Oliverian Domes, Related Plutonic Rocks, and Mantling Ammonoosuc Volcanics of the Bronson Hill Anticlinorium, New England Appalachians

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1516

Oliverian Domes, Related Plutonic Rocks, and Mantling Ammonoosuc Volcanics of the Bronson Hill Anticlinorium, New England Appalachians

By GERHARD W. LEO

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1516

Major- and trace-element geochemistry of the Oliverian Plutonic Suite (Middle Ordovician to Early Silurian?), associated volcanogenic gneisses, and mantling but chemically distinct Ammonoosuc Volcanics and related trondhjemite is interpreted to indicate a transitional oceanic-continental volcanic arc in west-central New England

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1991

U.S. DEPARTMENT OF THE INTERIOR

MANUEL LUJAN, JR., *Secretary*

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, *Director*

Library of Congress Cataloging in Publication Data

Leo, Gerhard W.
Oliverian domes, related plutonic rocks, and mantling Ammonoosuc Volcanics of the Bronson Hill Anticlinorium, New England Appalachians / by Gerhard W. Leo
p. cm. — (U.S. Geological Survey professional paper ; 1516)
Includes bibliographical references.
Supt. of Docs. no.: I 19.19:1516
1. Intrusions (Geology)—New England Region. 2. Geology, Stratigraphic—Ordovician. 3. Geology, Stratigraphic—Silurian. 4. Geology—New England Region. I. Title. II. Series.
QE611.5.N49L46 1991 551.7′3′0974—dc20 90-4951 CIP

For sale by the Books and Open-File Reports Section, U.S. Geological Survey,
Federal Center, Box 25425, Denver, CO 80225

CONTENTS

ILLUSTRATIONS

TABLES

OLIVERIAN DOMES, RELATED PLUTONIC ROCKS, AND MANTLING AMMONOOSUC VOLCANICS OF THE BRONSON HILL ANTICLINORIUM, NEW ENGLAND APPALACHIANS

By GERHARD W. LEO

ABSTRACT

The Oliverian domes are a series of 18 ellipsoidal structures arranged en echelon along the axis of the Bronson Hill anticlinorium, one of the major structural belts of New England, which trends some 430 km from northern New Hampshire to Long Island Sound. The Bronson Hill anticlinorium also exposes a sequence of Ordovician volcanic rocks and Silurian and Devonian sedimentary rocks whose deformation and metamorphism mainly date from the Acadian orogeny.

The Oliverian domes are cored mostly by plutons of the Oliverian Plutonic Suite of Late Ordovician age (444±8 Ma), which are mostly calc-alkaline granite. The Moody Ledge pluton(s) have yielded a tentative age of 435±3 Ma. Three domes, however, are cored by trondhjemite chemically related to the mantling Ammonoosuc Volcanics and distinct from the Oliverian Plutonic Suite. The Ammonoosuc Volcanics are a bimodal sequence of (1) amphibolite and (2) quartz-plagioclase gneiss and granofels, which reflect former basalt and quartz keratophyre, respectively. Amphibolite and quartz keratophyre are estimated to be about equally abundant.

The hornblende amphibolite phase of the Ammonoosuc Volcanics corresponds to basalt and basaltic andesite (SiO_2 47.0–54.4 percent, K_2O 0.18–2.1 percent). Amphibolites containing Ca-poor amphiboles (anthophyllite, cummingtonite, and (or) gedrite) have a broader compositional spectrum (SiO_2 48.8–64.1 percent, K_2O 0.13–1.5 percent). Trace-element discrimination diagrams in part resemble patterns for island-arc tholeiites and, in part, continental-arc basalt. Rare-earth element (REE) patterns are flat to slightly fractionated and have slight to negligible Eu anomalies. REE patterns for Ammonoosuc quartz keratophyre, trondhjemite, and rocks of the Holts Ledge volcanic sequence mostly show moderately fractionated LREE (light REE) patterns, moderate to pronounced negative Eu anomalies, and flat to slightly enriched HREE (heavy REE) patterns. These similarities reinforce the similar major-element chemistry of the K-poor Ammonoosuc-related rocks and suggest that these rocks are comagmatic, probably having an oceanic-crustal or mantle source.

Oliverian plutons locally intrude the Ammonoosuc at outcrop and map scales, but the contact is indeterminate in other places. Both intrusive and unconformable contacts have been tentatively identified between the Ammonoosuc Volcanics and the underlying Monson Gneiss, a complex unit mostly of volcanic origin and lithologically, structurally, and texturally distinct from the Oliverian Plutonic Suite. Gneisses comparable to the Monson (Fourmile, Swanzey) are widely distributed southward from northern Massachusetts but are absent along the Bronson Hill anticlinorium in New Hampshire.

Attempts to date the Ammonoosuc Volcanics and related plagioclase gneisses have in the past produced ambiguous results, particularly the determination of apparent Early Silurian ages on the Monson, which virtually compelled a younger (Silurian) age for overlying Ammonoosuc Volcanics. More precise recent dating suggests closely confined Late Ordovician ages in the range of 454 to 442 Ma for all these gneisses, at least in northern Massachusetts.

The calc-alkaline group of Oliverian gneisses varies erratically in major-element composition. The composition of gneisses of the Jefferson dome ranges from monzogranite to syenite (SiO_2 58.6–75.7 percent, CaO 0.34–5.7 percent, K_2O 1.3–9.0 percent). These gneisses have similar incompatible (mainly large-ion lithophile) elements, strongly fractionated REE patterns, and small to negligible Eu anomalies. Oliverian plutons in southwestern New Hampshire and northern Massachusetts generally show more homogeneous compositions corresponding to granite-monzogranite (SiO_2 61.9–77.8 percent, CaO 0.44–5.2 percent, K_2O 2.4–5.8 percent); less scatter on normalized diagrams of trace elements, marked by pronounced positive Rb-Th-Ce and negative Ta-Hf peaks; and moderately fractionated LREE patterns, slightly fractionated to unfractionated HREE patterns, and pronounced negative Eu anomalies. The Monson and Swanzey Gneisses, both of probable volcanic origin, are predominantly siliceous (SiO_2 65.1–77.5 percent) but have comparatively low CaO and K_2O contents (CaO 0.81–5.7 percent, K_2O 0.64–2.8 percent). They yield normalized trace-element patterns showing considerable scatter, but, overall, the patterns resemble those of Oliverian granites. REE patterns of the Monson and Swanzey Gneisses are broadly similar to one another and to those of the felsic Ammonoosuc Volcanics.

The Ammonoosuc Volcanics have lower Paleozoic counterparts in Newfoundland. The most plausible modern analog is the Fiji oceanic arc, which has high felsic-mafic ratios and a chemistry similar to that of the Ammonoosuc Volcanics. However, the major features of the Ammonoosuc (bimodal character, low K, and calc-alkaline chemistry) are unlike those of most modern arcs. The Bronson Hill assemblage of plutonic-volcanic rocks is interpreted as originating in an oceanic arc transitional to a convergent continental-margin arc. Early development of this composite arc took place in Middle Ordovician (Taconic) time and was followed by significant crustal shortening during the Late Ordovician and (or) during the Acadian orogeny. Partial melting of adjacent, dominantly continental crust may have produced the coeval Oliverian plutons.

INTRODUCTION

The so-called Oliverian domes are located along the axis of the Bronson Hill anticlinorium, one of the major

Manuscript approved for publication May 22, 1990.

structural features of the Appalachian Mountains in New England. Eighteen domes[1] are distributed en echelon at irregular intervals from northern New Hampshire to Long Island Sound (pl. 1). The sizes of the domes vary from 1.5×1 to 70×20 km. Billings (1937) introduced the name "Oliverian magma series" (after Oliverian Brook in west-central New Hampshire) to designate the granitic rocks in the interiors of the domes. The name was changed to Oliverian Plutonic Suite by Moench (1984). Billings (1937), however, referred to individual domes by geographic names (for example, Owls Head dome). The term "Oliverian dome" was first used by Chapman (1939, 1942), followed by Naylor (1969) and Leo and others (1984), among others. In view of its general acceptance, the term "Oliverian domes" is used here, but with a caveat.

The term **dome**, as used throughout this paper, designates structural features, usually of ellipsoidal outline, that involve both the interior Oliverian gneiss (Oliverian Plutonic Suite) and the mantling Ammonoosuc Volcanics as well as overlying Lower Paleozoic metasedimentary and metavolcanic rocks. The terms **pluton**, **gneiss**, or **granite**, in combination with the dome name, are used to denote the interior, usually granitic and intrusive rocks of the dome—thus, Owls Head dome and Owls Head pluton, gneiss, or granite. The term "Jefferson batholith" was introduced by Moench (1984) and is used here. Terms such as the above are intended to be informal and have a connotation similar to "gneiss of the Owls Head dome," "gneiss near Berlin, N.H.," and so on.

A possible source of confusion, which should be clarified at the outset, is the distinction between pluton and dome in designating any one of these bodies. In practice, these terms are commonly used interchangeably (for example, Lebanon dome, Lebanon pluton), but, in the case of some domes, previous usage gives preference to one or the other (for example, Jefferson dome and Sugar Hill pluton, not the other way around). This paper uses a term denoting intrusion (pluton, batholith) whenever the context requires it—that is, when the gneissic rocks are under discussion. Inasmuch as the Ammonoosuc Volcanics are discussed mainly in a general, petrologic context and not related to specific domes, this paper will, in practice, use **pluton** (or **batholith** in the case of the Jefferson) more commonly than it will use **dome**. Thus, the designation "Owls Head group of plutons" applies to six plutons, including the Owls Head; in a phrase such as "the Ammonoosuc Volcanics of the Owls Head dome," however, the entire dome is implied.

[1] A different total could be arrived at by different interpretations—for example, counting the two Moody Ledge plutons as being related to one dome and (or) regarding the Owls Head and Baker Pond plutons as either one dome or two.

Three small domes (Unity, Alstead, and Vernon) are cored entirely by the Ammonoosuc Volcanics and associated trondhjemite. These domes raise another problem in terminology, since the gneisses are not Oliverian but Ammonoosuc. Finally, gneissic rocks of probable volcanic origin, such as the Monson and Swanzey Gneisses, underlie Ammonoosuc along parts of the Bronson Hill anticlinorium and are structurally analogous to but chemically distinct from the Oliverian plutons. It could be argued that such rocks also are not Oliverian in the strict sense.

The rocks exposed in the cores of most of the Oliverian domes are calc-alkaline granitic gneiss of the Oliverian Plutonic Suite. These gneisses are mantled by and locally intrude the Ammonoosuc Volcanics, a dominantly bimodal, K-poor suite of hornblende-plagioclase-biotite amphibolite and quartz plagioclase granofels representing protoliths of (1) metamorphosed basalt and mafic tuffs and (2) quartz keratophyre tuffs and related trondhjemite, respectively (Leo, 1985). Locally, as in central Massachusetts and southwestern New Hampshire, the Ammonoosuc section is more varied and includes rhyolitic rocks in its upper part (Schumacher, 1988). Recent isotopic age determinations (see below) indicate that the Ammonoosuc Volcanics in northern Massachusetts and environs are not coeval with the Ammonoosuc in western and north-central New Hampshire.

The Bronson Hill anticlinorium was the focus of intense magmatic activity during the latter part of the Ordovician Taconic orogeny. The rocks of the domes appear to be the remnant of a magmatic arc formed during convergence of plates in the ancestral Atlantic (Iapetus) Ocean (Kay, 1951; Thompson and others, 1968; Osberg, 1978; Robinson and Hall, 1980, especially the interpretive cross sections; Hall and Robinson, 1982; Lyons and others, 1982). Several of the Oliverian domes and the Ammonoosuc Volcanics have been studied in some detail (Leo and others, 1984; Leo, 1985; Zartman and Leo, 1985; Webster and Wintsch, 1987; Schumacher, 1988). The main purpose of the present study is to examine critically the geochemistry and petrology of the northern part (mainly north of Massachusetts) of the Bronson Hill anticlinorium in the context of a magmatic arc. In fact, the bimodal and K-poor nature of the Ammonoosuc Volcanics, coupled with their relatively high proportion of felsic rocks, places constraints on any island-arc model and precludes close analogies with modern arcs (Seiders, 1978; Leo, 1985). This problem has additional regional significance because similar lithologies are found throughout the Appalachian chain (Higgins, 1972; Seiders, 1978; Whitney and others, 1978; Malpas, 1979; Payne and Strong, 1979; Southwick, 1979; Pavlides, 1981; Leo and others, 1984). A broad regional synthesis given by Tucker and Robinson (1990) is based primarily on new U-Pb isotopic ages on Ammonoosuc Volcanics and related rocks in northern Massachusetts.

The principal aims of this study were (1) to characterize in some detail the field relationships and petrographic variations of the Oliverian gneisses and of the Oliverian Plutonic Suite and the Ammonoosuc Volcanics, (2) to evaluate the geochemistry and petrogenesis of these rocks, and (3) to attempt to relate this assemblage of Oliverian gneiss and Ammonoosuc Volcanics to current plate tectonic models.

ACKNOWLEDGMENTS

Discussions with a number of individuals, both in the office and in the field, led to my better understanding of the geology of western New Hampshire and central Massachusetts. Chief among these are John Peper, Maurice H. Pease, Jr., Lincoln Page, and Robert E. Zartman (U.S. Geological Survey) and Peter Robinson (University of Massachusetts) and several of his students. Norman L. Hatch, Jr., and Richard Goldsmith (U.S. Geological Survey) reviewed an early draft of the manuscript. Thorough and careful reviews of later versions were provided by J. Wright Horton and David B. Stewart (U.S. Geological Survey); additional reviews, complete or partial, were done by Robert H. Moench (U.S. Geological Survey) and John Lyons (Dartmouth College). To all these colleagues, I am much indebted. I also want to express my sincere appreciation to Kathie R. Fraser (U.S. Geological Survey) for patient and thoroughly professional editorial work; to Leslie S. Weissleader (U.S. Geological Survey) for the excellent graphics; and to Jerry M. Russell (U.S. Geological Survey) for expert help in all phases of cartography, especially plate 1. Any remaining errors or misconceptions are strictly my own.

REGIONAL RELATIONSHIPS

The Bronson Hill anticlinorium shows the following lower to middle Paleozoic stratigraphic and (or) structural succession: (1) quartzofeldspathic granitoid gneisses (the Oliverian Plutonic Suite) and spatially associated Monson and Swanzey Gneisses and related rocks, (2) metamorphosed Middle Ordovician to Lower Silurian sedimentary and volcanic rocks (including the Ammonoosuc Volcanics), and (3) an unconformably overlying sequence of metamorphosed Silurian and Lower Devonian sedimentary and volcanic rocks (pl. 1). Contacts between Oliverian gneisses and the Ammonoosuc Volcanics are crosscutting or indeterminate (Zartman and Leo, 1985; R.H. Moench, written commun., 1988). The metamorphic grade is middle to upper amphibolite facies in most places southeast of the Ammonoosuc fault (pl. 1) and greenschist facies northwest of the fault. The Ammonoosuc fault is interpreted (Moench, 1989) as a normal fault that dropped the low-rank terrane to the west 3 to 5 km relative to the higher rank terrane to the east. The principal movement is thought to have occurred during the opening of the present Atlantic Ocean during Triassic time.

The stratigraphic sequence in the Bronson Hill anticlinorium has been described in detail by Billings (1937, 1956), Robinson (1967), and Thompson and others (1968); structural syntheses have been presented by Robinson and Hall (1980) and Hall and Robinson (1982). Major revisions have been made recently in the stratigraphy and structure of the Sherbrooke-Lewiston area (Moench, 1984; R.H. Moench, unpub. map; Lyons and others, 1986a; Aleinikoff and Moench, 1985, 1987; Moench and Aleinikoff, 1987; Moench, 1989, 1990; Moench and others, 1987). The Glastonbury Gneiss and related rocks have been studied by Leo and others (1984), the Killingworth dome by Webster and Wintsch (1987), and the Ammonoosuc Volcanics by Leo (1985) and Schumacher (1988). Brief summaries of the stratigraphy of the lower Paleozoic rocks, given below, are based mostly on the work of Billings (1956), Thompson and others (1968), and Moench (1989). They are followed by more detailed treatment of the Oliverian Plutonic Suite and the mantling Ammonoosuc Volcanics and related trondhjemite. Figure 1 is a schematic correlation diagram showing the stratigraphic and structural sequence along parts of the Bronson Hill anticlinorium.

