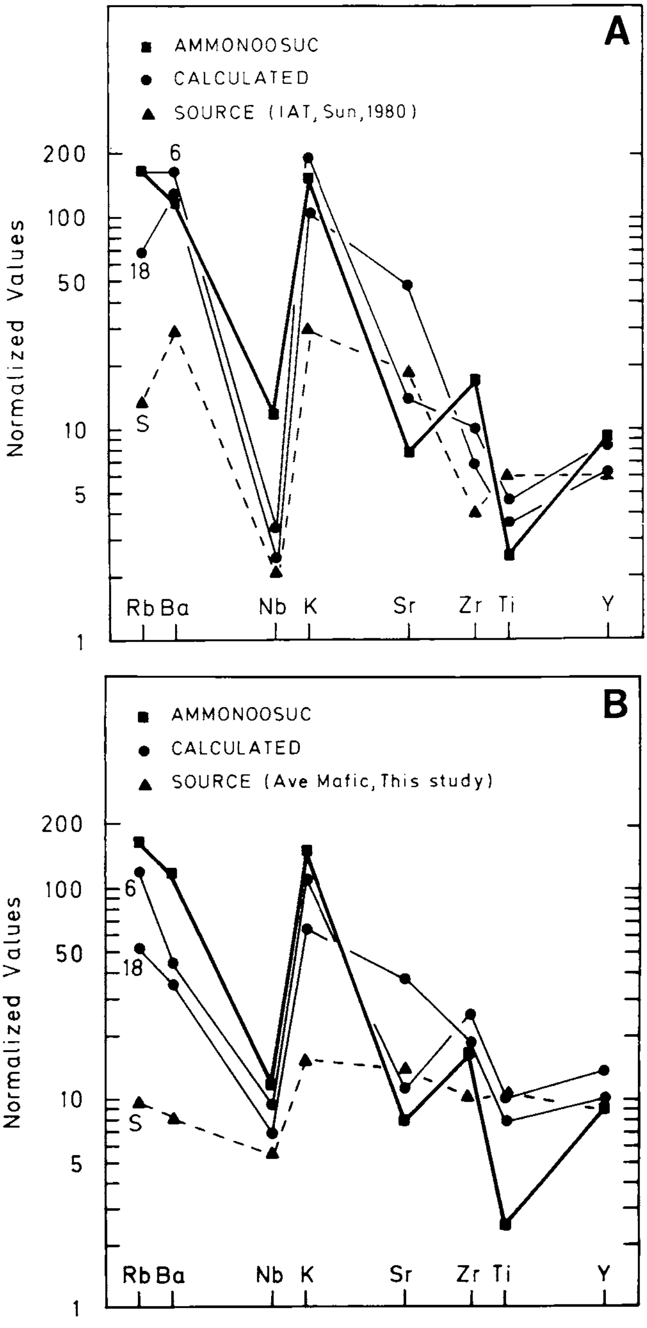


Fig. 14. Comparisons of mantle normlized element abundances of Rb, Ba, Th, Nb, K, Sr, P, Zr, Ti, and Y for calculated melt compositions (*lighter solid lines*) and Upper Member felsic rocks (*heavy solid line*). Normalizing factors from Sun (1980). The 6 and 18 denote element concentrations for these percentages of melt that were removed from a hornblende-plagioclase residuum. Mineral-melt partition coefficients used for hornblende/plagioclase were: Ti, 1.5/0.04; Zr, 0.5/0.01; Y, 1.0/0.03; Nb, 0.8/0.01 (Pearce and Norry, 1979); K, 0.081/0.10; Rb, 0.014/0.041; Sr, 0.022/4.40; Ba, 0.044/0.308 (Arth, 1976). (A) Element concentrations in the source were assumed to be equivalent to the average island arc tholeiite (*filled squares, dashed line*) of Sun (1980). (B) Element concentrations in the source were assumed to be equivalent to the average basaltic Ammonoosuc values (*filled squares, dashed line*).

source, would suggest that the Lower Member was generated by larger percentages of partial melting. The Y concent of the Upper Member rocks should also be greater; however, the reverse is true. This suggests that, although the sources were generally similar, minor differences existed, and that the felsic rocks from the Upper Member and Lower Member were probably not generated by partial melting of the same material.

The type-B Lower Member felsic rocks with extremely low Rb, Ba, and K are problematic. With the exception of the aforementioned three elements, the normalized element concentrations are comparable to type-A Lower Member felsic rocks (fig. 13B and C). If type-B rocks also represent partial melts, then their source must have had much lower values of Rb, Ba, and K. Alternatively, an alteration process that did not affect type-A felsic rocks may have acted on type-B rocks at some point in their complicated history.