ORDOVICIAN FORMATIONS

DEAD RIVER FORMATION (FORMER ALBEE FORMATION)

The Dead River Formation (formerly the Albee Formation) (R.H. Moench, unpub. map; written commun., 1988; Moench, 1989) consists of quartzite, quartz-mica schist and gray mica schist in regions of intermediate- to high-grade metamorphism, and a corresponding variety of phyllites and quartzites at lower metamorphic grades northwest of the Ammonoosuc fault. The Dead River crops out only northwest of the axis of the Bronson Hill anticlinorium, where it is conformably overlain by the Ammonoosuc Volcanics and intruded by Oliverian granite (R.H. Moench, written commun., 1988). The Dead River Formation is exposed in three major north-northeast-trending belts in eastern Vermont and northwestern New Hampshire. Moench (1989) renamed the Albee Formation the Dead River, because the Albee, thought by Billings (1937) to lie conformably beneath the Ammonoosuc Volcanics, is, in fact, in fault contact with the Ammonoosuc Volcanics in its type area on Gardiner

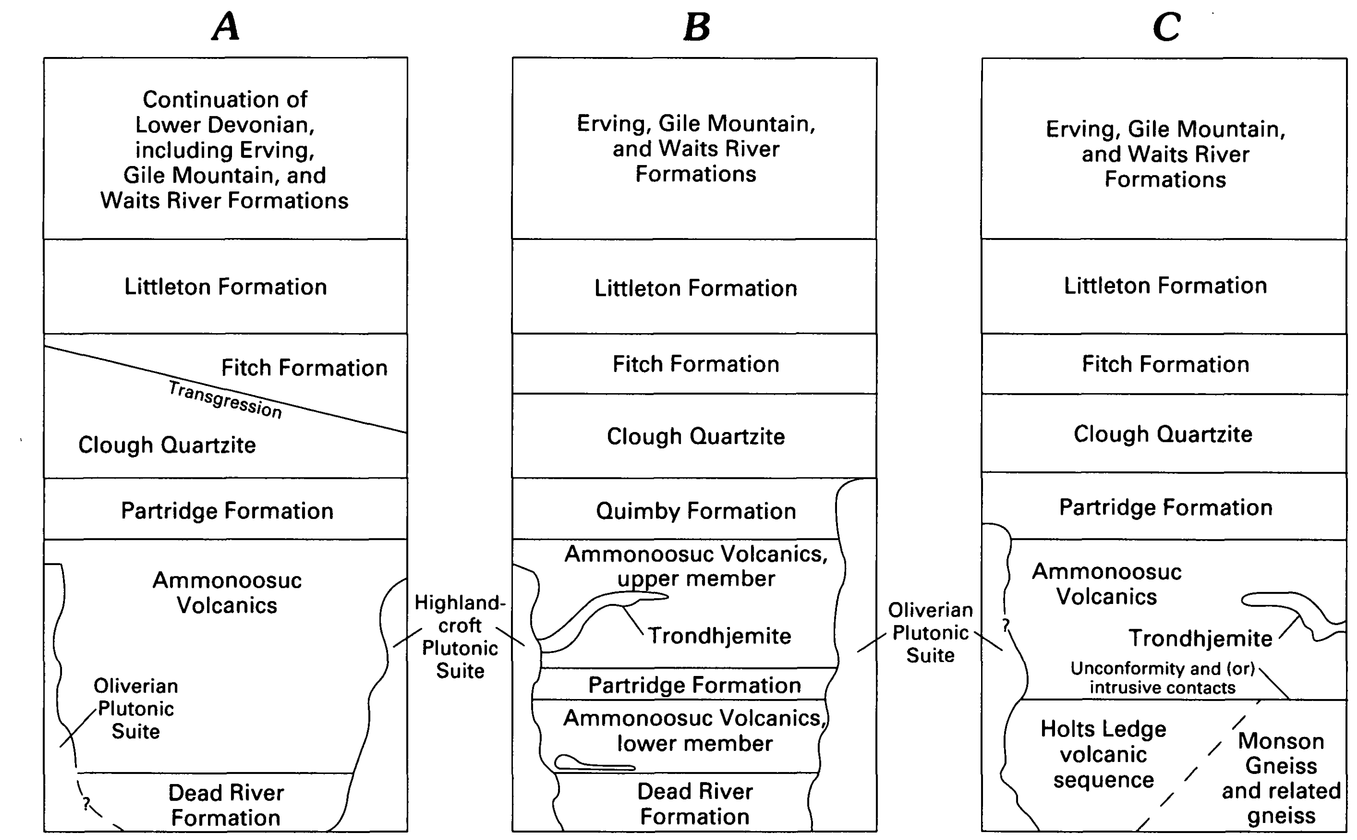


FIGURE 1.—Stratigraphy and structure of the Bronson Hill anticlinorium, New Hampshire and northern Massachusetts. *A*, Littleton area of New Hampshire, on the western side of the Bronson Hill anticlinorium; classic section of Billings (1937, 1956), somewhat modified by Moench (1984) and Moench and others (1987). *B*, Generalized New Hampshire section southeast of the Ammonoosuc fault, revision of Moench (1984), Moench and others (1987), Thompson and others (1968), and this report. *C*, Section in southern New Hampshire and northern Massachusetts showing postulated relationships on the Mascoma dome and possibly the Baker Pond and Warwick domes. The Holts Ledge volcanic sequence (herein renamed) is equivalent to the "stratified core gneiss" of Naylor (1969), the sub-Ammonoosuc quartz keratophyre of Leo (1985), and the Holts Ledge Gneiss of Naylor (1987). The dashed line between the Holts Ledge volcanic sequence and the Monson Gneiss suggests the apparent stratigraphic equivalence of the two units (see text).

Mountain (Billings, 1937) and is part of the Piermont allochthon. The Albee is stratigraphically equivalent to the Dead River Formation in northern New Hampshire and northwestern Maine (Moench, 1989).

ORFORDVILLE FORMATION (ABANDONED)

The Orfordville Formation, named by Hadley (1942), is a group of volcanic rocks and semipelitic, partly rusty schists distributed in western and northern New Hampshire. The name was effectively abandoned by 1968, when it was recognized that the Orfordville was largely or entirely equivalent to the Ammonoosuc Volcanics (Thompson and others, 1968, pl. 15–1A). Spear and Rumble (1986) assigned the Post Pond Volcanics member to the Ammonoosuc Volcanics and the rusty schist to the Partridge Formation, whereas Moench (1989) assigned the rusty schist to the Quimby Formation.

PARTRIDGE FORMATION

The Partridge Formation as mapped by Billings (1937) conformably overlies the Ammonoosuc Volcanics on a gradational contact and has a thickness in New Hampshire of 0 to 600 m (Billings, 1956, p. 19–21). However, as interpreted by Moench and others (1987), the Partridge Formation lies at a low stratigraphic level within the Ammonoosuc Volcanics. The Partridge consists predominantly of mica schist containing graphite and iron sulfides, mostly pyrrhotite. Weathering of the sulfides produces a characteristic "rusty" appearance. The formation also contains subordinate quartzite layers, including coticule (fine-grained quartz-garnet granofels). Mafic and felsic volcanic layers are locally abundant. The Partridge varies greatly in thickness and is lacking on several of the domes. One of its main outcrop areas (not distinguished from the Ammonoosuc Volcanics on pl. 1) is near the Ammonoosuc River between Bath and Littleton, N.H. (pl. 1), and another is south of Claremont in the southwestern part of the State.

QUIMBY FORMATION

The Quimby Formation is a newly mapped unit overlying the Partridge Formation along the axial trace of the Lisbon syncline (Moench, 1989). The Quimby consists of rusty-weathering, black, sulfidic schist and graded beds of metagraywacke.

SILURIAN FORMATIONS

CLOUGH QUARTZITE AND FITCH FORMATION

The Clough Quartzite consists dominantly of white orthoquartzite and stretched quartz-pebble conglomerate containing subordinate polymict conglomerate, micaceous quartzite, mica schist, and calc-silicate rocks. The Clough is 0 to 250 m thick and typically forms conspicuous cliffs, which constitute an excellent marker to decipher the regional structure. The Clough rests unconformably on the Partridge Formation, on the Ammonoosuc Volcanics, and, locally, directly on the Oliverian Plutonic Suite (Thompson and others, 1968). The Clough is locally fossiliferous and has been definitely established as late Early Silurian in age.

The Fitch Formation conformably overlies the Clough Quartzite and consists largely of calc-silicate granofels and biotite-plagioclase granofels. It is locally missing from the section and has a maximum thickness of about 120 m. A recent age determination based on conodonts (Harris and others, 1983) establishes the Fitch as latest Silurian.

DEVONIAN FORMATIONS

LITTLETON FORMATION

The Littleton Formation consists of gray-weathering mica schist or phyllite interlayered with quartzite and calc-silicate beds. Rocks of appropriate bulk composition contain garnet+staurolite. The Littleton is widespread in western and central New Hampshire, although recent stratigraphic revisions by Harris and others (1983) have shown that much of the section previously mapped as Littleton (Billings, 1937, 1956) actually can be correlated with Silurian formations in central and southwestern Maine (Harris and others, 1983). According to this recent work, the estimated thickness of the revised Devonian Littleton Formation in eastern New Hampshire is 1,000+ m, which is substantially thinner than previous estimates of 5,000 m (Billings, 1956, p. 33).

ERVING, GILE MOUNTAIN, AND WAITS RIVER FORMATIONS

The Erving, Gile Mountain, and Waits River Formations (pl. 1), which are not referred to further in this paper, comprise a sequence of quartz-feldspar granofels, mica schist, calcareous schist, and local volcanic rocks. Their main outcrop areas are in northern Massachusetts (Erving Formation) (Robinson, 1963) and eastern Vermont (Gile Mountain and Waits River Formations) (Doll, 1961; Hatch, 1988).

AMMONOOSUC VOLCANICS AND RELATED ROCKS

The Ammonoosuc Volcanics adjacent to the Oliverian plutons in western New Hampshire consist predominantly of two rock types: quartz-plagioclase granofels and hornblende-plagioclase amphibolite (see table 1). The volcanic character of these rocks is generally evident in outcrop, especially in the type area northwest of the Ammonoosuc fault, where the metamorphic grade is low and primary structures are relatively well preserved (Billings, 1937). Examples of volcanic structures include pillow lavas, breccias, agglomerates and conglomerates, and tuffs showing graded bedding and crossbedding. On the southeastern side of the Ammonoosuc fault (pl. 1), the more subtle primary volcanic features have generally been obliterated, but pyroclastic accumulations, mostly distinctly layered and containing clasts up to 30 cm across, are common and well preserved. Where a succession within the Ammonoosuc Volcanics has been identified, the lower part is dominantly mafic and the upper part dominantly felsic (for example, Naylor, 1969; Schumacher, 1988), but the uppermost part is mostly mafic (R.H. Moench, written commun., 1988). Rocks of intermediate composition are relatively scarce, and there is no significant andesitic component. Recent mapping (Moench and Aleinikoff, 1985; Moench, 1989) has resulted in further structural and lithologic subdivision of the Ammonoosuc Volcanics. The relative abundances of mafic and felsic Ammonoosuc, although nowhere accurately determined, are estimated to be about equal.

The mafic Ammonoosuc Volcanics southeast of the Ammonoosuc fault (pl. 1) are mostly hornblende-plagioclase-(biotite) amphibolite. The amphibolites are thoroughly recrystallized and tend to lack relict volcanic features. Although the distinction is clear in some places, it is not always possible to distinguish between tuffs, lava flows, and intrusive rocks. Pillow basalts are locally well preserved, notably on the northwestern side of the Ammonoosuc fault (see Aleinikoff, 1977).

Rocks containing Ca-poor amphiboles, accompanied by hornblende or not, constitute a distinctive but

TABLE 1.—*Summary of characteristics of the Oliverian Plutonic Suite, related gneisses, and the mantling Ammonoosuc Volcanics*

[Kspar, potassium feldspar (refers to microcline, typically in allotriomorphic interstitial grains, with or without quadrille twinning and perthitic structure); plag, plagioclase; qtz, quartz; ep, epidote; biot, biotite; musc, muscovite; hb, hornblende; ti, titanite; mt, magnetite; ged, gedrite; antho, anthophyllite; cum, cummingtonite; gar, garnet; car, carbonate. Numbers in parentheses following "Kspar" are estimated volume percentages; numbers following "plag" are estimated An contents determined optically on a flat stage by using albite-twinned plagioclase. C.I., estimated color index; NA, not applicable]

Name, form, and extent of dome or pluton	Oliverian gneiss phase(s) (includes Monson and Swanzey Gneisses)	Contact relationships between Oliverian phases	Nature of Ammonoosuc Volcanics, including related trondhjemite and the Holts Ledge volcanic sequence	Contact relationships between Oliverian gneiss and the Ammonoosuc Volcanics	Comments
		Jefferson dome and batholith (approximate dimensions of entire dome 70×20 km)			
Berlin, N.H., area ..	Gneiss at Berlin, medium to coarse grained, dominantly pink to gray (C.I. 5–8), plag(An_{17})-qtz-Kspar (15–25)-biot-musc gneiss (granite) carrying abundant pegmatites having sharp to blurred contacts. Equivalent to bqm of Billings and Fowler-Billings (1975) and Billings and others (1946) (see text). Also includes syenite in the Randolph area of New Hampshire to southwest (Foland and Loiselle, 1981; this paper, tables 2, 3, anal. 9). Light-gray (C.I. 8–12), well-foliated qtz-plag (An_{27})-Kspar (3–7)-biot-musc-ep-mt gneiss (quartz diorite-tonalite) and rare pegmatites. Equivalent to qd of Chapman (1949) and to Jefferson dome trondhjemite of Aleinikoff and Moench, (1987).	Quartz diorite gneiss is cut by pink aplitic granite that may or may not be part of main pink to gray granitic gneiss.	Hb-plag amphibolite, ged-antho rocks of mafic to felsic composition and qtz-plag-musc-biot metatuff (quartz keratophyre). Fairly abundant dikes and sills and a small plug of trondhjemite cut the Ammonoosuc Volcanics. Trondhjemite is granular qtz-plag (An_{5-15})±musc±biot±ep±hb±cum granofels. C.I. typically 5 to 10.	Oliverian gneiss cuts Ammonoosuc Volcanics at outcrop scale at various localities, locally at map scale (see also Billings and Fowler-Billings, 1975). The gneiss is cut by northeast-trending amphibolite dikes that may or may not be Ammonoosuc. Oliverian gneiss and trondhjemite are locally adjacent, but their mutual relationship is not clear. Northeast of Berlin in the Milan quadrangle, Oliverian granite cuts Ammonoosuc Volcanics and the Dead River Formation (R.H. Moench, written commun., 1988).	The estimated ratio of mafic to felsic Ammonoosuc Volcanics in the Berlin area is 2:1.
Whitefield, N.H., ... area.	Whitefield gneiss, pinkish gray to dark gray, strongly foliated qtz-plag-Kspar (0–15)-biot-hb-ep-ti gneiss (C.I. 10–25) (granodiorite to quartz monzodiorite). Bray syenite of Arndt (1949): Coarse-grained, porphyritic, gray to pink qtz-Kspar(40)-plag (An_{20-25})-hb-biot-ep-allanite-ti-car gneissic quartz syenite. Several similar medium-grained, pink to gray masses of gneissic granite, including the Scrag, Coarse, and Kimball Hill granites, which are probably comagmatic.	Whitefield gneiss is cut by Bray syenite and (or) other younger Oliverian phases.	Hb-plag amphibolite and biotitic granofels, both probably Ammonoosuc exposed in cuts on New Hampshire Route 116.	Bray syenite cuts Ammonoosuc(?) along New Hampshire Route 116. Whitefield Gneiss may cut Dead River but cannot be shown to cut Ammonoosuc Volcanics.	Plutons of the Highlandcroft Plutonic Suite, approximately contemporaneous with Oliverian plutons, extensively cut the Dead River Formation northwest of the Ammonoosuc fault.
		Owls Head group of plutons			
Four small............ plutons (Sugar Hill, Landaff, and northern and southern Moody Ledge, probably connected at depth).	Fine-grained, pinkish-tan (C.I. 5–10), weakly foliated granite; qtz-plag (An_{5-10})-Kspar (20–25)-biot-musc; allotriomorphic and slightly porphyritic texture. Associated hypabyssal phase is finer grained and has a conspicuous relict volcanic texture marked by a fine-grained recrystallized groundmass and relict quartz and plagioclase phenocrysts, especially noted in the Sugar Hill and northern Moody Ledge plutons.	Plutonic and hypabyssal phases are closely associated and possibly gradational; no sharp or otherwise distinctive contacts observed.	Laminated and sheared-appearing quartz keratophyre occurs in blocks near the northern Sugar Hill pluton contact. Southward is hb-plag-biot amphibolite. Around the Landaff pluton is dominantly amphibolite; local trondhjemite is of uncertain origin. Near the Moody Ledge pluton is characteristic mafic and felsic Ammonoosuc, modified by metasomatism in a zone near the northern pluton.	Granite of the Sugar Hill pluton intrudes mafic Ammonoosuc Volcanics on Ore Hill (see fig. 7) and has a distinct contact zone; iron mineralization adjacent to the contact may be volcanogenic (Annis, 1982). The Landaff pluton contains abundant angular and slabby amphibolite inclusions up to several meters long. The northern Moody Ledge pluton has an irregular contact zone in which the Ammonoosuc contains introduced K-feldspar.	

Name, form, and extent of dome or pluton	Oliverian gneiss phase(s) (includes Monson and Swanzey Gneisses)	Contact relationships between Oliverian phases	Nature of Ammonoosuc Volcanics, including related trondhjemite and the Holts Ledge volcanic sequence	Contact relationships between Oliverian gneiss and the Ammonoosuc Volcanics	Comments
Owls Head group of plutons—Continued					
Owls Head pluton (ellipsoidal outcrop area approximately 8×7 km).	Pinkish-gray (C.I. 7), fine-grained border phase of weakly foliated qtz-plag(An_{10})-Kspar (25–30)-biot-musc gneissic granite. Grades to medium-grained phase of similar composition in pluton interior. Few narrow, sharply bounded aplite dikes.	The described phases appear to be gradational; there is no evidence of crosscutting relationships among the plutonic rocks.	Hb-plag amphibolite, most abundant to the north and east of the Owls Head dome; locally interlayered with sugary-textured quartz keratophyre, which also predominates to the west and southwest of the Owls Head pluton and to the south and southwest of the Baker Pond pluton. Massively layered quartz keratophyre on the southwestern side of the Baker Pond pluton is interpreted as Holts Ledge volcanic sequence.	Extensive metasomatic introduction of Kspar into layered, predominantly felsic Ammonoosuc Volcanics on the western and southwestern sides of the pluton. Maximum width of contact zone about 1 km. Contact against felsic Ammonoosuc on southeastern side is sharp and looks intrusive.	
Baker Pond pluton (subellipsoidal outcrop area approximately 7×4 km; may be southwestern continuation of the Owls Head pluton).	Gray gneissic granite (qtz-plag-(An_{20-29})-Kspar (30)-bio-musc) generally similar to Owls Head granite; grades to more mafic border phase (hb-biot-ep 20–25); local porphyritic phase exhibits scattered K-spar porphyroblasts.	No contacts between the three phases seen.		Distribution of outcrops locally suggests intrusive contacts with Ammonoosuc Volcanics, but actual contacts not observed. No indication of metasomatism.	
Southern New Hampshire and northern Massachusetts domes and associated plutons					
Smarts Mountain dome (elongate outcrop area of granitic pluton(?) approximately 18×3 km. Appalachian Trail area (Mt. Cube summit)).	Light-gray (C.I.<5), fine- to medium-grained, evenly textured and slightly friable granitic rock. Texture is granoblastic, lacks hypidiomorphic appearance of other Oliverian gneisses. Composition qtz-plag (An_{16-20})-Kspar (30–10)-biot-ep-gar. No pegmatites or aplite dikes observed.	NA	Dominantly hb-plag amphibolite.	Applachian Trail area: Fairly sharp contact exposure near Mt. Cube summit but cannot be clearly identified either as intrusive or unconformable.	The lithology of Smarts Mountain is ambiguous relative to that of the other Oliverian domes in that none of the felsic rocks look clearly plutonic and the Pollard Hill sequence appears distinctly clastic. Rocks similar to the northern (Appalachian Trail area) granofels were not observed.
Pollard Hill area	Quartzofeldspathic granofels having relatively coarse and heterogeneous texture; interlayered with hb-plag-(ep)-(qtz) amphibolite.	NA		Felsic granofels and associated amphibolite are interlayered in a manner suggestive of a tuffaceous sequence. Contacts are sharp and parallel to the regional foliation.	