Pearce, Harris, and Tindle (1984) suggested that Rb, Ta, Y, and Nb are useful elements for distinguishing granitic rocks from ocean ridges (ORG), volcanic arcs (VAG), within plates (WPG), and areas of plate collision (COLG). Figure 15 compares Rb versus Y + Nb contents

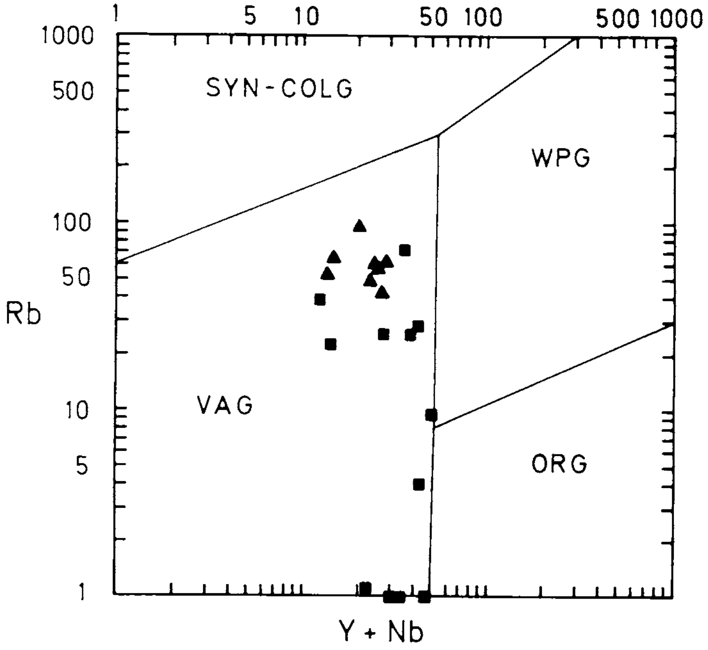


Fig. 15. A Rb-(Y + Nb) discriminant diagram for granitic rocks from various tectonic settings after Pearce, Harris, and Tindle (1984). SYN-COLG = syn-collision granites, VAG = volcanic arc granites, ORG = ocean ridge granites,and WPG = within plate granites. *Filled triangles* are Upper Member felsic rocks, and *filled squares* are Lower Member felsic rocks.

of the Upper Member and Lower Member felsic rocks with the granite fields of Pearce and others (1984). The Ammonoosuc rocks are interpreted to be extrusive rather than intrusive, so they cannot be compared strictly with the data base of Pearce, Harris, and Tindle (1984). Nevertheless, they are likely to represent the chemical equivalents of granites, and they fall within the VAG field (fig. 15). This is consistent with the implications of the immediately preceding discussion, as well as interpretation of the geologic setting and chemical data from the basaltic rocks from the Ammonoosuc Volcanics.

CONCLUSIONS

The internal stratigraphy of the Ammonoosuc Volcanics can be traced and correlated even in complexly deformed terrane. The Lower Member consists of highly-varied and interlayered felsic gneisses and amphibolites. The Upper Member consists chiefly of peraluminous felsic gneisses. Mafic rocks depleted in Ca and enriched in Mg relative to Al can be explained by high-temperature seawater alteration of mafic volcanics that involves one-for-one exchange of Mg in seawater for Ca in the rock. At upper amphibolite grade conditions these rocks have orthoamphibole as the chief mafic phase. Rocks that contain hornblende and minor orthoamphibole/cummingtonite and that are believed to have original basaltic compositions are richer in Mg than those with simple hornblende-plagioclase mineralogy.

Geochemical characteristics of the Ammonoosuc Volcanics support the regional interpretation that these rocks represent an Ordovician island arc. Element patterns for mantle normalized values of Rb, Ba, Nb, K, P, Sr, Zr, Ti, and Y for the Ammonoosuc Volcanics are similar to those of island arc basalts. Significantly, the Ammonoosuc basaltic rocks display the same low Nb to high K normalized values common in recent arc basalts but rare or absent in basalts from other tectonic settings.

Element patterns for mantle normalized values of Rb, Ba, Th, Nb, K, P, Sr, Zr, Ti, and Y for the felsic rocks from the Upper Member and most of the felsic rocks from the Lower Member are similar and can be explained by partial melting of an amphibolite source. The element patterns in the felsic rocks could be generated from a source with element abundances similar to those in island arc basalts. Rb-(Nb + Y) values are also consistent with those of volcanic-arc granites (Pearce, Harris, and Tindle, 1984). Higher K, Rb, and Ba and lower Y in the Upper Member relative to the Lower Member felsic rocks suggest the sources for these stratigraphically distinct rocks were slightly different.