TABLE 1.—*Summary of characteristics of the Oliverian Plutonic Suite, related gneisses, and the mantling Ammonoosuc Volcanics*—Continued

[Kspar, potassium feldspar (refers to microcline, typically in allotriomorphic interstitial grains, with or without quadrille twinning and perthitic structure); plag, plagioclase; qtz, quartz; ep, epidote; biot, biotite; musc, muscovite; hb, hornblende; ti, titanite; mt, magnetite; ged, gedrite; antho, anthophyllite; cum, cummingtonite; gar, garnet; car, carbonate. Numbers in parentheses following "Kspar" are estimated volume percentages; numbers following "plag" are estimated An contents determined optically on a flat stage by using albite-twinned plagioclase. C.I., estimated color index; NA, not applicable]

Name, form, and extent of dome or pluton	Oliverian gneiss phase(s) (includes Monson and Swanzey Gneisses)	Contact relationships between Oliverian phases	Nature of Ammonoosuc Volcanics, including related trondhjemite and the Holts Ledge volcanic sequence	Contact relationships between Oliverian gneiss and the Ammonoosuc Volcanics	Comments
Southern New Hampshire and northern Massachusetts domes and associated plutons—Continued					
Mascoma dome....... (ellipsoidal outcrop area of felsic gneiss measures approximately 29×10 km).	Interior phase (unstratified core gneiss of Naylor (1969): Pink (C.I.~5), medium-grained, weakly foliated granite, qtz-plag (An_{15-20})-Kspar (30)-biot-musc-ep-ti-gar. Some tabular aplite dikes, rare pegmatite.	NA	Holts Ledge volcanic sequence (see text), Ammonoosuc Volcanics: hb-plag amphibolite interlayered with qtz keratophyre tuff (qtz-plag-biot-mt±antho±cum±gar). Holts Ledge volcanic sequence (stratified core gneiss of Naylor (1969)): Contact with the Ammonoosuc Volcanics defined as lowest massive amphibolite layers. Holts Ledge sequence is thickly layered, locally crossbedded qtz-plag±(Kspar)-biot-musc granofels and contains flattened slabs of amphibolite. Similar to felsic Ammonoosuc but slightly coarser grained and containing a small proportion of Kspar that increases downsection.	An intrusive relationship between "unstratified core gneiss" and stratified core gneiss was mapped by Naylor (1969), although the contact was reported to be nowhere exposed.	Estimated ratio of amphibolite to qtz keratophyre in the Holts Ledge section is 5:1. Section at Holts Ledge continues downward to a granular qtz-plag-Kspar rock generally similar to the Smarts Mountain granitic phase.
Lebanon dome........ (ellipsoidal outcrop area of granitic pluton approximately 13×5 km).	Interior phase: Pink to tan (C.I.< 7), medium-grained granitic gneiss (qtz-plag(An_{13})-Kspar (30)-biot-musc. Relict hypidiomorphic texture modified by cataclasis near the Ammonoosuc fault. Shadowy to sharply bounded aplite dikes; pegmatite rare. Border phase: Dark-gray (C.I. 25), well-foliated qtz-plag-Kspar (10–20)-biot-ep granodiorite.	Contact between interior and border phases is gradational.	Ammonoosuc Volcanics comprise interlayered hb-plag-(qtz) amphibolite and qtz-plag-biot-musc-ep-car-schist. Qtz keratophyre, typical elsewhere, is absent. Trondhjemite widely exposed along Interstate 91 northeast of White River Junction, Vt., and also in West Lebanon, N.H., and in the Plainfield area of New Hampshire; shows mutually intrusive contacts with Ammonoosuc amphibolite.	Contact between mafic border gneiss of the Lebanon pluton and the Partridge Formation along Interstate 89 in West Lebanon is sharp and slightly folded but lacks evidence of intrusion (dikes, contact zone, and so on). This contact may be an unconformity or a fault. Similar situation on Lord's Hill (Mascoma 15-min quadrangle) at the northeastern end of the Lebanon pluton.	
Croydon dome........ (ellipsoidal outcrop area of pluton approximately 18×5 km. Dome truncated on southeast by Grantham fault).	Interior phase: Pink (C.I. 5), medium-grained, poorly foliated granite (qtz-plag (An_{25})-Kspar (30)-biot-musc-ep).	NA	Ammonoosuc Volcanics of the region comprise felsic granofels (qtz keratophyre locally containing Ca-poor amphiboles and hb-plag amphibolites. The northeastern end of the Croydon dome consists in part of trondhjemite displaying slabby or tabular inclusions of amphibolite.	No evidence.	Most of the area of the dome is inaccessible, and rocks were seen only in cuts on Interstate 89.

Name, form, and extent of dome or pluton	Oliverian gneiss phase(s) (includes Monson and Swanzey Gneisses)	Contact relationships between Oliverian phases	Nature of Ammonoosuc Volcanics, including related trondhjemite and the Holts Ledge volcanic sequence	Contact relationships between Oliverian gneiss and the Ammonoosuc Volcanics	Comments
Southern New Hampshire and northern Massachusetts domes and associated plutons—Continued					
Unity dome (ellipsoidal outcrop area (of Ammonoosuc) approximately 15×4 km. Interior gneiss is trondhjemite and comprises two plutons or lobes 3 km long (northern) and 8 km long (southern)).	Core gneiss is trondhjemite	NA	Ammonoosuc Volcanics include hb-plag-gar-amphibolite and qtz-plag-ged granofels. The two plutons consist of white to pale-pink (C.I. 8–15), medium-grained, poorly foliated qtz-plag-biot-(musc)-(gar) or qtz-plag-biot-hb-ep trondhjemite. Kspar locally constitutes less than 2 percent but is typically absent.	NA	
Alstead dome (ellipsoidal outcrop area approximately 20×3 km. Two lobes of trondhjemite mantled by layered Ammonoosuc are approximately 3 km long (northern) and 15 km-long (southern)).	Core gneiss is trondhjemite	NA	Ammonoosuc Volcanics include felsic, more or less friable qtz-plag-ged-ep-biot-(musc) granofels and (qtz)-plag-hb-ep amphibolite, commonly interlayered. Gedritic rocks are conspicuous. Trondhjemite is gray, medium-grained qtz-plag (An_{13-24})-biot-musc-ep-(ged)-(cum) gneiss intruding (An_{13-24}) layered Ammonoosuc as dikes and sills (notably in the northern lobe of the dome). In the southern part of the dome, trondhjemite forms more continuous exposures of foliated gneiss, locally hb bearing. Kspar typically nil, locally less than 5 percent.	NA	
Vernon dome (ellipsoidal outcrop area of central pluton approximately 13×5 km).	Core gneiss is trondhjemite	NA	Ammonoosuc Volcanics include hb-plag-amphibolite and qtz-plag-biot-(musc) granofels. The central pluton is light-gray (C.I.<10) to grayish-green, strongly foliated qtz-plag (An_{17-31})-musc-biot-epid-mt trondhjemite. Kspar locally present but lacking in most places.	NA	The Vernon dome is thought to be structurally connected to the Warwick dome to the south (P. Robinson, oral commun., 1982).

TABLE 1.—*Summary of characteristics of the Oliverian Plutonic Suite, related gneisses, and the mantling Ammonoosuc Volcanics*—Continued

[Kspar, potassium feldspar (refers to microcline, typically in allotriomorphic interstitial grains, with or without quadrille twinning and perthitic structure); plag, plagioclase; qtz, quartz; ep, epidote; biot, biotite; musc, muscovite; hb, hornblende; ti, titanite; mt, magnetite; ged, gedrite; antho, anthophyllite; cum, cummingtonite; gar, garnet; car, carbonate. Numbers in parentheses following "Kspar" are estimated volume percentages; numbers following "plag" are estimated An contents determined optically on a flat stage by using albite-twinned plagioclase. C.I., estimated color index; NA, not applicable]

Name, form, and extent of dome or pluton	Oliverian gneiss phase(s) (includes Monson and Swanzey Gneisses)	Contact relationships between Oliverian phases	Nature of Ammonoosuc Volcanics, including related trondhjemite and the Holts Ledge volcanic sequence	Contact relationships between Oliverian gneiss and the Ammonoosuc Volcanics	Comments
Southern New Hampshire and northern Massachusetts domes and associated plutons—Continued					
Warwick dome (ellipsoidal outcrop area of granitic pluton (Pauchaug Gneiss) approximately 20×6 km)).	Coarser grained, more potassic phase: Medium-grained, light-gray to pink (C.I. 6), foliated qtz-plag (An_{22})-Kspar (15–20) biot-musc-ep(3) gneiss (granodiorite). Border phase: Similar but finer grained, less Kspar (6) and more epidote (5).	Coarser phase appears to grade to border phase.	Ammonoosuc Volcanics in the region constitute a diversified lithology including amphibolites, semipelitic rocks, calcareous rocks including carbonate matrix conglomerate, gedrite- and anthophyllite-bearing rocks, and an upper sequence of Kspar-bearing metarhyolites (Schumacher, 1988). Trondhjemite is locally developed in the northern part of the dome; its relationship to layered Ammonoosuc is uncertain.	Layered Ammonoosuc Volcanics are considered to overlie Pauchaug Gneiss unconformably; part of border facies of Pauchaug has been assigned to lower Ammonoosuc (Schumacher, 1988).	The more diversified lithology of the Ammonoosuc Volcanics in Massachusetts in comparison with that farther north is notable but not fully understood. The unconformable Ammonoosuc-Monson contacts are distinct from intrusive contacts such as those in the Owls Head, Sugar Hill, and Jefferson domes. See text discussion.
Swanzey Gneiss (irregular outcrop area of gneiss approximately 34×12 km).	Medium-grained, moderately to strongly foliated (locally swirled foliation), light-gray qtz-plag-Kspar (0–10)-biot-hb granodiorite to tonalite. Locally shows some lithologic layering but is more commonly homogeneous in composition.	NA	Except for isolated amphibolite inclusions(?) (see next column), the Ammonoosuc Volcanics on the Keene dome were not studied.	Angular amphibolite slabs at Surrey Mountain dam have been interpreted as Ammonoosuc Volcanics (Moore, 1949a), but they are difficult to reach, and their nature has not been confirmed. A sharp contact between mafic Ammonoosuc and Swanzey Gneiss in a roadcut on New Hampshire Route 12, 8 km southeast of Keene, N.H., shows no convincing intrusive characteristics and may be an unconformity.	Observations are predominantly from eastern part of dome (east of the Connecticut Valley border fault). Because of the pervasive compositional and structural differences between Oliverian plutons and the Swanzey Gneiss (see text), the latter is not regarded as equivalent to the typical Oliverian domes.

Name, form, and extent of dome or pluton	Oliverian gneiss phase(s) (includes Monson and Swanzey Gneisses)	Contact relationships between Oliverian phases	Nature of Ammonoosuc Volcanics, including related trondhjemite and the Holts Ledge volcanic sequence	Contact relationships between Oliverian gneiss and the Ammonoosuc Volcanics	Comments
			Southern New Hampshire and northern Massachusetts domes and associated plutons—Continued		
Monson Gneiss .... (long, narrow bodies forming domes or parts of domes approximately from the Massachusetts-New Hampshire border to Long Island Sound, terminating in the Killingworth dome (Webster and Wintsch, 1987)).	Light- to dark-gray, medium- to coarse-grained qtz-plag (An_{20-37})-Kspar (0–10)-biot±hb±gar±ep gneiss. Typically shows some degree of layering, whether primary or transposed; however, is locally massive. Tabular gradational or sharply bounded amphibolite dikes(?) are locally abundant.	NA	See Warwick dome	Ammonoosuc Volcanics are widely distributed over Monson Gneiss. An unconformable contact has been interpreted as intermittently exposed over hundreds of meters (horizontally in the Quabbin Reservoir area of Massachusetts, notably on the Prescott Peninsula (P. Robinson, oral commun., 1985). The lowermost felsic Ammonoosuc is fairly similar to the uppermost Monson Gneiss. A Monson-Ammonoosuc unconformity is less clearly exposed in the Orange area of Massachusetts (Robinson, 1979, p. 137) and in the Palmer 7½-min quadrangle (Massachusetts). Elsewhere in the Palmer quadrangle, the contact has been regarded as gradational (Peper, 1966; J.D. Peper, oral commun., 1985). See related text for current status of isotopic age relationships between plagioclase gneisses and the Ammonoosuc Volcanics in southern Massachusetts.	The Monson Gneiss, like the Swanzey Gneiss, appears to be largely, if not entirely, volcanogenic.

subordinate Ammonoosuc lithology. Amphibole phases include cummingtonite, aluminous gedrite, and anthophyllite (Robinson and Jaffe, 1969; Schumacher, 1988). Rocks containing these amphiboles span the compositional range from mafic to felsic and thus constitute a departure from the dominantly bimodal assemblage. Gedrite-bearing rocks have mafic to intermediate compositions. They are high in MnO (0.19–0.55 percent) and conspicuously low in CaO (2.2–5.3 percent), slightly low in K_2O, and slightly high in Na_2O and FeO^{*2} in comparison with nongedritic samples (table 2, anals. 81–86). Similar Mn enrichment is attributed to hydrothermal alteration in marine volcaniclastic sediments at the Mattagami Lake Mine (Quebec) massive sulfide deposit (Costa and others, 1983). Schumacher (1988) reached the conclusion that mafic to intermediate gedrite-bearing rocks of the Ammonoosuc Volcanics in north-central Massachusetts could have been produced by seawater alteration and (or) by weathering before their metamorphism.

Felsic granofels of the Ammonoosuc Volcanics is typically white to very pale gray, fine grained, and equigranular, although graded sequences displaying clasts up to 10 cm long are known. The granofels consists of quartz, sodic plagioclase, and subordinate biotite, locally accompanied by cummingtonite, anthophyllite, garnet, magnetite, and (or) epidote. The SiO_2 contents of the felsic Ammonoosuc typically exceed 75 percent, whereas Al_2O_3 is mostly less than 13 percent and K_2O is less than 2 percent (table 2, anals. 87–100). These rocks are thinly to massively layered, typically interbedded with amphibolites, and interpreted as metamorphosed quartz keratophyre tuffs.

The Ammonoosuc Volcanics of the Owls Head dome, in addition to the common felsic granofels and hornblende-plagioclase amphibolite, include a distinctive metatuff that crops out mainly east of Limekiln Road in the northwestern part of the dome. This rock is gray brown, laminated, and marked by abundant subangular plagioclase grains that show relict primary twinning and zoning as well as abraded margins. The metatuff has the appearance of a moderately recrystallized lithic-crystal tuff and is compatible with the Ammonoosuc, both in its obvious volcaniclastic origin and in its bulk composition (see table 2, anal. 95).

Although the lower part of the Ammonoosuc is dominantly mafic and the upper part is dominantly felsic, there are departures from this general rule, and felsic and mafic rocks are locally interlayered on a scale of centimeters to tens of meters (also see descriptions of Ammonoosuc-Partridge section) (Moench, 1989). A lithologically more diversified section has been described by Schumacher (1988) in the Orange area of northern Massachusetts. Here, the lower part of the Ammonoosuc (Schumacher's informal lower member) consists dominantly of amphibolite, including gedrite-bearing rocks that also contain one or more aluminum silicate minerals such as cordierite, garnet, staurolite, kyanite, and sillimanite. Locally, in the upper part of the lower member, calcareous conglomerate, marble, and calcareous skarn are present. The upper part (Schumacher's upper member) consists mainly of quartz-feldspar-biotite gneiss, interpreted as metarhyolite, and has K_2O contents as high as 5.5 percent (Schumacher, 1988, table 5). Marbles, rocks bearing aluminosilicates, and high-K felsic gneisses were not observed in the Ammonoosuc of western New Hampshire, a fact that could be attributed either to nondeposition or to erosion of the part of the section that corresponded to Schumacher's upper member. The relationship of this Ammonoosuc section to the Ammonoosuc in west-central New Hampshire (Leo, 1985; R.H. Moench, unpub. map, 1989) is uncertain.

HOLTS LEDGE VOLCANIC SEQUENCE

A sequence of massively bedded, locally crossbedded K-poor felsic granofels and subordinate amphibolite layers (table 2, anals. 104–109) underlies the Ammonoosuc Volcanics in several domes. These rocks are similar in some respects to the fine-grained felsic rocks of the Ammonoosuc Volcanics. Such rocks were regarded in early studies (for example, Hadley, 1942) as early magmatic differentiates of Oliverian plutons. Naylor (1969) interpreted these rocks as volcaniclastic rather than magmatic differentiates. He designated them [Oliverian] "stratified core gneiss" and later (Naylor, 1987) proposed the informal name Holts Ledge Gneiss.[3] The informal term "Holts Ledge volcanic sequence" is proposed here both to emphasize the volcanic nature of the rocks and also because these rocks, unlike gneisses of the region, are characterized by a fine-grained granular texture and are distinctly friable even in fresh exposures. Comparable rocks of unknown extent crop out on the southwestern side of the Baker Pond pluton and in the Smarts Mountain and Warwick domes but were not found in any other domes. The Holts Ledge volcanic sequence will be described later in a discussion of the Mascoma dome.

[2] Total iron as FeO.

[3] sic: "informal," although the word "gneiss" is capitalized (Naylor, 1987, p. 244).

TABLE 2.—*Major-oxide and normative-mineral compositions (in weight percent) of the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*

[ND, absent or not determined; —, analysis inconclusive, calculations not made owing to lack of data, or not applicable. D.I., differentiation index (Q+OR+AB); FeOT, total iron as FeO(FeO+0.9×Fe_2O_3); FEMAG, FeOT/(FeOT+MgO)]

	JEFFERSON BATHOLITH															
	Berlin-Randolph area													Whitefield area		
Analysis no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Field no.	OL52–1	OL52–2	OL53–1	OL521–1	OL61–2	OL62–5	OL67	OL75–1	OL63	OL76–E	OL107–1	OL109	OL145	OL102	OL106	OL121–1
Major oxides																
SiO2	75.0	71.8	74.5	70.7	74.0	72.8	70.9	73.9	59.7	57.6	60.9	73.3	72.0	66.2	69.8	61.0
Al_2O_3	12.4	13.5	12.8	15.0	13.5	12.8	14.2	13.2	16.2	16.2	18.5	13.3	13.7	14.3	14.3	14.2
Fe_2O_3	.91	.52	1.1	.70	1.0	1.1	.84	.89	2.4	2.5	1.3	.85	1.3	2.0	1.4	2.6
FeO	.68	.50	.90	1.7	1.2	1.7	1.3	.36	2.2	3.0	1.8	.44	.62	2.8	2.0	3.4
MgO	.28	.29	.37	.77	.63	.98	.61	.21	2.1	3.6	1.1	.3	.36	2.0	1.1	3.8
CaO	1.1	.33	1.1	2.5	2.7	2.3	2.2	.74	4.0	5.6	2.8	1.4	.91	4.8	3.6	5.5
Na_2O	3.7	2.2	3.9	4.1	3.8	3.6	4.0	3.9	3.8	4.3	4.3	3.7	3.6	3.0	3.4	2.4
K_2O	4.6	8.8	4.2	2.7	2.1	2.5	3.9	4.9	6.2	4.2	6.2	5.0	6.0	1.3	2.3	4.0
H_2O	.58	.67	.66	.73	.79	.72	.64	.64	.95	.88	.95	.64	.75	1.6	1.06	1.11
TiO_2	.21	.15	.26	.45	.22	.24	.35	.18	.68	.86	.48	.23	.27	.34	.23	.63
P_2O_5	.05	.10	.06	.14	.08	.06	.13	.05	.32	.43	.21	.06	.07	.08	.07	.25
MnO	.06	.04	.06	.03	.06	.06	.03	.01	.11	.07	.04	.03	.07	.07	.04	.06
CO_2	.06	.01	.01	.01	.03	.02	.01	.01	.02	.01	.17	.09	.03	.54	.01	.06
Total (−0).	100	99	100	100	100	99	99	99	99	99	99	99	100	99	99	99
Adjusted oxides (H_2O-free)																
SiO_2	75.73	73.09	75.06	71.56	74.51	74.17	72.00	75.14	61.09	58.56	62.29	74.28	72.78	68.03	71.04	62.32
Al_2O_3	12.52	13.74	12.90	15.18	13.59	13.04	14.42	13.42	16.58	16.47	18.92	13.48	13.85	14.70	14.56	14.51
Fe_2O_3	.92	.53	1.11	.71	1.01	1.12	.85	.90	2.46	2.54	1.33	.86	1.31	2.06	1.42	2.66
FeO	.69	.51	.91	1.72	1.21	1.73	1.32	.37	2.25	3.05	1.84	.45	.63	2.88	2.04	3.47
MgO	.28	.30	.37	.78	.63	1.00	.62	.21	2.15	3.66	1.13	.30	.36	2.06	1.12	3.88
CaO	1.11	.34	1.11	2.53	2.72	2.34	2.23	.75	4.09	5.69	2.86	1.42	.92	4.93	3.66	5.62
Na_2O	3.74	2.24	3.93	4.15	3.83	3.67	4.06	3.97	3.89	4.37	4.40	3.75	3.64	3.08	3.46	2.45
K_2O	4.64	8.96	4.23	2.73	2.11	2.55	3.96	4.98	6.34	4.27	6.34	5.07	6.07	1.34	2.34	4.09
TiO_2	.21	.15	.26	.46	.22	.24	.36	.18	.70	.87	.49	.23	.27	.35	.23	.64
P_2O_5	.05	.10	.06	.14	.08	.06	.13	.05	.33	.44	.21	.06	.07	.08	.07	.26
MnO	.06	.04	.06	.03	.06	.06	.03	.01	.11	.07	.04	.03	.07	.07	.04	.06
Cl	.06	.01	.01	.01	.03	.02	.01	.01	.02	.01	.17	.09	.03	.55	.01	.06
Normative minerals (H_2O-free)																
Q	33.85	24.79	33.08	29.95	37.18	35.91	27.52	31.25	4.61	2.13	5.00	30.24	26.25	31.63	31.72	16.01
C	—	.02	.01	1.16	.33	.18	—	.28	—	—	.53	—	—	.69	—	—
OR	27.44	52.93	25.00	16.15	12.49	15.05	23.40	29.44	37.49	25.23	37.46	29.94	35.84	7.89	13.83	24.14
AB	31.61	18.95	33.25	35.11	32.38	31.03	34.37	33.55	32.90	36.99	37.20	31.72	30.79	26.06	29.28	20.74
AN	3.68	.94	5.04	11.56	12.77	11.97	9.42	3.34	9.04	12.71	11.70	4.98	3.54	20.40	17.27	16.51
WO	.47	—	—	—	—	—	.31	—	3.76	5.27	—	.45	.15	—	.16	3.89
EN	.70	.74	.93	1.94	1.58	2.49	1.54	.53	5.35	9.11	2.80	.76	.91	5.11	2.79	9.67
FS	.26	.32	.43	1.88	1.13	1.96	1.19	—	1.17	2.19	1.55	—	—	3.14	2.25	3.24
MT	1.33	.77	1.61	1.03	1.46	1.63	1.24	.68	3.56	3.69	1.93	.86	1.46	2.98	2.07	3.85
HM	—	—	—	—	—	—	—	.43	—	—	—	.27	.31	—	—	—
IL	.40	.29	.50	.87	.42	.46	.68	.35	1.32	1.66	.93	.44	.52	.66	.45	1.22
AP	.12	.24	.14	.34	.19	.15	.31	.12	.78	1.04	.51	.14	.17	.19	.17	.61
CC	.14	.02	.02	.02	.07	.05	.02	.02	.05	.02	.40	.21	.07	1.26	.02	.14
D.I.	92.90	96.67	91.33	81.21	82.05	81.99	85.30	94.24	75.00	64.34	79.67	91.89	92.88	65.57	74.84	60.90
FeOT	1.51	.99	1.90	2.36	2.11	2.74	2.01	1.18	4.46	5.34	3.04	1.22	1.81	4.72	3.32	5.86
FEMAG	.84	.77	.84	.75	.77	.73	.77	.85	.68	.59	.73	.80	.83	.70	.75	.60

TABLE 2.—*Major-oxide and normative-mineral compositions (in weight percent) of the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*—Continued

[ND, absent or not determined; —, analysis inconclusive, calculations not made owing to lack of data, or not applicable. D.I., differentiation index (Q+OR+AB); FeOT, total iron as FeO($FeO+0.9\times Fe_2O_3$); FEMAG, FeOT/(FeOT+MgO)]

	OWLS HEAD GROUP OF PLUTONS															
	Sugar Hill pluton			Landaff pluton		Moody Ledge plutons			Owls Head pluton					Baker Pond pluton		
Analysis no.	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Field no.	OL122	OL127	OL213	OL130	OL339–1	OL156	OL229	OL160	OL133–1	OL151	OL146–2	OL147	OL246	OL165	OL142	OL143
Major oxides																
SiO_2	75.5	77.6	73.8	77.0	68.3	73.9	73.6	70.5	72.4	74.4	75.5	72.0	73.1	69.7	69.6	61.3
Al_2O_3	12.3	11.6	12.6	11.6	14.7	12.9	13.2	13.5	13.7	13.1	11.9	13.7	13.5	14.1	14.2	15.3
Fe_2O_3	.66	.98	1.8	.95	3.19	1.1	1.2	1.2	.95	1.0	.76	1.0	.97	1.4	1.3	2.5
FeO	.56	.56	1.2	.58	1.8	.60	.68	1.2	1.2	1.2	.6	1.2	1.3	1.7	1.5	2.9
MgO	.50	.19	1.1	.18	.65	.26	.34	.69	.66	.56	.25	.54	.65	1.4	.90	2.8
CaO	.44	.56	1.3	.44	1.61	.72	1.0	1.7	1.7	1.1	.44	1.0	.89	2.9	2.4	5.1
Na_2O	3.9	4.2	4.6	4.4	5.72	4.0	4.2	4.3	3.7	5.3	3.0	3.8	3.2	2.9	3.5	3.2
K_2O	4.3	3.8	4.0	3.7	2.42	4.6	4.2	3.8	4.6	2.4	5.7	5.7	4.7	4.5	4.6	4.2
H_2O	.74	.45	.73	.47	.44	.67	.67	.92	.75	.73	.73	.71	.58	1.05	.76	1.1
TiO_2	.2	.15	.20	.14	.58	.28	.27	.40	.25	.24	.19	.30	.23	.33	.33	.56
P_2O_5	.05	.04	.05	.03	.17	.05	.05	.09	.11	.07	.05	.08	.08	.15	.12	.23
MnO	.01	.07	.08	.06	.06	.04	ND	.06	.03	.09	.06	.10	.02	.07	.12	.13
CO_2	ND	ND	.01	.01	.01	.01	.01	.38	.08	.01	.01	.15	.01	ND	.01	.01
Total(−0)	99	100	101	100	100	99	99	99	100	100	99	100	99	100	99	99
Adjusted oxides (H_2O-free)																
SiO_2	76.71	77.79	73.26	77.71	68.85	75.06	74.53	72.14	72.87	74.80	76.68	72.34	74.10	70.30	70.60	62.41
Al_2O_3	12.50	11.63	12.51	11.71	14.82	13.10	13.37	13.81	13.79	13.17	12.09	13.76	13.69	14.22	14.40	15.58
Fe_2O_3	.67	.98	1.79	.96	3.22	1.12	1.22	1.23	.96	1.01	.77	1.00	.98	1.41	1.32	2.55
FeO	.57	.56	1.19	.59	1.81	.61	.69	1.23	1.21	1.21	.61	1.21	1.32	1.71	1.52	2.95
MgO	.51	.19	1.09	.18	.66	.26	.34	.71	.66	.56	.25	.54	.66	1.41	.91	2.85
CaO	.45	.56	1.29	.44	1.62	.73	1.01	1.74	1.71	1.11	.45	1.00	.90	2.92	2.43	5.19
Na_2O	3.96	4.21	4.57	4.44	5.77	4.06	4.25	4.40	3.72	5.33	3.05	3.82	3.24	2.92	3.55	3.26
K_2O	4.37	3.81	3.97	3.73	2.44	4.67	4.25	3.89	4.63	2.41	5.79	5.73	4.76	4.54	4.67	4.28
TiO_2	.20	.15	.20	.14	.58	.28	.27	.41	.25	.24	.19	.30	.23	.33	.33	.57
P_2O_5	.05	.04	.05	.03	.17	.05	.05	.09	.11	.07	.05	.08	.08	.15	.12	.23
MnO	.01	.07	.08	.06	.06	.04	ND	.06	.03	.09	.06	.10	.02	.07	.12	.13
CO_2	ND	ND	.01	.01	.01	.01	.01	.39	.08	.01	.01	.15	.01	ND	.01	.01
Normative minerals (H_2O-free)																
Q	35.29	37.51	27.92	36.61	22.03	31.76	31.00	27.87	28.88	31.08	35.51	24.44	33.77	27.53	25.53	13.17
C	.56	—	—	—	.18	.18	.07	.33	—	—	.14	—	1.77	—	—	—
OR	25.82	22.51	23.46	22.07	14.41	27.61	25.13	22.96	27.35	14.26	34.21	33.16	28.15	26.82	27.57	25.27
AB	33.53	35.63	38.64	37.57	48.79	34.38	35.99	37.20	31.50	45.09	25.78	31.66	27.45	24.75	30.04	27.50
AN	1.89	1.58	1.91	.98	6.87	3.23	4.63	5.57	7.23	4.89	1.82	3.44	3.88	12.27	9.59	15.29
WO	—	.39	1.72	.40	—	—	—	—	.01	.03	—	—	—	.52	.68	3.72
EN	1.27	.47	2.72	.45	1.63	.66	.86	1.76	1.65	1.40	.63	1.32	1.64	3.52	2.27	7.10
FS	.17	.10	.53	.16	—	—	—	.68	1.07	1.16	.28	2.05	1.26	1.56	1.38	2.63
MT	.97	1.42	2.59	1.39	4.35	1.27	1.43	1.78	1.39	1.46	1.12	2.86	1.43	2.05	1.91	3.69
HM	—	—	—	—	.22	.24	.23	—	—	—	—	—	—	—	—	—
IL	.39	.29	.38	.27	1.11	.54	.52	.78	.48	.46	.37	.56	.44	.63	.64	1.08
AP	.12	.10	.12	.07	.41	.12	.12	.22	.26	.17	.12	.19	.19	.36	.29	.56
CC	—	—	.02	.02	.02	.02	.02	.88	.18	.02	.02	.34	.02	—	.02	.02
D.I.	94.64	95.65	90.02	96.25	85.23	93.74	92.13	88.02	87.73	90.42	95.51	89.26	89.37	79.10	83.23	65.97
FeOT	1.17	1.45	2.80	1.45	4.71	1.62	1.78	2.33	2.07	2.11	1.30	3.94	2.20	2.99	2.71	5.24
FEMAG	.70	.88	.72	.89	.88	.86	.84	.77	.76	.79	.84	.88	.77	.68	.75	.65

TABLE 2.—*Major-oxide and normative-mineral compositions (in weight percent) of the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*—Continued

[ND, absent or not determined; —, analysis inconclusive, calculations not made owing to lack of data, or not applicable. D.I., differentiation index (Q+OR+AB); FeOT, total iron as FeO(FeO+0.9×Fe_2O_3); FEMAG, FeOT/(FeOT+MgO)]

	SOUTHERN NEW HAMPSHIRE AND NORTHERN MASSACHUSETTS PLUTONS										
	Smarts Mountain pluton		Mascoma pluton			Lebanon pluton			Croydon pluton	Warwick pluton	
Analysis no.	33	34	35	36	37	38	39	40	41	42	43
Field no.	OL46	OL47	OL30–1	OL30–2	OL171	OL33–1	OL43–1	OL35–2	OL173	OL4	OL9
Major oxides											
SiO_2	75.0	73.4	73.9	76.0	73.5	76.1	71.8	60.9	70.6	74.9	72.7
Al_2O_3	13.0	13.0	13.5	12.8	13.3	13.3	13.3	16.2	14.4	13.4	13.6
Fe_2O_3	1.2	1.1	1.0	.37	.89	.77	1.5	1.8	1.2	.97	1.2
FeO	1.0	1.3	.52	.16	.64	.44	.80	4.1	1.1	.48	1.8
MgO	.47	.62	.44	.09	.42	.23	.62	2.5	.79	.33	.78
CaO	1.8	1.3	1.7	.90	1.5	.93	2.0	4.4	2.3	1.9	2.7
Na_2O	4.8	3.5	3.3	2.6	3.5	3.0	3.2	3.5	3.6	3.0	3.6
K_2O	1.9	4.5	4.7	5.7	4.7	5.1	4.6	3.3	4.3	4.5	2.8
H_2O	.72	.85	.29	.35	.58	.39	.75	.92	.81	.30	.66
TiO_2	.30	.33	.16	.09	.18	.11	.20	.57	.18	.09	.17
P_2O_5	.06	.06	.05	.03	.07	.06	.07	.28	.10	.04	.09
MnO	.16	.09	.07	.02	.05	.01	.08	.09	.05	.01	.13
CO_2	.01	ND	.02	.02	.01	.08	.02	.89	.02	.06	.01
Total(−0)	100	100	100	99	99	101	99	99	99	100	100
Adjusted oxides (H_2O-free)											
SiO_2	75.23	73.99	74.38	76.94	74.42	76.02	73.13	61.94	71.58	75.15	73.01
Al_2O_3	13.04	13.10	13.59	12.96	13.47	13.29	13.55	16.48	14.60	13.44	13.66
Fe_2O_3	1.20	1.11	1.01	.37	.90	.77	1.53	1.83	1.22	.97	1.21
FeO	1.00	1.31	.52	.16	.65	.44	.81	4.17	1.12	.48	1.81
MgO	.47	.62	.44	.09	.43	.23	.63	2.54	.80	.33	.78
CaO	1.81	1.31	1.71	.91	1.52	.93	2.04	4.47	2.33	1.91	2.71
Na_2O	4.81	3.53	3.32	2.63	3.54	3.00	3.26	3.56	3.65	3.01	3.62
K_2O	1.91	4.54	4.73	5.77	4.76	5.09	4.69	3.36	4.36	4.52	2.81
TiO_2	.30	.33	.16	.09	.18	.11	.20	.58	.18	.09	.17
P_2O_5	.06	.06	.05	.03	.07	.06	.07	.28	.10	.04	.09
MnO	.16	.09	.07	.02	.05	.01	.08	.09	.05	.01	.13
CO_2	.01	ND	.02	.02	.01	.08	.02	.91	.02	.06	.01
Normative minerals (H_2O-free)											
Q	35.29	32.04	32.83	37.60	31.88	37.13	31.44	15.81	27.48	36.06	33.50
C	—	.15	.06	.85	—	1.48	11	1.63	—	.38	—
OR	11.26	26.81	27.95	34.10	28.12	30.99	27.69	19.79	25.76	26.68	16.62
AB	40.74	29.86	28.10	22.27	29.99	25.35	27.43	30.06	30.88	25.47	30.59
AN	8.34	6.11	8.03	4.19	6.78	3.71	8.58	14.59	10.58	8.81	12.73
WO	.07	—	—	—	.09	—	.03	—	.08	—	.03
EN	1.17	1.56	1.10	.23	1.06	.57	.44	6.32	2.00	.83	1.95
FS	.65	1.11	—	—	.24	.01	1.57	5.35	.84	—	2.29
MT	1.75	1.61	1.45	.32	1.31	1.12	.05	2.65	1.76	1.32	1.75
HM	—	—	.01	.15	—	—	2.21	—	—	.06	—
IL	.57	.63	.31	.17	.35	.21	.39	1.10	.35	.17	.32
AP	.14	.14	.12	.07	.17	.14	.17	.67	.24	.10	.21
CC	.02	—	.05	.05	.02	.18	.01	2.05	.05	.14	.02
D.I.	87.29	88.97	88.88	93.97	89.99	92.58	86.56	65.66	84.12	88.20	80.70
FeOT	2.09	2.31	1.43	.50	1.46	1.13	2.19	5.81	2.21	1.36	2.89
FEMAG	.82	.79	.76	.85	.77	.83	.78	.70	.73	.80	.79

TABLE 2.—*Major-oxide and normative-mineral compositions (in weight percent) of the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*—Continued

[ND, absent or not determined; —, analysis inconclusive, calculations not made owing to lack of data, or not applicable. D.I., differentiation index (Q+OR+AB); FeOT, total iron as FeO(FeO+0.9×Fe_2O_3); FEMAG, FeOT/(FeOT+MgO)]