The suggested petrogenesis of these rocks taken together with their relative stratigraphic position has a number of implications for the tectonic setting of the Ammonoosuc Volcanics. By analogy with modern volcanic arcs the genesis of the basaltic rocks seems to require that 80 to 100 km below the Ammonoosuc vents, subducted oceanic crust was dehydrating and releasing water into an overlying mantle wedge. Concurrent with eruption of the basalts, low-K dacitic and rhyolitic rocks formed by partial melting of depleted basaltic material (amphibolite) in the crust (15–20 km?). This phase of volcanism ended and was followed by predominantly dacitic and rhyolitic volcanism. Apparently, these later felsic volcanics were also derived from partial melts of amphibolites under H_2O-rich conditions in the lower crust. The trace-element abundances suggest that the sources of the Upper Member and Lower Member felsic rocks were different.

ACKNOWLEDGMENTS

The author wishes to thank G. W. Leo, J. C. Hepburn, and R. A. Coish for painstakingly thorough critical reviews of this manuscript; views expressed herein may not be entirely embraced by all the reviewers. In addition, I wish to thank S. A. Morse, H. W. Jaffe, J. M. Rhodes, and K. T. Hollocher for many helpful discussions concerning the geochemistry of the Ammonoosuc Volcanics and earlier versions of this manuscript, also R. Schumacher for careful reading of the final draft. The XRF analyses could not have been done without the help of Joel Sparks. Peter Robinson was instrumental in introducing the fine points of Ammonoosuc stratigraphy to the author, and his advice and untiring enthusiasm for New England geology provided much of the impetus for this project. This work is part of a Ph.D. dissertation done in the Department of Geology and Geography at the University of Massachusetts. Valuable assistance in figure preparations was provided by M. Litterer, B. Mader, and B. Mackewic. This work was supported, in part, by NSF Grants EAR-79-11207 and EAR-81-16197 (to Peter Robinson and J. M. Rhodes).

APPENDIX

Descriptions of samples analyzed. Numbers 1 to 64 are used in the text. The field numbers are in parentheses: prefix 'O' = localities from the Orange area, Massachusetts and southwestern New Hampshire and prefix 'Q' = localities from the Quabbin Reservoir area, Massachusetts (Robinson, ms, and unpublished). Localities of Schumacher have no prefix.

Lower Member Specimens with Low-K Basaltic Composition

1-(3B9A) Coarse-grained hornblendite with minor plagioclase and biotite and traces of chlorite, zircon, and apatite.
2-(O-3R9) Medium-grained hornblende-plagioclase amphibolite. Outcrops show possible pillow structure.
3-(1A93) Coarse-grained hornblendite with only minor plagioclase.
4-(O-I34A) Medium-grained hornblende-plagioclase amphibolite.
5-(O-K44BX) Medium-grained hornblende-anthophyllite-plagioclase amphibolite (see Robinson and Jaffe, 1969b, sample K44C).
6-(O-6E6B) Medium-grained hornblende-plagioclase amphibolite.
7-(O-659A) Medium-grained hornblende-plagioclase amphibolite.
8-(O-0S7) Medium-grained hornblende-plagioclase amphibolite.
9-(O-1B7A) Medium-grained hornblende-plagioclase amphibolite that contains minor garnet and traces of sphene and zircon.
10-(O-0S7) Medium-grained hornblende-plagioclase amphibolite.

11-(Q-C27R) Medium-grained hornblende-plagioclase amphibolite.

12-(Q-C27M) Coarse-grained hornblende-gneiss with minor anthophyllite.

13-(O-6A9) Medium-grained hornblende-anthophyllite-plagioclase amphibolite (see Robinson and Jaffe, 1969b).

14-(1A52C) Medium-grained hornblende-plagioclase amphibolite with minor quartz, magnetite, and ilmenite and traces of biotite and zircon.

15-(1A52A) Medium-grained hornblende-plagioclase amphibolite with minor quartz, magnetite, and ilmenite and traces of zircon and chlorite (retrograde).

16-(1A52D) Medium-grained hornblende-plagioclase amphibolite.

17-(O-T59BX) Medium-grained hornblende-plagioclase-anthophyllite amphibolite with minor magnetite (see Robinson and Jaffe, 1969b, sample T59B).

18-(Q-H5) Medium-grained hornblende-plagioclase amphibolite.

19-(O-778) Medium-grained hornblende-plagioclase amphibolite. One centimeter layers vary slightly in horneblende to plagioclase ratio.

Lower Member Specimens with Low-K Basaltic Andesite Composition

20-(Q-6E5A) Medium-grained hornblende-plagioclase-cummingtonite amphibolite with minor quartz and magnetite, and trace of zircon.

21-(Q-795P) Medium-grained hornblende-plagioclase-cummingtonite amphibolite with minor garnet.

22-(O-7A8BX) Medium-grained hornblende-plagioclase-cummingtonite amphibolite with minor quartz and ilmenite. The outcrop shows pillow structures, and the analysis is from the central parts of one pillow (see Robinson and Jaffe, 1969b).