	SWANZEY AND MONSON GNEISSES AND HIGHLANDCROFT PLUTONIC SUITE														
	Swanzey Gneiss				Monson Gneiss							Highlandcroft Plutonic Suite[1]			
Analysis no.	44	45	46	47	48	49	50	51	52	53	54	55	56	59	60
Field no.	OL23	OL278	OL289	OL290–1	WD40	WD64–2	WD64–3	WD65	WD67–3	WD77–1	WD79	OL95	OL97A	OL425A	OL424–1
	Major oxides														
SiO_2	71.7	74.5	75.6	77.5	67.9	77.1	77.4	71.7	69.2	65.1	66.4	64.1	68.5	56.2	46.2
Al_2O_3	13.4	13.3	12.5	12.9	14.2	12.6	12.6	13.6	14.5	16.9	17.5	14.6	14.7	16.8	20.5
Fe_2O_3	1.7	1.0	.98	.44	2.0	.56	.66	1.6	2.3	1.9	1.4	2.1	1.4	3.6	3.5
FeO	2.8	1.2	1.6	.64	4.0	.76	.76	2.5	2.6	2.2	2.0	2.6	.86	4.1	6.2
MgO	.65	.43	.73	.16	1.9	.21	.23	.78	1.3	2.1	1.7	2.7	1.2	3.3	4.8
CaO	3.6	2.3	2.47	1.6	5.3	1.0	.80	3.9	5.6	4.4	5.7	3.8	1.8	6.5	4.3
Na_2O	4.0	3.4	3.99	3.55	3.0	4.8	5.7	3.5	3.0	6.2	3.4	3.2	4.2	2.4	3.8
K_2O	.63	2.8	1.3	3.47	1.1	2.0	.93	1.1	.69	.37	1.1	3.0	4.4	2.3	2.7
H_2O	.38	.56	.39	.27	.60	.35	.36	.59	.40	.68	.64	2.06	1.35	2.17	4.14
TiO_2	.32	.11	.21	.10	.34	.10	.10	.38	.28	.32	.34	.47	.34	.71	1.7
P_2O_5	.10	.07	.06	.03	.08	.04	.01	.11	.08	.18	.10	.14	.15	.26	.60
MnO	.09	.10	.07	.04	.14	.06	.04	.11	.11	.10	.06	.07	ND	.16	.14
CO_2	.02	ND	ND	ND	.03	.02	.03	.02	.02	.03	.03	.07	.29	.22	.02
Total(−0)	99	100	100	99	101	100	100	100	100	100	100	99	99	99	99
	Adjusted oxides (H_2O-free)														
SiO_2	72.42	75.09	75.97	77.17	67.91	77.68	77.98	72.21	69.42	65.23	66.58	66.20	70.06	58.24	48.91
Al_2O_3	13.53	13.41	12.56	12.84	14.20	12.70	12.69	13.70	14.55	16.93	17.55	15.08	15.03	17.41	21.70
Fe_2O_3	1.72	1.01	.98	.44	2.00	.56	.66	1.61	2.31	1.90	1.40	2.17	1.43	3.73	3.71
FeO	2.83	1.21	1.61	.64	4.00	.77	.77	2.52	2.61	2.20	2.01	2.69	.88	4.25	6.56
MgO	.66	.43	.73	.16	1.90	.21	.23	.79	1.30	2.10	1.70	2.79	1.23	3.42	5.08
CaO	3.64	2.32	2.48	1.59	5.30	1.01	.81	3.93	5.62	4.41	5.72	3.92	1.84	6.74	4.55
Na_2O	4.04	3.43	4.01	3.53	3.00	4.84	5.74	3.52	3.01	6.21	3.41	3.30	4.30	2.49	4.02
K_2O	.64	2.82	1.31	3.46	1.10	2.02	.94	1.11	.69	.37	1.10	3.10	4.50	2.38	2.86
TiO_2	.32	.11	.21	.10	.34	.10	.10	.38	.28	.32	.34	.49	.35	.74	1.80
P_2O_5	.10	.07	.06	.03	.08	.04	.01	.11	.08	.18	.10	.14	.15	.27	.64
MnO	.09	.10	.07	.04	.14	.06	.04	.11	.11	.10	.06	.07	ND	.17	.15
CO_2	.02	ND	ND	ND	.03	.02	.03	.02	.02	.03	.03	.07	.30	.23	.02
	Normative minerals (H_2O-free)														
Q	36.57	38.31	40.53	39.49	30.67	39.13	38.68	37.02	35.04	15.42	27.16	22.23	23.30	14.96	—
C	—	.67	.18	.47	—	.87	.86	—	—	—	.66	—	.80	—	5.28
OR	3.76	16.68	7.72	20.42	6.50	11.91	5.54	6.55	4.09	2.19	6.52	18.30	26.58	14.08	16.89
AB	34.19	29.00	33.93	29.91	25.39	40.92	48.59	29.83	25.47	52.57	28.85	27.96	36.32	21.03	34.04
AN	16.92	11.04	11.92	7.71	22.03	4.61	3.74	18.28	24.14	17.22	27.51	17.15	6.25	29.29	18.30
WO	.14	—	—	—	1.48	—	—	.15	1.29	1.37	—	.38	—	.38	—
EN	1.64	1.08	1.83	.40	4.73	.53	.58	1.96	3.25	5.24	4.25	6.94	3.01	8.51	3.51
FS	3.41	1.39	1.92	.72	5.39	.89	.77	2.87	2.63	2.13	2.07	2.47	—	3.81	1.74
FO	—	—	—	—	—	—	—	—	—	—	—	—	—	—	6.41
FA	—	—	—	—	—	—	—	—	—	—	—	—	—	—	3.52
MT	2.49	1.46	1.43	.64	2.90	.82	.96	2.34	3.35	2.76	2.04	3.14	1.83	5.41	5.37
HM	—	—	—	—	—	—	—	—	—	—	—	—	.17	—	—
IL	.61	.21	.40	.19	.65	.19	.19	.73	.53	.61	.65	.92	.66	1.40	3.42
AP	.24	.17	.14	.07	.19	.10	.02	.26	.19	.43	.24	.34	.36	.64	1.51
CC	.05	—	—	—	.07	.05	.07	.05	.05	.07	.07	.16	.67	.52	.05
D.I.	74.52	83.99	82.18	89.82	62.56	91.96	92.81	73.39	64.59	70.18	62.53	68.49	86.20	50.07	50.93
FeOT	4.37	2.12	2.49	1.03	5.80	1.26	1.35	3.94	4.67	3.91	3.26	4.64	2.17	7.60	9.90
FEMAG	.87	.83	.77	.87	.75	.86	.86	.84	.78	.65	.66	.62	.64	.69	.66

[1] Analyses 57 and 58 omitted.

TABLE 2.—*Major-oxide and normative-mineral compositions (in weight percent) of the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*—Continued

[ND, absent or not determined; —, analysis inconclusive, calculations not made owing to lack of data, or not applicable. D.I., differentiation index (Q+OR+AB); FeOT, total iron as FeO(FeO+0.9×Fe_2O_3); FEMAG, FeOT/(FeOT+MgO)]

	MAFIC AND INTERMEDIATE AMMONOOSUC VOLCANICS														
	Hornblende-plagioclase amphibolite[2]														
Analysis no.	61	62	63	64	65	66	67	69	70	71	72	73	74	75	76
Field no.	H–2	5	M–8	M–10	M–12	M–15	OL524	OL79–6	G136	OL386	OL120–1	OL120A	OL361–1	OL361–3	OL373–3
	Major oxides														
SiO_2	49.6	49.5	54.5	49.1	47.8	48.6	48.8	49.7	49.2	52.1	52.9	54.0	48.5	49.3	51.1
Al_2O_3	15.0	16.6	15.4	14.8	17.3	15.5	16.0	14.5	14.0	15.7	17.3	16.3	16.6	15.2	16.7
Fe_2O_3	2.1	2.8	.89	2.1	3.5	3.4	3.1	3.8	2.5	3.1	1.9	2.2	3.07	1.48	2.55
FeO	9.5	6.5	7.9	8.1	7.2	8.2	6.6	8.0	7.6	7.9	6.8	7.3	11.8	7.9	5.1
MgO	6.7	6.3	7.9	8.2	7.6	7.2	6.7	8.3	8.3	6.5	6.6	5.9	9.1	7.2	6.1
CaO	7.5	9.1	7.1	10.0	10.2	11.4	11.0	8.7	11.9	5.5	5.9	5.4	4.86	14.43	11.3
Na_2O	3.5	3.6	2.4	3.2	3.1	2.0	2.7	3.4	3.1	3.3	3.9	3.6	.98	.89	3.49
K_2O	.49	.71	.26	.53	.18	.53	1.1	.16	.31	2.1	1.9	1.8	.97	.20	.48
H_2O	2.14	2.63	2.08	.84	.82	.48	.71	.95	.90	1.39	1.79	1.74	4.07	.60	.34
TiO_2	2.1	1.5	.39	1.1	.95	2.0	1.8	1.4	.58	.69	.87	.63	.79	.43	1.39
P_2O_5	.34	.33	.10	.26	.27	.36	.23	.13	.11	.11	.15	.14	.06	.17	.26
MnO	.25	.27	.14	.26	.19	.35	.17	.21	.20	.27	.08	.14	.21	.17	.17
CO_2	.01	.03	.06	1.0	.02	.01	.01	.01	.01	.01	.01	.02	.09	2.0	.01
Total(−0)	99	100	99	99	99	100	99	100	99	99	100	99	101	100	99
	Adjusted oxides (H_2O-free)														
SiO_2	51.14	50.91	56.17	49.89	48.62	48.87	49.69	50.56	50.30	53.56	53.81	55.43	50.00	49.84	51.80
Al_2O_3	15.47	17.07	15.87	15.04	17.60	15.59	16.29	14.75	14.31	16.14	17.60	16.73	17.11	15.37	16.93
Fe_2O_3	2.17	2.88	.92	2.13	3.56	3.42	3.16	3.87	2.56	3.19	1.93	2.26	3.16	1.50	2.58
FeO	9.80	6.68	8.14	8.23	7.32	8.25	6.72	8.14	7.77	8.12	6.92	7.49	2.16	7.99	5.17
MgO	6.91	6.48	8.14	8.33	7.73	7.24	6.82	8.44	8.49	6.68	6.71	6.06	9.38	7.28	6.18
CaO	7.73	9.36	7.32	10.16	10.38	11.46	11.20	8.85	12.17	5.65	6.00	5.54	5.01	14.59	11.45
Na_2O	3.61	3.70	2.47	3.25	3.15	2.01	2.75	3.46	3.17	3.39	3.97	3.70	1.01	.90	3.54
K_2O	.51	.73	.27	.54	.18	.53	1.12	.16	.32	2.16	1.93	1.85	1.00	.20	.49
TiO_2	2.06	1.54	.40	1.12	.97	2.01	1.83	1.42	.59	.71	.88	.65	.81	.43	1.41
P_2O_5	.35	.34	.10	.26	.27	.36	.23	.13	.11	.11	.15	.14	.06	.17	.26
MnO	.26	.28	.14	.26	.19	.25	.17	.21	.20	.28	.08	.14	.22	.17	.17
CO_2	.01	.03	.06	1.02	.02	.01	.01	.01	.01	.01	.01	.02	.09	2.02	.01
	Normative minerals (H_2O-free)														
Q	—	—	7.94	—	—	1.38	—	—	—	—	—	1.98	7.45	6.34	—
C	—	—	—	—	—	—	—	—	—	—	—	—	5.62	—	—
OR	2.99	4.32	1.58	3.18	1.08	3.15	6.62	.96	1.87	12.77	11.42	10.92	5.91	1.19	2.88
AB	30.54	31.33	20.93	27.45	26.68	17.02	23.26	29.26	26.43	28.70	33.57	31.27	8.55	7.58	29.94
AN	24.51	27.81	31.41	24.79	33.32	31.93	28.81	24.24	23.89	22.43	24.50	23.61	23.86	37.12	28.87
NE	—	—	—	—	—	—	—	—	.21	—	—	—	—	—	—
WO	4.80	6.77	1.60	7.25	6.78	9.40	10.51	7.82	14.89	2.01	1.76	1.18	—	8.80	10.93
EN	14.69	10.84	20.28	12.69	9.32	18.03	12.33	16.72	9.09	15.73	10.66	15.08	23.36	18.05	14.30
FS	11.33	5.28	13.80	7.34	4.49	9.46	5.10	7.79	4.97	10.99	6.25	11.09	18.78	12.97	4.97
FO	1.76	3.71	—	5.61	6.96	—	3.27	3.02	8.44	.64	4.25	—	—	—	.77
FA	1.50	1.99	—	3.58	3.70	—	1.49	1.55	5.09	.49	2.74	—	—	—	.30
MT	3.14	4.18	1.33	3.09	5.16	4.96	4.58	5.60	3.71	4.62	2.80	3.27	4.59	2.16	3.75
HM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
IL	3.92	2.93	.76	2.12	1.84	3.82	3.48	2.71	1.13	1.35	1.68	1.23	1.55	.82	2.68
AP	.83	.80	.24	.62	.65	.86	.56	.31	.27	.27	.36	.34	.15	.41	.62
CC	.02	.07	.14	2.31	.05	.02	.02	.02	.02	.02	.02	.05	.21	4.58	.02
D.I.	33.52	35.64	30.45	30.62	27.76	21.55	29.88	30.23	28.52	41.46	44.99	44.16	21.90	15.11	32.81
FeOT	11.74	9.28	8.97	10.13	10.53	11.32	9.56	11.62	10.07	10.99	8.66	9.53	15.01	9.29	7.50
FEMAG	.63	.59	.52	.55	.58	.61	.58	.58	.54	.62	.56	.61	.62	.56	.55

[2] Analysis 68 omitted.

TABLE 2.—*Major-oxide and normative-mineral compositions (in weight percent) of the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*—Continued

[ND, absent or not determined; —, analysis inconclusive, calculations not made owing to lack of data, or not applicable. D.I., differentiation index (Q+OR+AB); FeOT, total iron as FeO($FeO+0.9\times Fe_2O_3$); FEMAG, FeOT/(FeOT+MgO)]

	MAFIC AND INTERMEDIATE AMMONOOSUC VOLCANICS									
	Hornblende-plagioclase amphibolite				Amphibolite containing Ca-poor amphiboles					
Analysis no.	77	78	79	80	81	82	83	84	85	86
Field no.	OL161	OL449–1	OL32A	OL267–2	G291	OL402	G112A	OL79–2	G109A	G189A
					Major oxides					
SiO_2	47.0	53.6	49.3	49.1	48.8	49.9	54.4	55.2	57.0	64.1
Al_2O_3	14.0	14.8	16.7	16.3	16.2	18.8	14.8	15.8	15.4	14.1
Fe_2O_3	1.2	3.2	1.7	4.0	4.2	2.2	5.3	2.2	4.4	1.2
FeO	7.6	7.5	7.9	7.1	10.6	8.6	7.4	7.6	7.8	8.3
MgO	14.2	6.1	8.0	7.7	9.8	7.8	5.0	5.9	4.7	3.2
CaO	10.2	8.5	8.8	8.6	2.2	3.2	5.2	5.3	3.0	2.6
Na_2O	1.5	.54	3.4	4.4	3.7	4.3	3.6	4.5	5.1	3.7
K_2O	.17	1.2	.86	.03	.86	1.5	.38	.34	.13	.29
H_2O	2.78	2.0	1.02	.65	1.27	1.22	1.32	.86	.90	.78
TiO_2	.57	.62	1.1	.87	1.9	.69	1.6	.61	1.1	.65
P_2O_5	.09	.15	.17	.13	.15	.11	.20	.08	.20	.13
MnO	.15	.30	.15	.13	.37	.55	.22	.19	.37	.45
CO_2	ND	.02	ND	.01	.08	.02	.10	ND	ND	ND
Total(−0)	100	99	99	99	101	99	100	99	100	100
					Adjusted oxides (H_2O-free)					
SiO_2	48.6	55.53	50.27	49.91	49.37	51.09	55.41	56.49	57.46	64.93
Al_2O_3	14.5	15.33	17.03	16.57	16.39	10.25	15.07	16.17	15.52	14.28
Fe_2O_3	1.2	3.32	1.73	4.07	4.25	2.25	5.40	2.25	4.44	1.22
FeO	8.0	7.77	8.05	7.22	10.72	8.81	7.54	7.78	7.86	8.41
MgO	14.7	6.32	8.16	7.83	9.91	7.99	5.09	6.04	4.74	3.24
CaO	10.6	8.81	8.97	8.74	2.23	3.28	5.30	5.42	3.02	2.63
Na_2O	1.5	.56	3.47	4.47	3.74	4.40	3.67	4.60	5.14	3.75
K_2O	.18	1.24	.88	.03	.87	1.54	.39	.35	.13	.29
TiO_2	.59	.64	1.12	.88	1.92	.71	1.63	.62	1.11	.66
P_2O_5	.10	.16	.17	.13	.15	.11	.20	.08	.20	.13
MnO	.16	.31	.15	.13	.37	.56	.22	.19	.37	.46
CO_2	ND	.02	ND	.01	.08	.02	.10	ND	ND	ND
					Normative minerals (H_2O-free)					
Q	—	16.18	—	—	—	—	11.44	3.48	9.69	25.44
C	—	—	—	—	5.79	4.70	—	—	1.91	3.33
OR	1.04	7.35	5.18	.18	5.14	9.08	2.29	2.06	.77	1.74
AB	13.13	4.73	29.33	36.79	31.67	37.25	31.02	38.97	43.50	31.71
AN	32.03	35.65	28.31	25.05	9.54	15.39	23.53	22.42	13.69	12.21
WO	—	—	—	.57	—	—	—	—	—	—
EN	8.23	2.88	6.29	7.27	—	—	.32	1.65	—	—
FS	18.45	15.74	5.79	4.69	22.64	8.18	12.68	15.04	11.80	8.07
FO	6.42	11.05	3.36	2.09	12.57	5.83	7.11	11.75	9.64	14.20
FA	12.70	—	10.18	10.38	1.43	8.21	—	—	—	—
MT	4.87	—	6.51	5.09	.88	6.45	—	—	—	—
HM	1.80	4.81	2.51	5.90	6.16	3.27	7.83	3.26	6.43	1.76
IL	—	—	—	—	—	—	—	—	—	—
AP	1.12	1.22	2.13	1.68	3.65	1.34	3.09	1.19	2.11	1.25
CC	.22	.37	.41	.31	.36	.27	.48	.19	.48	.31
D.I.	14.17	28.26	34.52	37.54	36.81	46.33	44.75	44.50	53.97	58.89
FeOT	8.98	10.75	9.62	10.88	14.55	10.83	12.39	9.80	11.86	9.50
FEMAG	.38	.63	.54	.58	.60	.58	.71	.62	.71	.75

TABLE 2.—*Major-oxide and normative-mineral compositions (in weight percent) of the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*—Continued

[ND, absent or not determined; —, analysis inconclusive, calculations not made owing to lack of data, or not applicable. D.I., differentiation index (Q+OR+AB); FeOT, total iron as FeO(FeO+0.9×Fe_2O_3); FEMAG, FeOT/(FeOT+MgO)]

	Felsic Ammonoosuc Volcanics (quartz keratophyre)														Metasomatized felsic Ammonoosuc		
Analysis no.	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Field no.	OL79–7	OL198–1	OL398	OL219–2	OL316–1	OL356	OL235–1	OL235–2	OL445	OL451–1	OL139	OL32C	OL270–1	OL11	OL241	OL241C	OL244
							Major oxides										
SiO_2	75.2	76.2	78.4	79.0	79.2	75.0	71.7	77.8	70.1	69.4	78.8	77.0	75.7	73.3	69.4	72.4	65.9
Al_2O_3	11.5	12.6	11.9	9.6	11.3	13.8	14.0	11.9	13.6	14.0	10.6	12.5	10.5	12.7	15.5	14.5	16.3
Fe_2O_3	2.0	1.0	.46	.66	.56	.47	.86	.94	1.6	.93	.86	.88	.54	1.4	.97	1.0	1.6
FeO	1.5	.96	1.2	.56	.84	1.1	2.1	.72	2.6	3.7	.88	.96	2.5	2.2	1.6	1.0	1.6
MgO	.79	.65	.53	.44	.52	.71	1.2	.25	1.2	2.4	1.3	.65	2.2	1.3	.87	.64	1.1
CaO	1.6	.88	.54	1.4	1.65	2.43	1.7	.38	.67	2.2	.72	1.6	2.3	2.2	1.5	1.5	1.9
Na_2O	5.5	6.0	5.0	4.3	3.84	4.52	4.7	5.8	5.9	3.3	3.6	5.2	4.2	5.0	4.1	4.1	4.3
K_2O	.12	.32	.99	1.1	1.19	.92	2.1	.67	1.6	1.2	1.6	.31	.05	.29	3.7	2.8	4.7
H_2O	.56	.82	.51	.71	.52	.49	.84	.65	.74	1.4	.94	.58	.59	.49	2.7	.86	.87
TiO_2	.25	.19	.12	.17	.22	.24	.39	.20	.45	.39	.16	.21	.38	.33	.34	.33	.51
P_2O_5	.05	.08	.03	.03	.09	.10	.10	.08	.14	.11	.05	.07	.07	.09	.16	.13	.23
MnO	.01	.07	.04	.02	.08	.10	.12	.06	.06	.11	.08	.06	.02	.04	.11	.08	.12
CO_2	.01	.03	.01	.92	.01	.01	.02	.01	.01	.01	.01	.08	.01	.04	.01	.01	—
Total(−0)	99	100	100	99	100	100	100	99	99	99	100	100	99	99	101	99	99
							Adjusted oxides (H_2O-free)										
SiO_2	76.32	76.99	79.02	80.45	79.60	75.45	72.43	78.74	71.58	71.00	79.87	77.39	76.88	74.13	70.63	73.51	67.14
Al_2O_3	11.67	12.73	11.99	9.78	11.36	13.88	14.14	12.04	13.89	14.32	10.74	12.56	10.66	12.84	15.77	14.72	16.61
Fe_2O_3	2.03	1.01	.46	.67	.56	.47	.87	.95	1.63	.95	.87	.88	.55	1.42	.99	1.02	1.53
FeO	1.52	.97	1.21	.57	.84	1.11	2.12	.73	2.66	3.79	.89	.96	2.54	2.22	1.63	1.02	1.63
MgO	.80	.66	.53	.45	.52	.71	1.2	.25	1.23	2.46	1.32	.65	2.23	1.31	.89	.65	1.12
CaO	1.62	.89	.54	1.43	1.66	2.44	1.72	.38	.68	2.25	.73	1.61	2.34	2.22	1.53	1.52	1.94
Na_2O	5.58	6.06	5.04	4.38	3.86	4.55	4.75	5.87	6.02	3.38	3.65	5.23	4.27	5.06	4.17	4.16	4.38
K_2O	.12	.32	1.00	1.12	1.20	.93	2.12	.68	1.63	1.23	1.62	.31	.05	.29	3.77	2.84	4.79
TiO_2	.25	.19	.12	.17	.22	.24	.39	.20	.46	.40	.16	.21	.39	.33	.35	.34	.52
P_2O_5	.05	.08	.03	.03	.09	.10	.10	.08	.14	.11	.05	.07	.07	.09	.16	.13	.23
MnO	.01	.07	.04	.02	.08	.10	.12	.06	.06	.11	.08	.06	.02	.04	.11	.08	.12
CO_2	.01	.03	.01	.94	.01	.01	.02	.01	.01	.01	.01	.08	.01	.04	.01	.01	—
							Normative minerals (H_2O-free)										
Q	38.82	37.57	43.26	49.50	48.13	38.82	30.30	40.90	26.11	35.92	48.72	41.42	42.39	36.12	27.02	34.30	17.67
C	—	1.05	1.73	1.01	.94	1.22	1.20	1.17	1.33	3.64	1.80	1.06	—	.47	2.47	2.37	1.26
OR	.72	1.91	5.90	6.62	7.07	5.47	12.54	4.01	9.65	7.25	9.58	1.84	.30	1.73	22.25	16.80	28.29
AB	47.23	51.29	42.64	37.05	32.66	38.48	40.18	49.67	50.98	28.57	30.88	44.21	36.09	42.78	35.31	35.22	37.07
AN	6.43	3.69	2.44	.95	7.57	11.41	7.73	1.31	2.40	10.37	4.22	7.01	9.80	10.19	6.44	6.63	8.07
WO	.51	—	—	—	—	—	—	—	—	—	—	—	.53	—	—	—	—
EN	2.00	1.64	1.33	1.12	1.30	1.78	3.02	.63	3.05	6.11	3.28	1.63	5.56	3.27	2.20	1.62	2.79
FS	.72	.76	1.71	.24	.87	1.43	2.75	.33	2.88	5.71	.80	.80	3.61	2.44	1.81	.62	1.10
MT	2.94	1.46	.67	.97	.82	.69	1.26	1.38	2.37	1.38	1.26	1.28	.79	2.05	1.43	1.47	2.22
HM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
IL	.48	.36	.23	.33	.42	.46	.75	.38	.87	.76	.31	.40	.73	.63	.66	.64	.99
AP	.12	.19	.07	.07	.21	.24	.24	.19	.34	.27	.12	.17	.17	.22	.39	.31	.55
CC	.02	.07	.02	2.13	.02	.02	.05	.02	.02	.02	.02	.18	.02	.09	.02	.02	—
D.I.	86.77	90.77	91.79	93.17	87.85	82.76	83.01	94.58	86.75	71.74	89.18	87.47	78.78	80.64	84.58	86.32	83.03
FeOT	3.35	1.88	1.63	1.17	1.35	1.53	2.90	1.58	4.12	4.64	1.68	1.76	3.03	3.50	2.52	1.93	3.00
FEMAG	.81	.74	.75	.72	.72	.68	.70	.86	.77	.65	.56	.73	.58	.73	.74	.75	.73

TABLE 2.—*Major-oxide and normative-mineral compositions (in weight percent) of the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*—Continued

[ND, absent or not determined; —, analysis inconclusive, calculations not made owing to lack of data, or not applicable. D.I., differentiation index (Q+OR+AB); FeOT, total iron as FeO(FeO+0.9×Fe_2O_3); FEMAG, FeOT/(FeOT+MgO)]

	Holts Ledge volcanic sequence					
Analysis no.	104	105	106	107	108	109
Field no.	OL163	OL252-2	OL32F	OL32G	OL32H	OL32K
Major oxides						
SiO_2	70.8	75.4	77.3	77.2	74.2	73.7
Al_2O_3	13.8	12.9	11.6	12.8	13.0	13.3
Fe_2O_3	1.5	1.4	1.3	.97	1.3	1.3
FeO	.96	.92	1.0	.72	1.2	1.0
MgO	1.4	.42	.76	.21	.60	.51
CaO	5.8	2.8	1.1	2.7	4.1	2.9
Na_2O	4.2	4.4	5.3	4.3	3.1	3.9
K_2O	.32	.55	.10	.19	.11	.99
H_2O	.55	.49	.60	.41	.45	.46
TiO_2	.42	.29	.12	.17	.30	.24
P_2O_5	.09	.12	.05	.04	.09	.08
MnO	.04	.04	.02	.03	.08	.06
CO_2	.01	ND	.02	.08	.06	.04
Total(−0)	100	100	99	100	99	98
Adjusted oxides (H_2O-free)						
SiO_2	71.27	75.98	78.35	77.67	75.62	75.20
Al_2O_3	13.89	13.00	11.76	12.88	13.25	13.57
Fe_2O_3	1.51	1.41	1.32	.98	1.32	1.33
FeO	.97	.93	1.01	.72	1.22	1.02
MgO	1.41	.42	.77	.21	.61	.52
CaO	5.84	2.82	1.11	2.72	4.18	2.96
Na_2O	4.23	4.43	5.37	4.33	3.16	3.98
K_2O	.32	.55	.10	.19	.11	1.01
TiO_2	.42	.29	.12	.17	.31	.24
P_2O_5	.09	.12	.05	.04	.09	.08
MnO	.04	.04	.02	.03	.08	.06
CO_2	.01	ND	.02	.08	.06	.04
Normative minerals (H_2O-free)						
Q	33.35	41.67	43.09	45.83	47.00	41.19
C	—	.27	.95	.90	.69	.84
OR	1.90	3.28	.60	1.13	.66	5.97
AB	35.78	37.52	45.45	36.60	26.73	33.67
AN	17.98	13.21	5.07	12.70	19.74	13.89
WO	4.32	—	—	—	—	—
EN	3.51	1.05	1.92	.53	1.52	1.30
FS	—	.13	.61	.30	.80	.49
FO	—	—	—	—	—	—
FA	—	—	—	—	—	—
MT	2.02	2.05	1.91	1.42	1.92	1.92
HM	.12	—	—	—	—	—
IL	.80	.56	.23	.33	.58	.47
AP	.22	.29	.12	.10	.22	.19
CC	.02	—	.05	.18	.14	.09
D.I.	71.03	82.47	89.15	83.56	74.39	80.82
FeOT	2.33	2.20	2.20	1.60	2.42	2.21
FEMAG	.62	.84	.74	.88	.80	.81

TABLE 2.—*Major-oxide and normative-mineral compositions (in weight percent) of the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*—Continued

[ND, absent or not determined; —, analysis inconclusive, calculations not made owing to lack of data, or not applicable. D.I., differentiation index (Q+OR+AB); FeOT, total iron as FeO(FeO+0.9×Fe_2O_3); FEMAG, FeOT/(FeOT+MgO)]

	AMMONOOSUC TRONDHJEMITE																	
	Berlin area			Landaff	West Lebanon-White River Junction area				Croydon dome		Unity dome		Alstead dome			Vernon dome		Warwick dome
Analysis no.	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127
Field no.	OL60	OL203	OL208	OL341	OL39-1	OL507-1	OL507-2	OL502	OL309-2	OL310	OL293	OL301	OL267A	OL272-1	OL561-1	OL15	OL20	OL288A
	Major oxides																	
SiO_2	73.2	76.7	77.8	80.6	78.8	77.1	75.5	73.3	75.8	78.3	79.0	75.4	78.7	73.1	74.7	75.1	74.8	77.0
Al_2O_3	12.8	12.3	11.9	11.4	11.7	11.6	11.6	13.2	12.5	11.3	11.8	12.6	11.3	13.5	13.8	13.3	12.9	12.9
Fe_2O_3	1.7	.47	.88	—	.92	2.1	.9	1.5	1.85	.79	.49	1.57	.67	1.1	1.7	1.2	1.2	.68
FeO	.96	.88	.88	.44	.54	1.2	2.2	2.1	1.6	1.0	1.1	1:1	.76	2.2	1.9	.80	1.4	.92
MgO	.83	1.2	.49	—	.21	.54	1.3	.99	.50	.14	.55	.43	.65	.98	.96	.35	.45	.30
CaO	1.7	1.6	.98	.66	1.1	1.2	.85	3.1	2.77	1.72	.34	3.12	1.4	3.6	3.5	2.9	2.4	2.19
Na_2O	5.1	4.6	5.6	6.21	5.6	5.7	5.5	3.1	3.83	4.45	5.05	3.53	5.2	4.2	3.7	3.8	4.6	4.53
K_2O	1.1	1.2	.31	.26	.82	.20	.03	1.2	1.22	1.28	.98	1.26	.25	.35	1.0	1.4	.68	1.01
H_2O	1.06	.58	.64	.27	.67	.61	1.24	1.5	.33	.36	.47	.40	.61	.71	.68	.52	.55	.44
TiO_2	.33	.24	.10	.16	.07	.23	.23	.21	.30	.18	.10	.21	.21	.21	.22	.22	.22	.15
P_2O_5	.08	.09	.07	.04	.03	.05	.05	.05	.07	.03	.03	.06	.02	.09	.08	.05	.05	.04
MnO	.15	.05	.06	.02	.14	.03	.04	.02	.05	.03	.05	.08	ND	.14	.12	.01	.01	.07
CO_2	.01	.03	.01	ND	.06	.23	.24	.86	.02	.06	.01	.01	.01	.03	.02	.02	.02	.01
Total(−0)	99	100	100	100	101	101	100	101	101	100	100	100	100	102	100	100	99	100
	Adjusted oxides (H_2O-free)																	
SiO_2	74.73	77.20	78.52	80.77	78.82	77.00	76.74	73.72	75.42	78.88	79.40	75.88	79.36	73.47	73.45	75.75	75.77	77.16
Al_2O_3	13.07	12.38	12.01	11.42	11.70	11.59	11.79	13.28	12.44	11.38	11.86	12.68	11.39	13.57	13.57	13.41	13.07	12.93
Fe_2O_3	1.74	.47	.89	—	.92	2.10	.91	1.51	1.84	.80	.49	1.58	.68	1.11	1.67	1.21	1.22	.68
FeO	.98	.89	.89	.44	.54	1.20	2.24	2.11	1.59	1.01	1.11	1.11	.77	2.21	1.87	.81	1.42	.92
MgO	.85	1.21	.49	—	.21	.54	1.32	1.00	.50	.14	.55	.43	.66	.98	.94	.35	1.46	.30
CaO	1.74	1.61	.99	.66	1.10	1.20	.86	3.12	2.76	1.73	.34	3.14	1.41	3.62	3.44	2.92	2.43	2.19
Na_2O	5.21	4.63	5.65	6.22	5.60	5.69	5.59	3.12	3.81	4.48	5.08	3.55	5.24	4.22	3.64	3.83	4.66	4.54
K_2O	1.12	1.21	.31	.26	.82	.20	.03	1.21	1.21	1.29	.98	1.27	.25	.35	.98	1.41	.69	1.01
TiO_2	.34	.24	.10	.16	.07	.23	.23	.21	.30	.18	.10	.21	.21	.21	.22	.22	.22	.15
P_2O_5	.08	.09	.07	.04	.03	.05	.05	.05	.07	.03	.03	.06	.02	.09	.08	.05	.05	.04
MnO	.15	.05	.06	.02	.14	.03	.04	.02	.05	.03	.05	.08	ND	.14	.12	.01	.01	.07
CO_2	.01	.03	.01	ND	.06	.23	.24	.86	.02	.06	.01	.01	.01	.03	.02	.02	.02	.01
	Normative minerals (H_2O-free)																	
Q	35.38	40.31	41.44	42.13	40.61	40.43	39.69	44.16	41.75	43.95	43.96	42.99	43.75	37.32	39.15	41.39	39.77	41.41
C	.35	.82	.77	—	—	.48	1.68	3.29	.06	—	1.92	—	—	—	.50	.43	.40	.49
OR	6.64	7.14	1.85	1.54	4.85	1.18	.18	7.12	7.17	7.62	5.82	7.49	1.49	2.08	5.81	8.34	4.07	5.98
AB	44.05	39.18	47.83	52.66	47.39	48.15	47.28	26.33	32.24	37.93	42.95	30.06	44.37	35.72	30.79	32.43	39.43	38.41
AN	8.01	7.21	4.38	2.47	4.37	4.17	2.41	9.65	13.09	7.13	1.44	14.91	6.81	17.04	16.44	14.05	11.60	10.56
WO	—	—	—	.23	.22	—	—	—	—	.37	—	.09	—	.06	—	—	—	—
EN	2.11	3.01	1.23	—	.52	1.34	3.29	2.48	1.24	.35	1.38	1.08	1.63	2.45	2.35	.88	1.14	.75
FS	.09	.93	.84	.58	.38	.14	3.04	2.32	1.00	.95	1.55	.53	.50	3.06	1.91	.13	1.25	1.01
MT	2.52	.69	1.29	—	1.33	3.04	1.33	2.18	2.67	1.15	.71	2.29	.98	1.60	2.42	1.76	1.76	.99
HM	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
IL	.64	.46	.19	.31	.13	.44	.44	.40	.57	.34	.19	.40	.40	.40	.41	.42	.42	.29
AP	.19	.22	.17	.10	.07	.12	.12	.12	.17	.07	.07	.14	.05	.21	.19	.12	.12	.10
CC	.02	.07	.02	—	.14	.52	.55	1.96	.05	.14	.02	.02	.02	.07	.05	.05	.05	.02
D.I.	96.32	86.07	91.11	96.32	92.85	89.76	87.15	77.61	81.17	89.50	92.72	80.55	89.61	75.12	75.24	82.16	83.26	85.80
FeOT	.44	2.54	1.69	.44	1.37	3.08	3.06	3.46	3.25	1.72	1.55	2.53	1.37	3.21	3.43	1.90	2.51	1.54
FEMAG	1.00	.75	.77	1.00	.87	.85	.70	.78	.87	.92	.74	.85	.68	.77	.78	.84	.85	.84

AMMONOOSUC TRONDHJEMITE

DIKES AND SILLS

Pale-gray, fine- to medium-grained metamorphosed trondhjemite, described in detail elsewhere (Leo, 1985), is widely distributed in several of the domes and constitutes most if not all of the felsic gneiss phase in three small domes. Trondhjemite ubiquitously intrudes the Ammonoosuc Volcanics as sills, dikes, and small plugs. It consists dominantly of quartz, plagioclase, and biotite, locally accompanied by muscovite and (or) hornblende (rarely Ca-poor amphibole). Thus, it resembles the quartz keratophyre of the Ammonoosuc Volcanics, differing from it principally in its relict hypidiomorphic texture, which probably accounts for its greater relative resistance to weathering. This unit will henceforth be referred to informally as Ammonoosuc trondhjemite.

The chemistry of trondhjemite is similar to that of Ammonoosuc quartz keratophyre (tables 2, 3, anals. 110–127) (Leo, 1985). On the basis of chemistry and field relations, the trondhjemite is apparently comagmatic with the Ammonoosuc Volcanics and is thus unlikely to be petrogenetically related to the Oliverian Plutonic Suite. The point is pertinent for two reasons. First, in many areas of K-poor silicic tuffs along the Appalachian chain, it has not been possible to relate quartz keratophyre and keratophyre tuffs to a magmatic source. The spatially related and chemically almost identical trondhjemite suggests at least a partial source for the felsic tuffs of the Ammonoosuc. Second, chemical and spatial relationships tend to refute an earlier mistaken assumption that the trondhjemite, especially where it constitutes larger masses, is comagmatic with Oliverian granitic gneiss (for example, Chapman, 1942; Kruger, 1946; Hepburn and others, 1984).

Trondhjemite is widely distributed in the Berlin area of New Hampshire and is common around White River Junction, Vt. Trondhjemite also crops out locally in the Croydon and Landaff plutons and forms most, if not all, of the plutonic phases of the Unity, Alstead, and Vernon domes and the northern part of the Warwick dome (pl. 1). Because of its generally inconspicuous character and local resemblance to phases of the Oliverian gneiss (for example, in the Berlin area and in the Landaff pluton), trondhjemite could have gone unidentified in other exposures.