23-(O-X90Y) Medium-grained hornblende-plagioclase amphibolite with minor quartz, magnetite, and biotite.

Lower Member Specimen with Low-K Andesitic Composition

24-(Q-795R) Medium grained feldspathic amphibolite composed chiefly of plagioclase and hornblende with lesser amounts of cummingtonite, quartz, and magnetite.

Lower Member Specimens with Low-K Dacitic Composition

25-(6B2) Medium-grained plagioclase-quartz-cummingtonite-biotite-chlorite gneiss. This sample represents felsic material between chlorite-cummingtonite veins in "patch rock."

26-(O-Y42) Coarse-grained plagioclase-quartz-cummingtonite gneiss associated with "patch rock." See Robinson and Jaffe (1969b).

27-(O-X87Y) Medium-grained plagioclase-quartz-garnet-biotite gneiss with minor hornblende and magnetite and traces of apatite and zircon.

28-(O-X91Y) Medium-grained plagioclase-quartz-garnet-biotite-hornblende gneiss.

29-(1A52E) Medium-grained plagioclase-quartz-hornblende gneiss with magnetite and cummingtonite and traces of biotite and apatite. Retrograde chlorite, sphene, and epidote are also present.

Lower Member Specimens with Low-K Rhyolitic Composition

30-(Q-795N) Medium-grained quartz-plagioclase-hornblende-garnet gneiss with minor magnetite and a trace of zircon.

31-(3B8) Medium-grained plagioclase-quartz-garnet gneiss with minor biotite and magnetite and a trace of pyrite.

32-(1A46B) Medium-grained quartz-platioclase-garnet-magnetite gneiss.

33-(O-0S7) Coarse-grained quartz-plagioclase-gedrite-garnet gneiss.

34-(1A46A) Medium-grained quartz-plagioclase-biotite-chlorite-garnet-magnetite gneiss.

35-(Q-954) Medium-grained plagioclase-quartz-biotite gneiss. Felsic clast in a mafic matrix (see #47).

36-(1A2) Medium-grained quartz-plagioclase-biotite-garnet gneiss with very minor muscovite.

Lower Member Specimens with Modified Composition

37-(O-I34EX) Coarse-grained gedrite-cordierite gneiss with enclaves of staurolite in cordierite (Schumacher, ms; Schumacher and Robinson, 1987). This sample may represent a mafic volcanic altered by high temperature seawater.

38-(O-I34EX) Same as 54 but from a staurolite-free layer.

39-(O-I34DX) Coarse-grained anthophyllite-hornblende gneiss with minor phlogopite and rutile and secondary talc and chlorite. This sample may represent a mafic volcanic altered by high temperature seawater.

40-(O-I34CX) Same as above with greater abundances of hornblende.

41-(O-I34BXY) Coarse-grained anthophyllite-hornblende-plagioclase amphibolite with minor phlogopite and rutile and secondary talc and chlorite. This sample may represent a mafic volcanic altered by high temperature seawater.

42-(O-W95JS) Coarse-grained gedrite-cordierite gneiss with enclaves of aluminous minerals in cordierite (see Robinson and Jaffe, 1969a, b; Schumacher, 1981, ms; Schumacher and Robinson, 1987). This sample may represent a mafic volcanic altered by high temperature seawater.

43-(O-X91Z) Coarse-grained hornblendite with minor zoned zoisite-ferrian zoisite, anorthite, and traces of K-feldspar and apatite. This sample may represent basalt contaminated by carbonate.

44-(O-7A0BX) Coarse-grained gedrite-garnet-cordierite-staurolite-biotite-plagioclase-quartz gneiss with minor kyanite, sillimanite, and ilmenite. See discussion in text.

45-(Q-144X) Coarse-grained gedrite-plagioclase gneiss with minor quartz, and traces of anthophyllite and biotite. This sample may represent basaltic lava altered at high temperature by seawater.

46-(O-W77) Medium-grained plagioclase-chlorite-garnet-pyrrhotite gneiss. This sample is a felsic interior of "patch rock."

47-(Q-954) Medium-grained chlorite gneiss. Specimen is composed of a chlorite-muscovite matrix surrounding clasts (up to 10 cm across) and discontinuous layers of plagioclase-quartz-biotite gneiss. The outcrop is a possible volcanic conglomerate.

48-(Q-544X) Coarse-grained gedrite-staurolite-quartz-garnet-magnetite gneiss with minor plagioclase, cordierite, titano-hematite, and kyanite. This specimen may represent an intermediate volcanic rock altered at high temperature by seawater. Sample contains zoned gedrite of extreme Na and Al content (Schumacher, 1980b).