The relationships between trondhjemite and the Ammonoosuc Volcanics are locally well displayed in the Berlin area (figs. 2, 3) and in cuts on Interstate 91 near West Lebanon, N.H., and White River Junction (figs. 4,

TABLE 3.—*Trace-element abundances (in parts per million) in the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*

[ND, not determined or absent; —, analysis inconclusive, calculation not made owing to lack of data, or not applicable]

	JEFFERSON BATHOLITH															
	Berlin-Randolph area													Whitefield area		
Analysis no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Field no.	OL52–1	OL52–2	OL53–1	OL521–1	OL61–2	OL62–5	OL67	OL75–1	OL63	OL76E	OL107–1	OL109	OL145	OL102	OL106	OL121–1
Rb	136	258	131	89	54	81	180	123	173	95	121	91	130	46	67	105
Sr	140	159	120	433	136	105	458	278	1473	1443	719	412	343	246	229	709
Ba	924	1653	936	1411	ND	712	1538	715	1686	1636	3168	1077	895	418	530	1739
Th	11.1	1.4	ND	14.8	7.9	ND	ND	ND	21.8	ND	ND	ND	21.4	ND	ND	12.2
Zr	137	ND	ND	231	103	ND	ND	ND	487	ND	ND	ND	210	ND	ND	320
Hf	4.5	2.4	ND	6.1	2.8	ND	ND	ND	12.8	ND	ND	ND	6.5	ND	ND	6.6
Ta	.63	.64	ND	.26	.57	ND	ND	ND	.97	ND	ND	ND	1.90	ND	ND	.90
Y	15	ND	ND	ND	22	ND	ND	ND	11	ND	ND	ND	ND	ND	ND	ND
Co	1.6	1.8	ND	3.9	3.4	ND	ND	ND	12.0	ND	ND	ND	1.9	ND	ND	20.4
Cr	5.9	2.3	ND	7.2	2.7	ND	ND	ND	20.2	ND	ND	ND	—	ND	ND	93.4
Sc	2.25	2.25	ND	4.38	5.96	ND	ND	ND	8.38	ND	ND	ND	2.16	ND	ND	20.1
La	ND	5	ND	43	22	ND	ND	ND	86	ND	ND	ND	74	ND	ND	40
Ce	74.6	10	ND	76	36	ND	ND	ND	159	ND	ND	ND	124	ND	ND	75
Nd	25.2	4	ND	26	15	ND	ND	ND	68	ND	ND	ND	45	ND	ND	36
Sm	3.22	1.2	ND	4.9	3.0	ND	ND	ND	8.4	ND	ND	ND	7.4	ND	ND	6.5
Eu	.624	.54	ND	.92	.46	ND	ND	ND	2.41	ND	ND	ND	1.24	ND	ND	1.43
Gd	1.75	1.3	ND	4.0	.7	ND	ND	ND	6.7	ND	ND	ND	4.3	ND	ND	ND
Tb	ND	.21	ND	.33	.34	ND	ND	ND	.61	ND	ND	ND	.73	ND	ND	.73
Dy	.798	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Er	.291	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Yb	.245	.8	ND	1.2	1.9	ND	ND	ND	1.4	ND	ND	ND	1.9	ND	ND	1.5
Lu	ND	.12	ND	.16	.29	ND	ND	ND	.19	ND	ND	ND	.29	ND	ND	.20
K/Rb	281	282	266	252	322	256	180	330	296	366	424	456	382	234	284	316
K/Ba	41.3	44.2	37.2	15.6	—	29.1	21.0	56.8	30.6	11.0	16.2	386	145	25.8	36.0	19.1
Rb/Sr	.971	1.62	1.09	.206	.397	.771	.393	.442	.117	.058	.168	.221	.379	.187	.293	.148
[1] Eu/Eu^*_n	.73	1.33	ND	.62	.70	—	—	—	.95	—	—	—	.62	—	—	—
[2] Ce/Yb_n	78.3	5.64	ND	16.2	4.9	—	—	—	76.4	—	—	—	16.8	—	—	12.9

TABLE 3.—*Trace-element abundances (in parts per million) in the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*—Continued

[ND, not determined or absent; —, analysis inconclusive, calculation not made owing to lack of data, or not applicable]

	OWLS HEAD GROUP OF PLUTONS															
	Sugar Hill pluton			Landaff pluton		Moody Ledge plutons			Owls Head pluton					Baker Pond pluton		
Analysis no.	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Field no.	OL122	OL127	OL213	OL130	OL339-1	OL156	OL229	OL160	OL133-1	OL151	OL146-2	OL147	OL246	OL165	OL142	OL143
Rb	73	80	60	80	46	130	130	83	150	95	162	149	165	138	154	109
Sr	104	35	157	36	129	97	138	203	237	91	79	120	191	572	469	900
Ba	842	1533	1035	1420	1212	1360	1382	1816	1710	577	700	2080	1990	1921	1690	1675
Th	7.9	14.7	6.9	13.5	8.0	17.9	ND	ND	19.3	ND	28.7	22.1	ND	ND	25.0	25.3
Zr	115	199	132	240	551	290	ND	ND	147	ND	193	260	ND	ND	330	331
Hf	3.0	6.6	3.2	6.0	11.9	6.6	ND	ND	4.2	ND	5.2	6.3	ND	ND	6.8	7.2
Ta	.51	.73	.46	.57	.55	.98	ND	ND	.45	ND	.67	.49	ND	ND	.74	.62
Y	23	59	ND	ND	ND	27	ND	ND	19	ND	ND	ND	ND	ND	ND	ND
Co	1.4	.9	1.8	.6	2.0	1.2	ND	ND	2.8	ND	.9	1.6	ND	ND	3.9	15.6
Cr	2.2	—	4.2	—	—	—	ND	ND	—	ND	—	—	ND	ND	—	48.2
Sc	5.2	3.73	5.74	4.14	13	3.75	ND	ND	4.56	ND	3.35	5.01	ND	ND	6.81	14.7
La	21	40	18	52	42	38	ND	ND	80	ND	39	61	ND	ND	48	63
Ce	40	93	32	100	96	80	ND	ND	121	ND	74	102	ND	ND	86	113
Nd	15	37	13	47	50	25	ND	ND	36	ND	33	38	ND	ND	33	46
Sm	3..6	7.4	2.5	10.2	11.9	4.6	ND	ND	4.6	ND	5.0	5.7	ND	ND	6.1	7.1
Eu	.50	.62	.56	.70	2.87	.66	ND	ND	.72	ND	.49	1.0	ND	ND	1.25	1.57
Gd	2.8	5.9	2.7	8.5	12.1	3.9	ND	ND	2.8	ND	3.4	4.3	ND	ND	4.2	ND
Tb	.39	1.35	.38	1.75	1.81	.60	ND	ND	.36	ND	—	.58	ND	ND	.59	—
Dy	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Er	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Yb	2.2	6.4	2.0	6.8	8.7	2.6	ND	ND	1.9	ND	2.1	2.3	ND	ND	1.8	1.7
Lu	.34	.91	.32	.98	1.26	.40	ND	ND	.33	ND	.33	.36	ND	ND	.32	.23
K/Rb	489	394	554	384	436	292	268	380	254	210	292	318	236	170	248	320
K/Ba	42.4	20.6	32.0	21.6	16.6	28	25.2	17.4	22.4	34.6	67.6	22.8	19.6	19.4	22.6	20.8
Rb/Sr	.702	12.28	.382	2.22	.357	1.34	.942	.409	.633	1.04	2.05	1.24	.864	.241	.328	.121
[1] Eu/Eu^*_n	.47	.28	.66	.23	.73	.47	—	—	.57	—	.35	.60	—	—	.72	—
[2] Ce/Yb_n	4.7	3.7	4.1	3.8	2.8	7.9	—	—	16.4	—	9.1	11.4	—	—	12.3	17.0

	SOUTHERN NEW HAMPSHIRE AND NORTHERN MASSACHUSETTS PLUTONS										
	Smarts Mountain pluton		Mascoma pluton			Lebanon pluton			Croydon pluton	Warwick pluton	
Analysis no.	33	34	35	36	37	38	39	40	41	42	43
Field no.	OL46	OL47	OL30-1	OL30-2	OL171	OL33-1	OL43-1	OL35-2	OL173	OL4	OL9
Rb	45	119	159	178	144	187	146	112	131	145	90
Sr	184	131	338	183	380	108	331	624	473	256	76
Ba	1218	1555	1600	677	ND	432	1213	1250	1920	1205	380
Th	10.0	9.3	22.2	32.5	ND	39.3	ND	11.1	27.3	31.1	5.7
Zr	125	180	128	—	ND	—	ND	190	270	79	70
Hf	4.1	4.7	3.9	2.5	ND	4.8	ND	4.5	3.4	2.2	2.2
Ta	.26	.28	.78	1.01	ND	.95	ND	.51	.63	1.09	.44
Y	23	ND	17	ND	ND	ND	ND	ND	ND	20	ND
Co	2.2	3.0	1.9	.7	ND	1.5	ND	12.9	4.1	1.2	3.7
Cr	—	—	—	—	ND	—	ND	25.0	4	1.9	—
Sc	7.37	8.87	2.71	1.55	ND	3.07	ND	18.3	4.91	2.68	9.8
La	21	19	42	18	ND	54	ND	33	67	32	12
Ce	43	36	66	37	ND	99	ND	63	103	52	27
Nd	15	11	18	19	ND	36	ND	34	32	15	9
Sm	3.0	2.7	3.0	4.0	ND	6.5	ND	5.9	4.1	2.8	2.0
Eu	.57	.40	.57	.39	ND	.52	ND	1.20	.81	.41	.36
Gd	2.2	2.5	—	4.1	ND	4.3	ND	5.4	—	—	2.2
Tb	.51	—	—	.37	ND	.55	ND	.62	.3	—	.39
Dy	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Er	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Yb	2.9	2.0	1.3	1.3	ND	1.7	ND	1.8	1.0	1.2	2.5
Lu	.44	.29	.19	.20	ND	.27	ND	.29	.15	.20	.41
K/Rb	350	314	246	266	270	226	260	244	272	258	258
K/Ba	12.9	24.0	24.4	69.8	ND	98.0	31.4	21.8	18.6	31.0	61.2
Rb/Sr	.245	.908	.470	.973	.379	1.73	.441	.179	.277	.566	1.18
[1] Eu/Eu^*_n	.65	.47	—	.29	—	.29	—	.64	—	—	.53
[2] Ce/Yb_n	3.8	4.6	13.1	7.3	—	15.0	—	9.0	26.5	11.2	2.8

TABLE 3.—*Trace-element abundances (in parts per million) in the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*—Continued

[ND, not determined or absent; —, analysis inconclusive, calculation not made owing to lack of data, or not applicable]

SWANZEY AND MONSON GNEISSES AND HIGHLANDCROFT PLUTONIC SUITE

Analysis no.	Swanzey Gneiss 44	45	46	47	Monson Gneiss 48	49	50	51	52	53	54	Highlandcroft Plutonic Suite[3] 55	56	59	60
Field no.	OL23	OL278	OL289	OL290-1	WD40	WD64-2	WD64-3	WD65	WD67-3	WD77-1	WD79	OL95	OL97A	OL425A	OL424-1
Rb	21	122	44	101	41	62	18	39	25	18	42	86	92	55	63
Sr	137	74	104	76	113	52	48	132	159	659	596	563	634	459	490
Ba	190	432	311	603	206	395	345	229	175	153	484	1182	1076	1444	1220
Th	1.1	7.3	4.2	9.8	2.57	6.2	6.01	ND	ND	37.1	ND	ND	ND	ND	ND
Zr	—	73	100	110	80	94	126	82	56	160	76	ND	ND	145	1598
Hf	1.0	1.9	2.6	2.9	2.35	3.38	4.27	ND	ND	4.14	ND	ND	ND	ND	ND
Ta	—	.52	.28	.22	.183	.358	.333	ND	ND	1.32	ND	ND	ND	ND	ND
Y	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Co	4.3	2.9	3.5	1.0	12	.7	.4	ND	ND	9.9	ND	ND	ND	ND	ND
Cr	—	2.2	—	.9	7.6	<2	3.6	ND	ND	27.7	ND	ND	ND	ND	ND
Sc	14.5	9.46	11.0	4.10	22.7	9.1	11.0	ND	ND	9.7	ND	ND	ND	ND	ND
La	5	ND	16	29	10.4	14.5	13.4	6	6	72.7	5	ND	ND	ND	ND
Ce	11	39	30	55	19.0	37.7	28.5	25	24	112	15	ND	ND	ND	ND
Nd	7	16	15	23	10.1	<24	18.0	ND	ND	37.2	ND	ND	ND	ND	ND
Sm	2.6	2.8	3.3	3.8	3.18	4.89	4.50	ND	ND	5.83	ND	ND	ND	ND	ND
Eu	1.22	.39	.60	.42	.635	.480	.561	ND	ND	1.14	ND	ND	ND	ND	ND
Gd	—	2.8	3.7	2.4	3.2	5.5	5.6	ND	ND	3.9	ND	ND	ND	ND	ND
Tb	.66	.33	.55	.58	.509	.790	.912	ND	ND	.402	ND	ND	ND	ND	ND
Dy	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Er	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Yb	2.2	1.5	4.7	2.2	2.74	5.22	5.52	ND	ND	1.20	ND	ND	ND	ND	ND
Lu	.39	.25	.73	.37	.423	.76	.821	ND	ND	.222	ND	ND	ND	ND	ND
K/Rb	250	191	246	286	446	534	858	468	458	340	434	290	389	348	356
K/Ba	—	53.8	17.9	47.8	88.6	84.0	44.8	79.8	65.4	40.2	37.8	21.0	34.0	13.2	18.4
Rb/Sr	.153	1.65	.423	1.33	.362	1.19	.375	.295	.159	.027	.070	.153	.145	.119	.129
[1] Eu/Eu^*_n	—	.42	.53	.40	.61	.28	.34	—	—	.69	—	—	—	—	—
[2] Ce/Yb_n	1.3	6.7	1.6	6.4	1.79	1.86	1.33	—	—	24.1	—	—	—	—	—

MAFIC AND INTERMEDIATE AMMONOOSUC VOLCANICS[4]

Analysis no.	Hornblende-plagioclase amphibolite 61	62	63	64	65	66	67	69	70	71	72	73	74	75	76
Field no.	H-2	H-5	M-8	M-10	M-12	M-15	OL524	OL79-6	G136	OL386	OL120-1	OL120A	OL361-1	OL361-3	OL373-3
Rb	<2	7	4	3	<2	9	48	2	3	55	31	20	21	<2	5
Sr	102	274	158	112	162	174	211	115	130	122	224	197	117	185	311
Ba	56	108	ND	36	51	189	83	38	44	ND	282	ND	363	27	77
Th	.8	.4	.6	1.4	.6	.4	.8	ND	.6	ND	2.2	3.3	1.4	.9	ND
Zr	133	112	38	55	48	—	133	ND	35	ND	90	74	41	23	72
Hf	3.8	2.8	.7	1.5	1.1	3.6	3.3	ND	.7	ND	1.3	2.1	1.2	.7	2.4
Ta	.20	.20	.06	—	.06	—	.26	ND	.07	ND	.29	.42	—	—	—
Y	38	23	9	19	15	ND	34	ND	9	ND	13	21	20	15	30
Co	45	40	38	46	48	45	42	ND	44	ND	25	32	44	34	43
Cr	152	220	312	452	269	212	241	ND	140	ND	90	160	31	33	194
Sc	44	37	41	43	53	42	39	ND	41	ND	33	27	53	41	39
La	8	6	2	3	4	ND	ND	ND	3	ND	ND	12	6	7	20
Ce	20	15	5	12	10	22	23.4	ND	6	ND	21.1	24	15	12	45
Nd	18	13	—	11	9	18.7	17.9	ND	5	ND	9.67	13	9	8	14
Sm	6.1	4.6	.9	2.9	2.6	5.69	5.10	ND	1.1	ND	2.55	2.9	2.3	1.8	2.8
Eu	1.71	1.26	.35	.82	.84	2.04	1.78	ND	.41	ND	.835	.74	.61	.50	.68
Gd	6.4	5.1	1.3	3.4	2.8	7.31	5.1	ND	1.5	ND	2.60	2.5	2.4	—	3.4
Tb	1.28	1.16	—	—	—	ND	ND	ND	.24	ND	ND	.39	.40	.26	.32
Dy	ND	ND	ND	ND	ND	7.8	6.95	ND	ND	ND	2.61	ND	ND	ND	ND
Er	ND	ND	ND	ND	ND	4.67	4.19	ND	ND	ND	1.59	ND	ND	ND	ND
Yb	4.5	3.2	1.0	2.3	1.9	4.15	3.82	ND	1.1	ND	1.49	1.9	1.9	1.3	2.4
Lu	.74	.45	.17	.36	.34	ND	ND	ND	.18	ND	ND	.31	.31	.23	.39
K/Rb	2034	842	340	1466	728	488	190	664	858	306	508	748	384	830	796
K/Ba	72.6	54.6	—	122	29.2	49.4	110	35.0	58.6	—	56.0	—	22.2	61.4	51.8
Rb/Sr	.020	.026	.025	.026	.008	.052	.227	.017	.023	.451	.138	.102	.179	.011	.016
[1] Eu/Eu^*_n	.84	.80	1.0	.80	.96	.98	1.06	—	—	—	.99	.81	.79	—	.68
[2] Ce/Yb_n	1.14	1.20	1.28	1.34	1.35	1.36	1.57	—	—	—	3.65	3.25	2.04	2.38	4.83

TABLE 3.—*Trace-element abundances (in parts per million) in the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*—Continued

[ND, not determined or absent; —, analysis inconclusive, calculation not made owing to lack of data, or not applicable]

	MAFIC AND INTERMEDIATE AMMONOOSUC VOLCANICS									
	Hornblende-plagioclase amphibolite				Amphibolite containing Ca-poor amphiboles					
Analysis no.	77	78	79	80	81	82	83	84	85	86
Field no.	OL161	OL449-1	OL32A	OL262	G291	OL402	G112-A	OL79-2	G109A	G189A
Rb	4	36	41	<2	31	74	20	7	11	12
Sr	143	326	203	241	120	118	249	214	112	97
Ba	ND	342	592	38	258	260	84	62	44	191
Th	.5	ND	1.2	1.1	1.1	ND	ND	1.4	ND	4.9
Zr	40	77	71	38	90	31	79	58	ND	ND
Hf	.9	ND	2.0	1.2	2.2	ND	ND	1.4	ND	2.9
Ta	.03	ND	.09	.06	.10	ND	ND	.14	ND	.5
Y	10	36	21	16	38	74	24	16	ND	ND
Co	59.7	ND	39	46	41	ND	ND	35	ND	15.6
Cr	486	ND	257	—	19	ND	ND	12	ND	—
Sc	23	ND	34	35	52	ND	ND	36	ND	23
La	3	ND	ND	ND	5	ND	ND	4	ND	15
Ce	8	ND	18.7	14.2	14	ND	ND	10	ND	30
Nd	—	ND	12.2	8.42	9	ND	ND	6	ND	15
Sm	1.5	ND	3.26	2.31	3.2	ND	ND	2.0	ND	3.4
Eu	.62	ND	1.10	.744	.90	ND	ND	.75	ND	.85
Gd	—	ND	3.71	2.62	3.8	ND	ND	—	ND	3.5
Tb	—	ND	ND	ND	1.04	ND	ND	—	ND	.89
Dy	ND	ND	3.92	2.63	ND	ND	ND	ND	ND	ND
Er	ND	ND	2.41	1.55	ND	ND	ND	ND	ND	ND
Yb	1.1	ND	2.24	1.40	4.5	ND	ND	2.1	ND	2.9
Lu	.15	ND	ND	ND	.63	ND	ND	.30	ND	.40
K/Rb	352	276	174	124	230	168	158	404	98.2	200
K/Ba	—	29.2	12.0	6.52	27.6	47.8	37.6	45.4	24.6	12.6
Rb/Sr	.028	.110	.202	.008	.258	.627	.080	.033	.098	.124
[1] Eu/Eu^*_n	—	—	.98	.93	.80	—	—	—	—	.76
[2] Ce/Yb_n	1.87	—	2.14	2.62	.80	—	—	1.22	—	2.67