49-(1B7B) Coarse-grained plagioclase-quartz-biotite-muscovite-kyanite schist with minor tourmaline. This specimen may represent a weathering horizon.

50-(Q-144YA) Medium-grained plagioclase-quartz-garnet-biotite gneiss with minor staurolite, kyanite, and gedrite.

Upper Member Specimen with Basaltic Composition

51-(O-598Y) Medium-grained hornblende-plagioclase amphibolite.

Upper Member Specimen with Dacitic Composition

52-(1B7E) Medium-grained plagioclase-quartz-biotite-muscovite gneiss.

Upper Member Specimens with Rhyolitic Composition

53-(O-2P6) Medium-grained plagioclase-quartz-biotite-muscovite-garnet gneiss.

54-(3B0) Medium-grained plagioclase-quartz-microcline-biotite-muscovite-garnet gneiss.

55-(O-2P7) Medium-grained plagioclase-quartz-biotite-muscovite-garnet gneiss.

56-(2B5) Medium-grained plagioclase-quartz-biotite-garnet gneiss with traces of kyanite and staurolite.

57-(O-778) Medium-grained plagioclase-quartz-microcline-biotite-muscovite-garnet gneiss.

58-(5B0) Medium-grained plagioclase-quartz-biotite-garnet-muscovite gneiss.

59-(O-778) same as 57.

Upper Member Specimens with Modified Composition

60-(O-1S0) Medium-grained plagioclase-quartz-muscovite-sillimanite-biotite gneiss. This specimen may represent a weathered or hydrothermally altered felsic volcanic.

61-(Q-756) Medium-grained muscovite-quartz-plagioclase schist with minor secondary chlorite. This specimen may represent a weathered or hydrothermally altered felsic volcanic.

62-(Q-756) Same as 61.

63-(O-598X) Medium-grained plagioclase-quartz-biotite-sillimanite-garnet gneiss. This specimen may represent a weathered or hydrothermally altered felsic volcanic.

64-(Q-748) Medium-grained plagioclase-quartz-biotite-garnet gneiss. Outcrop shows delicate compositional layering on a scale of 0.5 cm.

REFERENCES

Aleinikoff, J. N., 1977, Petrochemistry and tectonic origin of the Ammonoosuc Volcanics, New Hampshire-Vermont: Geol. Soc. America Bull., v. 88, p. 1546–1552.

Andrews, A. J., 1977, Low temperature fluid alteration of oceanic layer II basalts, DSDP, Leg 37: Canadian Jour. Earth Sci., v. 14, p. 911–926.

Arculus, R. J., 1981, Island arc magmatism in relation to the evolution of the crust and mantle: Teconophysics, v. 75, p. 113–133.

Arth, J. G., 1976, Behavior of trace elements during magmatic processes; a summary of theoretical models and their applications: U. S. Geol. Survey Jour. Research, v. 4, p. 41–47.

Ashenden, D. D., ms, 1973, Stratigraphy and structure, northern portion of the Pelham dome, north-central Massachusetts: M. S. thesis, Univ. Massachusetts Dept. Geology Contr. 16, 132 p.

Balk, Robert, 1956, Bedrock geology of the Northfield Quadrangle, Massachusetts: U. S. Geol. Survey Quad. Map, GQ-92.

Basaltic Volcanism Study Project, 1981, Basaltic volcanism of the terrestrial planets: New York, Pergamon Press, 1286 p.

Billings, M. P., 1937, Regional metamorphism of the Littleton Moosilauke area, New Hampshire: Geol. Soc. America Bull., v. 48, p. 463–566.

——— 1956, The geology of New Hampshire, Part II—bedrock geology: New Hampshire State Plan. and Devel. Comm., 200 p.

Bird, J. M. and Dewey, J. F., 1970, Lithosphere plate: Continental margin tectonics and the evolution of the Appalachian orogen: Geol. Soc. America Bull., v. 81, p. 1031–1060.

Bischoff, J., and Dickson, F. W., 1975, Seawater—basalt interaction at 200° and 500 bars: implications for the origin of sea floor heavy-metal deposits and regulation of seawater chemistry: Earth Planetary Sci. Letters, v. 25, p. 385–397.

Blatt, Harvey, Middleton, Gerald, Murry, Raymond, 1972, Origin of sedimentary rocks, 2d ed.: Englewood Cliffs, N. J., Prentice-Hall, 634 p.

Bryan, W. B., Stice, G. D., and Ewart, A., 1972, Geology, petrography, and geochemistry of the volcanic islands of Tonga: Jour. Geophys. Research, v. 75, p. 1566–1585.

Carmichael, I. S. E., Turner, F. J., and Verhoogen, J., 1974, Igneous Petrology: New York, McGraw-Hill, p. 739.

Ewart A., 1979, A review of the mineralogy and chemistry of Tertiary-Recent dacitic, latitic, rhyolitic, and related salic volcanic rocks, in, Barker, F., ed., Trondhjemites, dacites, and related rocks: Amsterdam, Elsevier, p. 13–121.

Ewart, A., and Bryan, W. B., 1972, Petrography and geochemistry of the igneous rocks from Eua, Tongan Islands: Geol. Soc. America Bull., v. 83, p. 3281–3298.

Field, M. T., ms, 1975, Bedrock geology of the Ware area, central Massachusetts: Ph. D. dissert., Univ. Massachusetts Geology Dept. Contr. 22, 186 p.

Floyd, P. A., and Winchester, J. A., 1978, Identification and discrimination of altered and metamorphosed volcanic rocks using immobile elements: Chem. Geology, v. 21, 291–306.

Goldich, S. S., 1938, A study of rock weathering: Jour. Geology, v. 46, p. 17–58.

Green T. H., 1980, Island arc and continent building magmatism—a review of petrogenetic models based on experimental petrology and geochemistry: Tectonophysics, v. 63, p. 367–385.

Hadley, J. B., 1942, Stratigraphy, structure, and petrology of the Mount Cube area, New Hampshire: Geol. Soc. America Bull., v. 53, p. 113–176.

——— 1949, Bedrock geology of the Mount Grace Quadrangle, Massachusetts: U. S. Geol. Survey Quad. Map.

Hajash, A., and Chandler, G. W., 1981, An experimental investigation of high-temperature interactions between seawater, rhyolite, andesite, basalt, and peridotite: Contr. Mineralogy Petrology, v. 78, p. 240–254.

Hall, L. M., and Robinson, Peter, 1982, Stratigraphic-tectonic subdivisions of southern New England: Geol. Assoc. Canada Spec. Paper 24, p. 15–41.

Hart, S. R., 1969, K, Rb, Cs contents and K/Rb, K/Cs ratios of fresh and altered submarine basalts: Earth Planetary Sci. Letters, v. 6, p. 295–303.

Helz, R. T., 1976, Phase relations of basalts in their melting ranges at P_{H_2O} = 5 Kb. Part II Melt compositions: Jour. Petrology, v. 17, p. 139–193.

Hodgkins, C. E., ms, 1985, Major and trace element geochemistry and petrology of the late Precambrian Dry Hill Gneiss, Pelham dome, central Massachusetts: M. S. thesis, Univ. Massachusetts Dept. Geology Contr. 48, 135 p.

Hollocher, K. T., 1983, Major element geochemistry and possible origin of volcanic rocks in the Middle Ordovician Partridge Formation, central Massachusetts: Geol. Soc. America Abs. with Programs, v. 15, p. 172.

——— ms, 1985, Geochemistry of the metamorphosed volcanic rocks in the Middle Ordovician Partridge Formation and amphibole dehydration reactions in the high-grade metamorphic zones of central Massachusetts: Ph. D. dissert., Univ. Massachusetts Dept. Geology Contr. 56, 275 p.

——— 1987, Petrology ond geochemistry of the Monson Gneiss and related rocks, Bronson Hill anticlinorium, Massachusetts: Geol. Soc. America Abs. with Programs, v. 19, p. 19.

Humphris, S. E., and Thompson, G., 1978, Hydrothermal alteration of oceanic basalts by seawater: Geochim. et Chosmochim. Acta, v. 42, p. 107–125.

Leo, G. W., 1980, Petrology and geochemistry of Oliverian core gneisses: A progress report: Geol. Soc. America Abs. with Programs, v. 12, p. 69.

——— 1985, Trondhjemite and metamorphosed quartz keratophyre tuff of the Ammonoosuc Volcanics (Ordovician), western New Hampshire and adjacent Vermont and Massachusetts: Geol. Soc. Amerca Bull., v. 96, p. 1493–1507

Leo, G. W., Zartman, R. E., and Brookins, D. G., 1984, Glastonbury Gneiss and mantling rocks (a modified Oliverian dome) in south-central Massachusetts and north-central Connecticut: Geochemistry, petrogenesis, and isotopic age: U. S. Geol. Survey Prof. Paper 1295, 47 p.

Loughnan, F. C., 1969, Chemical weathering of silicate minerals: New York, American Elsevier, 154 p.

Lundgren, L., Jr., 1966, The bedrock geology of the Hamburg Quadrangle: Connecticut Geol. and Nat. History Survey Quad. Rept. 19, 41 p.

Lundgren, L., Jr., Ashmead, L. P., and Snyder, G. L., 1971, The bedrock geology of the Moodus and Colchester Quadrangles: Connecticut Geol. and Nat. History Survey Quad. Rept. 27, 24 p.

Moore, G. E., Jr., 1949, Structure and metamorphism of the Keene-Brattleboro area, New Hampshire-Vermont: Geol. Soc. America Bull., v. 60, p. 1613–1669.

Mottl, M. J., ms, 1976, Chemical exchange between seawater and basalt during hydrothermal alteration of oceanic crust: Ph. D. dissert., Harvard Univ., Cambridge, Mass.

——— 1983, Metabasalts, axial hot springs, and the structure of hydrothermal systems at mid-ocean ridges: Geol. Soc. America Bull., v. 94, p. 161–180.

Naylor, R. S., Boone, G. M., Boudette, E. L., Ashenden, D. D., and Robinson, Peter, 1973, Pre-Ordovician rocks in the Bronson Hill and Boundary Mountain anticlinoria, New England, U. S. A.: EOS, v. 54, p. 495.

Nicholls, I. A., and Ringwood, A. E., 1972, Production of silica-saturated tholeiitic magmas in island arcs: Earth Planetary Sci. Letters, v. 17, p. 243–246.

Nockolds, S. R., 1954, Average chemical composition of some igneous rocks: Geol. Soc. America Bull., v. 65, p. 1007–1032.

Norrish, K., and Chappell, B. W., 1967, X-ray fluorescence spectrography, in Zussman, J., ed., Physical methods in determinative mineralogy: New York, Academic Press, p. 161–214.

Norrish, K., and Hutton, J. T., 1969, An accurate X-ray spectrographic method for analysis of a wide range of geologic samples: Geochim. et Cosmochim. Acta, v. 33, p. 431–454.

Pearce, J. A., and Cann, J. R., 1973, Tectonic setting of basic volcanic rocks determined using trace element analyses: Earth Planetary Sci. Letters, v. 19, p. 290–300.

Pearce, J. A., Harris, N. B. W., and, Tindle, A. G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Jour. Petrology, v. 25, p. 956–983.

Pearce, J. A., and Norry, M. J., 1979, Petrographic implications of Ti, Zr, Y, and Nb variations in volcanic rocks: Contr. Mineralogy Petrology, v. 69, p. 33–47.

Peper, J. D., ms, 1966, Stratigraphy and structure of the Monson area, Massachusetts and Connecticut: Ph. D. dissert., Univ. Rochester, New York, 126 p.

——— 1967, Stratigraphy and structure of the Monson area, Massachusetts and Connecticut, *in* Robinson, Peter, and Drake, D. P., eds., New England Intercollegiate Geol. Conf., 59th Annual Mtg., Guidebook: p. 105–113.

Ridley, W. I., Rhodes, J. M., Reid, A. M., Jakes, P., Shih, C., and Bass, M., 1974, Basalts from Leg 6 of the Deep Sea Drilling Project: Jour. Petrology, v. 15, p. 140–159.

Ringwood, A. E., 1974, The petrological evolution of island arc systems: Geol. Soc. London Jour. v. 130, p. 183–204.

——— 1975, Composition and petrology of the earth's mantle: New York, McGraw-Hill, 618 p.

Robinson, Peter, ms, 1963, Gneiss domes of the Orange area, west-central Massachusetts and New Hampshire: Ph. D. dissert., Harvard Univ., Cambridge, Mass. 253 p.

——— 1967, Gneiss domes and recombant folds of the Orange area, west-central Massachusetts, *in* Robinson, Peter and, Drake, D. P., eds. New England Intercollegiate Geol. Conf., 59th Annual Mtg., Guidebook: p. 12–47.

——— 1977, Interim geologic map of the Orange area, Massachusetts and New Hampshire, consisting of the Orange and Mt. Grace Quadrangles and portions of the Northfield, Millers Falls, and Athol Quadrangles: U. S. Geol. Survey Open File Rept. p. 77–788.

——— 1979, Bronson Hill anticlinorium and Merrimack synclinorium in central Massachusetts, in Skehan, J. W., S. J., and Osberg, P. H., eds. The Caledonides in the U. S. A., Geological excursions in the northeast Appalachians: Project 27, Caledonide Orogen 1979: Weston, Mass., Boston College, Dept. Geology-Geophys., p. 126–150.

Robinson, Peter, and Hall, L. M., 1980, Tetonic synthesis of southern New England, in Wones, D. R., ed., Proceedings: The Caledonides in the U. S. A., IGCP Project 27: Caledonide Orogen: Blacksburg, Va.,Virginia Polytech. Ints. and State Univ., p. 73–82.

Robinson, Peter and Jaffe, H. W., 1969a, Aluminous enclaves in gedrite-cordierite gneiss from southwestern New Hampshire: Am. Jour. Sci., v. 267, p. 389–421.

——— 1969b, Chemographic exploration of amphibole assemblages from central Massachusetts and southwestern New Hampshire: Mineralog. Soc. America Spec. Paper 2, p. 251–274.

Robinson, Peter, Tracy, R. J., Hollocher, K. T., and Dietsch, C. W., 1982, High grade Acadian regional metamorphism in south-central Massachusetts, in Joesten, R. A., Quarrier, S. S., eds., Guidebood for Fieldtrips in Connecticut and South-Central Massachusetts: Connecticut Geol. and Nat. History Survey Guidebook 15: p. 289–339.

Rodgers, John, 1970, The tectonics of the Appalachians: New York, Wiley-Intersci., 271 p.

Rumble, Douglas, III, ms, 1969, Stratigraphic, structural, and petrologic studies in the Mount Cube area, New Hampshire: Ph. D. dissert., Harvard Univ., Cambridge, Mass. 105 p.

Schumacher, J. C., 1980a. Detailed stratigraphy of the metamorphosed Middle Ordovician Ammonoosuc Volcanics, Warwick gneiss dome, north-central Massachussets: Geol. Soc. America Abs. with Programs, v. 12, p. 81.

——— 1980b, Gedrite of extreme Al and Na content in the metamorphosed Ammonoosuc Volcanics, sillimanite-staurolite zone, central Massachusetts: Geol. Soc. America with Abs. Programs, v. 12, p. 518.

——— 1981, Preliminary geochemistry of the metamorphosed Ammonoosuc Volcanics, north-central Massachusetts: Geol. Soc. America Abs. with Programs, v. 13, p. 175.

——— 1982, Elemental characteristics of the Middle Ordovician Ammonoosuc Volcanics from central Massachusetts: Geol. Soc. America Abs. with Programs, v. 14, p. 612.

Seyfried, W.E., and Bischoff, J. L., 1981, Experimental seawater-basalt interaction at 300°C and 500 bar: Chemical exchange, secondary mineral formation and implications for the transport of heavy metals: Geochim. et Cosmochim. Acta, v. 45, p. 135–147.

Seyfried, W. E., and Mottl, M. J., 1982, Hydrothermal alteration of basalt by seawater under seawater dominated conditons: Geochim. et Cosmochim. Acta, v. 46, p. 985–1002.

Smith, I. E. M., and Johnson, R. W., 1981, Contrasting rhyolite suites in the late Cenozoic of Papua New Guinea: Jour Geophys. Research, v. 86, p. 10257–10272.

Sun, S.-S., 1980, Lead isotopic study of young volcanic rocks from mid-ocean ridges, ocean island and island arcs: Royal Soc. London Philos. Trans., v. A 297, p. 409–445.

Thirlwall, M. F., and Bluck, B. J., 1984, Sr-Nd isotope and chemical evidence that the Ballantrae 'ophiolite', SW Scotland is polygenetic, *in* Gass, I. G., and others, eds., Ophiolites and oceanic lithosphere: Geol. Soc. London Spec. Pub. 13, p. 215–230.

Thompson, G. A., 1973, A geochemical study of the low-temperature interaction of sea water and oceanic igneous rocks: EOS, v. 54, p. 1015-1018.

Thompson, J. B., Jr., Robinson, Peter, Clifford, T. N., Trask, N. J., Jr., 1968, Nappes and gneiss domes in west-central New England, *in* Zen, E., and others, eds., Studies of Appalachian geology: Northern and Maritime: New York, John Wiley, p. 203-218.

Tracy, R. J., Robinson, Peter, and Thompson, A. B., 1976, Garnet composition and zoning in the determination of temperature and pressure of metamorphism, central Massachusetts: Am. Mineralogist, v. 61, p. 762–776.

Tracy, R. J., Robinson, Peter, and Wolf, R.A., 1984, Metamorphosed ultramafic rocks in the Bronson Hill anticlinorium, central Massachusetts: Am. Jour. Sci., v. 284, p. 530–558.

Tucker, R. D., ms, 1977, Bedrock geology of the Barre area, central Massachusetts: M. S. thesis, Univ. Massachusetts Dept. Geology Contr. 30, 132 p.

Wahlstrom, E. E., 1948, Pre-Fountain and Recent weathering on the Flagstaff Mountain near Boulder, Colorado: Geol. Soc. America Bull., v. 59, p. 1173-1189.

Zartman, R. E., and Leo, G. W., 1981. New radiometric ages of Oliverian core gneisses and contact relationships with the Ammonoosuc Volcanics: Geol. Soc. America Abs. with Programs, v. 13, p. 185.

——— 1985, New radiometric ages on gneisses of the Oliverian domes in New Hampshire and Massachusetts: Am. Jour. Sci., v. 285, p. 267–280.

Zartman, R. E., and Naylor, R. S., 1984, Structural implications of some radiometric ages of igneous rocks in southeastern New England: Geol. Soc. America Bull., v. 95, p. 522–539.