	Felsic Ammonoosuc Volcanics (quartz keratophyre)													Metasomatized felsic Ammonoosuc		
Analysis no.	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Field no.	OL79-7	OL198-1	OL398	OL219-2	OL316-1	OL356	OL235-1	OL235-2	OL445	OL451	OL139	OL32C	OL270-1	OL11	OL241	OL241C	OL244
Rb	4	<2	39	22	31	32	84	24	25	23	32	11	3	6	125	86	126
Sr	81	102	43	70	143	87	237	78	181	225	64	93	214	110	309	335	374
Ba	48	69	259	336	531	212	1930	187	861	3520	794	245	86	20	1956	1139	2783
Th	4.5	ND	8.1	6.0	5.9	5.6	13.1	ND	ND	ND	5.9	4.0	5.5	3.1	ND	21.1	ND
Zr	190	ND	180		180	110	160	ND	ND	173	120	130	220	120	ND	198	ND
Hf	4.4	ND	4.3	3.6	2.8	3.1	4.8	ND	ND	ND	3.7	3.5	5.2	4.8	ND	5.5	ND
Ta	.65	ND	.58	.6	.33	.38	.36	ND	ND	ND	.47	.21	.50	.17	ND	.27	ND
Y	ND	ND	60	ND	ND	16	ND	ND	ND	22	ND	22	ND	ND	ND	—	ND
Co	3.8	ND	1.4	.8	4.5	2.9	3.8	ND	ND	ND	1.2	5.6	11	5.9	ND	1.3	ND
Cr	—	ND	—	1.5	1	1	4.1	ND	ND	ND	—	1.1	2	—	ND	2.7	ND
Sc	10.9	ND	7.3	6.9	5.2	6.2	7.5	ND	ND	ND	6.0	6.5	11.1	13.7	ND	5.7	ND
La	16.6	ND	28.9	ND	ND	ND	ND	ND	ND	ND	—	—	—	—	ND	72	ND
Ce	35.9	ND	56.8	ND	ND	ND	ND	ND	ND	ND	35.5	28.7	40.5	ND	—	122	ND
Nd	22.1	ND	26.8	ND	ND	ND	ND	ND	ND	ND	15.8	14.0	22.6	ND	ND	39	ND
Sm	5.65	ND	6.20	ND	ND	ND	ND	ND	ND	ND	3.21	2.94	5.34	ND	ND	5.7	ND
Eu	1.22	ND	.758	ND	ND	ND	ND	ND	ND	ND	.434	.579	.971	ND	ND	.92	ND
Gd	7.3	ND	7.5	ND	ND	ND	ND	ND	ND	ND	2.26	2.46	4.59	ND	ND	4.3	ND
Tb	1.05	ND	1.08	ND	ND	ND	ND	ND	ND	ND	ND	.52	ND	ND	ND	—	ND
Dy	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	.933	1.36	3.11	ND	ND	ND	ND
Er	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	.268	.529	1.51	ND	ND	ND	ND
Yb	4.75	ND	4.06	ND	ND	ND	ND	ND	ND	ND	.258	.558	1.50	ND	ND	1.6	ND
Lu	.755	ND	.661	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	.24	ND
K/Rb	249	1328	210	416	318	238	207	230	532	434	416	234	138	402	246	270	310
K/Ba	20.8	38.2	22.8	27.2	18.6	36.0	18.7	29.8	15.4	2.42	16.7	10.5	4.8	120	15.7	20.4	14.0
Rb/Sr	.049	.02	.907	.314	.217	.368	.354	.308	.138	.102	.500	.118	.014	.055	.405	.242	.337
[1] Eu/Eu^*_n	.78	—	.45	—	—	—	—	—	—	—	.47	.65	.59	—	—	.55	—
[2] Ce/Yb_n	20.66	—	18.82	—	—	—	—	—	—	—	35.47	13.27	6.96	—	—	19.5	—

TABLE 3.—*Trace-element abundances (in parts per million) in the Oliverian Plutonic Suite and related gneisses, the adjacent Ammonoosuc Volcanics, and associated trondhjemite*—Continued

[ND, not determined or absent; —, analysis inconclusive, calculation not made owing to lack of data, or not applicable]

	Holts Ledge volcanic sequence					
Analysis no.	104	105	106	107	108	109
Field no.	OL163	OL252–2	OL32F	OL32G	OL32H	OL32K
Rb	5	12	<2	6	7	22
Sr	310	263	98	191	310	139
Ba	ND	281	28	232	96	680
Th	4.8	4.4	3.4	3.8	3.7	3.4
Zr	—	100	226	133	120	—
Hf	2.6	3.6	6.5	3.7	3.0	3.2
Ta	—	.26	.23	.31	.30	—
Y	ND	35	ND	ND	25	ND
Co	2.9	1.2	.4	1.5	2.9	3.3
Cr	—	—	—	—	—	—
Sc	15.2	9.7	5.1	7.3	9.3	8.4
La	ND	11.6	10.5	13	ND	ND
Ce	ND	22.1	22.5	27.	ND	ND
Nd	ND	16	18	15	ND	ND
Sm	ND	3.7	5.38	3.7	ND	ND
Eu	ND	.78	1.31	.55	ND	ND
Gd	ND	4.3	7.6	5.0	ND	ND
Tb	ND	.77	1.56	.51	ND	ND
Dy	ND	ND	ND	ND	ND	ND
Er	ND	ND	ND	ND	ND	ND
Yb	ND	4.1	9.46	3.9	ND	ND
Lu	ND	.61	1.29	.54	ND	ND
K/Rb	531	190	208	131	65.3	187
K/Ba	ND	8.12	14.8	3.40	4.76	6.04
Rb/Sr	.016	.046	.020	.033	.023	.158
[1] Eu/Eu^*_n	—	.60	.63	.47	—	—

	Ammonoosuc trondhjemite																	
	Berlin area			Landaff pluton	West Lebanon–White River Junction area				Croydon dome		Unity dome		Alstead dome			Vernon dome		Warwick dome
Analysis no.	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127
Field no.	OL60	OL203	OL208	OL341	OL39–1	OL507–1	OL507–2	OL502	OL309–2	OL310	OL293	OL301	OL267A	OL272–1	OL561–1	OL15	OL20	OL288A
Rb	32	53	7	<2	20	3	<2	29	22	16	22	41	2	9	34	46	21	98
Sr	174	146	51	38	90	98	103	120	119	97	39	101	112	159	121	88	205	96
Ba	763	225	107	70	404	69	30	326	340	676	270	290	26	99	236	282	95	216
Th	3.7	8.0	ND	11.6	10.9	3.5	ND	ND	3.3	5.6	4.3	3.3	6.17	3.5	3.6	4.0	4.7	6.0
Zr	196	135	ND	240	66	121	148	62	100	180	150	100	135	56	80	—	93	130
Hf	5.1	3.3	ND	7.3	ND	4.1	ND	ND	2.8	5.0	4.4	3.0	3.98	2.5	41	2.6	2.5	3.1
Ta	.3	.42	ND	.63	ND	.56	ND	ND	.22	.37	.31	.20	.39	.33	.27	—	—	3.9
Y	28	ND	ND	70	26	40	45	23	ND	70	43	ND	ND	ND	18	—	28	40
Co	2.2	.6	ND	.3	ND	1.3	ND	ND	4.0	1.6	.7	2.8	4.0	4.2	5.5	1.9	2.8	2.0
Cr	—	1.4	ND	—	ND	—	ND	ND	1.6	1.5	2.4	1.4	<2	2.8	1.9	2	—	1.1
Sc	9.8	5.3	ND	5.0	ND	13.4	ND	ND	11.3	12.6	9.0	13.5	9.19	16.3	15	9	11.8	6.9
La	ND	26.4	ND	ND	26.6	ND	15.4	10.0	ND	ND	11.8	ND	15.2	9.9	12.6	18.8	ND	ND
Ce	ND	46.5	ND	ND	48.7	ND	31.8	19.2	ND	ND	27.2	ND	32.1	20.5	23.6	37.2	ND	ND
Nd	ND	20	ND	ND	22	ND	19	ND	ND	ND	14.6	ND	17	—	—	20	ND	ND
Sm	ND	4.3	ND	ND	4.7	ND	4.83	2.6	ND	ND	4.00	ND	4.1	2.79	2.8	4.20	ND	ND
Eu	ND	.73	ND	ND	.421	ND	1.03	.50	ND	ND	.392	ND	.52	.57	.69	.790	ND	ND
Gd	ND	4.2	ND	ND	4.3	ND	5.3	2.8	ND	ND	4.4	ND	4.0	3.1	—	3.3	ND	ND
Tb	ND	.66	ND	ND	.64	ND	.90	.45	ND	ND	.86	ND	.78	.63	.54	.66	ND	ND
Dy	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Er	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Yb	ND	3.20	ND	ND	2.74	ND	4.81	2.23	ND	ND	5.22	ND	3.8	2.91	2.89	3.20	ND	ND
Lu	ND	.539	ND	ND	.404	ND	.721	.393	ND	ND	.768	ND	.57	.483	.470	.53	ND	ND
K/Rb	286	188	368	1080	340	554	124	344	460	664	370	256	1038	323	244	252	134	85.6
K/Ba	12.0	44.2	24.0	308	16.8	24.0	8.32	30.6	29.8	15.7	30.2	36.0	79.8	29.4	35.2	41.2	29.7	38.8
Rb/Sr	.183	.363	.137	.053	.222	.031	.019	.242	.185	.165	.564	.406	.018	.057	.281	.523	.102	1.02
[1] Eu/Eu^*_n	—	.52	—	—	.28	—	.62	.30	—	—	.32	—	.47	.60	—	.56	—	—
[2] Ce/Yb_n	—	3.72	—	—	4.54	—	1.69	2.20	—	—	1.33	—	2.16	1.80	2.09	2.99	—	—

[1] $Eu^*_n=(Sm_n-Gd_n)/2$. $(Eu/Eu^*_n)<1$ corresponds to a negative Eu anomaly; $(Eu/Eu^*_n)>1$ corresponds to a positive Eu anomaly. Normalizing values (Anders and Ebihara, 1982): La, 0.309; Ce, 0.807; Nd, 0.599; Sm, 0.195; Eu, 0.073; Gd, 0.258; Tb, 0.047; Yb, 0.208; Lu, 0.032.

[2] Ce/Yb_n is normalized Ce/Yb ratio. See footnote 1 for normalizing values.

[3] Analyses 57 and 58 omitted.

[4] Analysis 68 omitted.

5*A*). In the Berlin area, trondhjemite typically forms dikes and small plugs cutting the Ammonoosuc Volcanics (fig. 3*A–D*). An isolated exposure of amphibolite cut by trondhjemite occurs just south of West Lebanon (fig. 4*A*). Near White River Junction, abundant sills of trondhjemite have been injected into dark-gray, pervasively silicified chloritic schist and dark graphitic phyllite (gneiss at White River Junction of Lyons (1955)) (fig. 4*B–D*). The aspect in these cuts is highly chaotic, in places an intrusive breccia of fractured and deformed rocks (fig. 4*B–C*). The trondhjemite sills (dikes), mostly concordant but locally crosscutting, range from a few centimeters to several meters thick, commonly widening and narrowing over short distances as though tectonically (plastically?) thinned and boudinaged (fig. 4*D*). The intrusive relationship appears reversed in some places where angular trondhjemite blocks in an amphibolite matrix form an intrusive breccia in which basalt was the mobile phase (fig. 5*A*). These rocks are intensely sheared and fractured, possibly a consequence of their location within a few hundred meters west of the Ammonoosuc fault. Along Interstate 91, 3.5 km north of the Ompompanoosuc River and about 2.5 km southeast of the Ammonoosuc fault, trondhjemite sills enclose angular amphibolite fragments, whereas, elsewhere in the same cut, amphibolite forms straight-walled sills (dikes) having chilled margins (fig. 5*B*).

LARGER TRONDHJEMITE MASSES

Trondhjemite gradational to tonalite forms a subelliptical plug 10 km southeast of Lebanon, N.H. (gneiss east of Plainfield, N.H. (Lyons, 1955, p. 121)) (pl. 1). Contacts between this tonalitic gneiss and Ammonoosuc amphibolite east of Plainfield are locally sharp (fig. 5*C*); elsewhere, the tonalitic gneiss is gradational over distances of tens of meters to rather mafic compositions (up to 50 percent hornblende+epidote+chlorite). At the northeastern margin of the Croydon dome, trondhjemite intrudes mafic Ammonoosuc in a zone hundreds of meters wide in which trondhjemite becomes progressively more abundant relative to amphibolite (fig. 5*D*).

In the Alstead dome, the small northern lobe of core gneiss is overlain by a mixture of Ammonoosuc Volcanics and intruding trondhjemite dikes and sills (see fig. 13*A*). The relatively small area of trondhjemite and the relatively broad aureole of Ammonoosuc Volcanics suggest a high erosion level in the cupola of this dome. By contrast, in the Unity and Vernon domes (to the north and south of the Alstead dome, respectively), trondhjemite gneiss is relatively homogeneous and lacks inclusions or inliers of the Ammonoosuc Volcanics. A well-exposed contact on the eastern side of the Vernon dome north and south of the town of Hinsdale, N.H., is sharp, parallels the trace of the regional foliation, and shows only rare trondhjemite dikes intruding amphibolite. No granitic rocks were found in either dome. The erosional levels in these two domes evidently are deeper than the level in the Alstead dome, which lies between them.

CONTACT RELATIONSHIPS OF THE AMMONOOSUC VOLCANICS

Significant contact relationships, summarized in table 1, are discussed in more detail under descriptions of individual domes. Some Oliverian plutons (for example, the Jefferson batholith and the Sugar Hill pluton) locally intrude the Ammonoosuc Volcanics, but others (for example, the Whitefield Gneiss) appear to be nonconformably overlain by the Ammonoosuc. Nonconformable contacts between the Ammonoosuc Volcanics and the underlying Monson Gneiss are locally exposed in northern Massachusetts, notably in the Quabbin Reservoir area (P. Robinson, oral commun., 1985), but the Ammonoosuc-Monson contact may be intrusive elsewhere (Tucker and others, 1989) (see "Isotopic Age(s) of the Ammonoosuc Volcanics and Related Rocks").

Many documented Oliverian-Ammonoosuc intrusive contacts are confined to small intrusions within the Ammonoosuc Volcanics, but others are more extensive. In the northeastern part of the Jefferson batholith, Oliverian gneiss cuts the Dead River Formation, the Ammonoosuc Volcanics, and the Quimby Formation (R.H. Moench, written commun., 1988). Lebanon gneiss near the southern end of the Lebanon pluton cuts the Partridge and Quimby Formations (J.B. Lyons, oral commun., 1988). Oliverian granite appears to cut the Holts Ledge volcanic sequence in the Mascoma dome (Naylor, 1969) (see fig. 1*C*). Nevertheless, the relative vertical confinement of the Oliverian plutons, in a regional sense, is one reason why their crosscutting relationships with the Ammonoosuc Volcanics are still being questioned (for example, Robinson and others, 1986, p. 196). Although the geometry of the domes in this context is still incompletely known, available data suggest that they are cored by relatively shallow plutons that may constitute several sheets of varying thickness and extent (see Billings and Fowler-Billings, 1975).

ISOTOPIC AGE(S) OF THE AMMONOOSUC VOLCANICS AND RELATED ROCKS

Isotopic dating of the Ammonoosuc Volcanics and associated subjacent gneisses has, until recently, yielded less than satisfactory results, mainly because of the negligible zircon content in the felsic phase of the Ammonoosuc Volcanics. Whole-rock Rb-Sr isochron dating typically produced scattered data that could not be

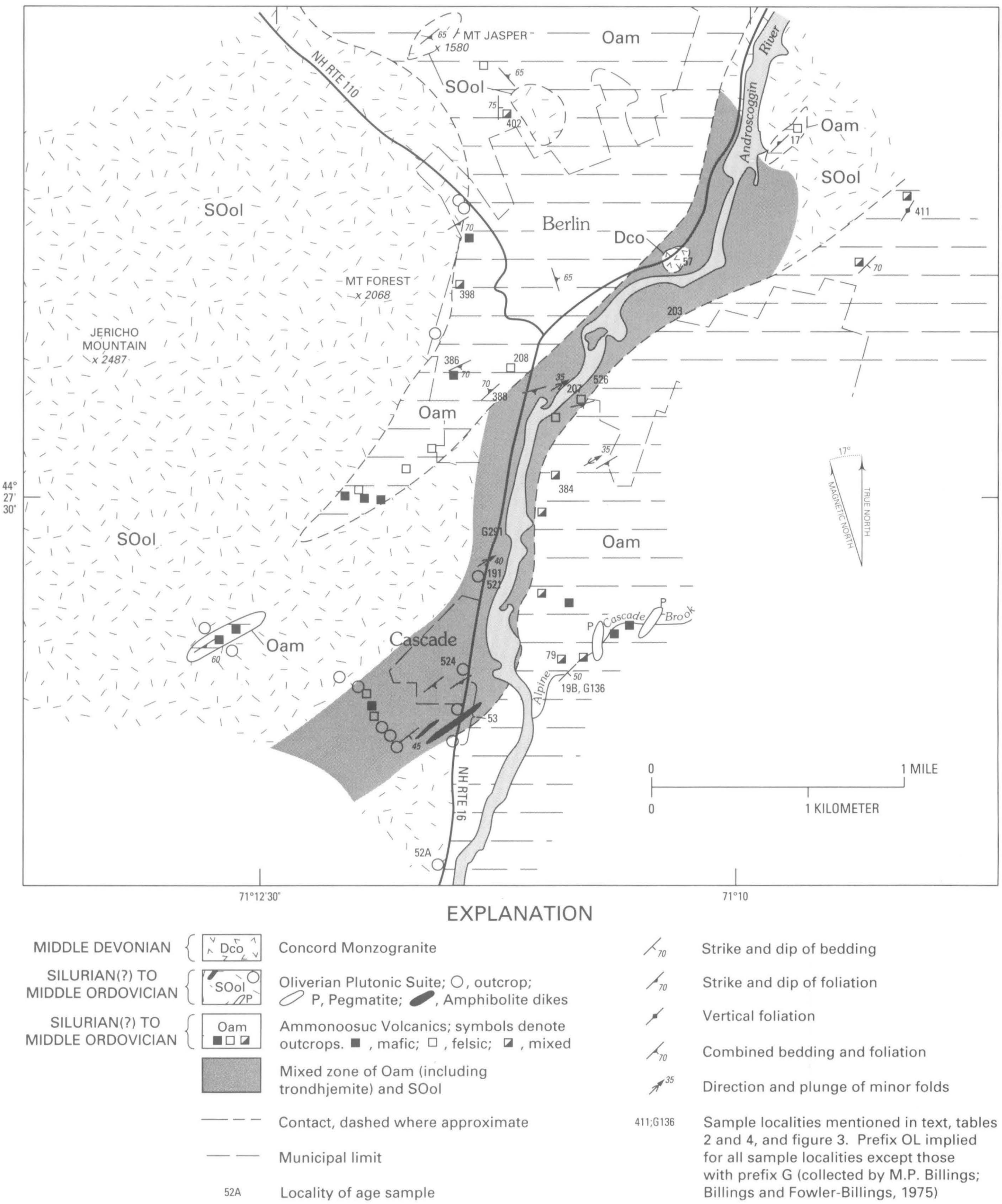


FIGURE 2.—Geology of the Berlin area of New Hampshire (northern part of Gorham 7½-min quadrangle of New Hampshire).

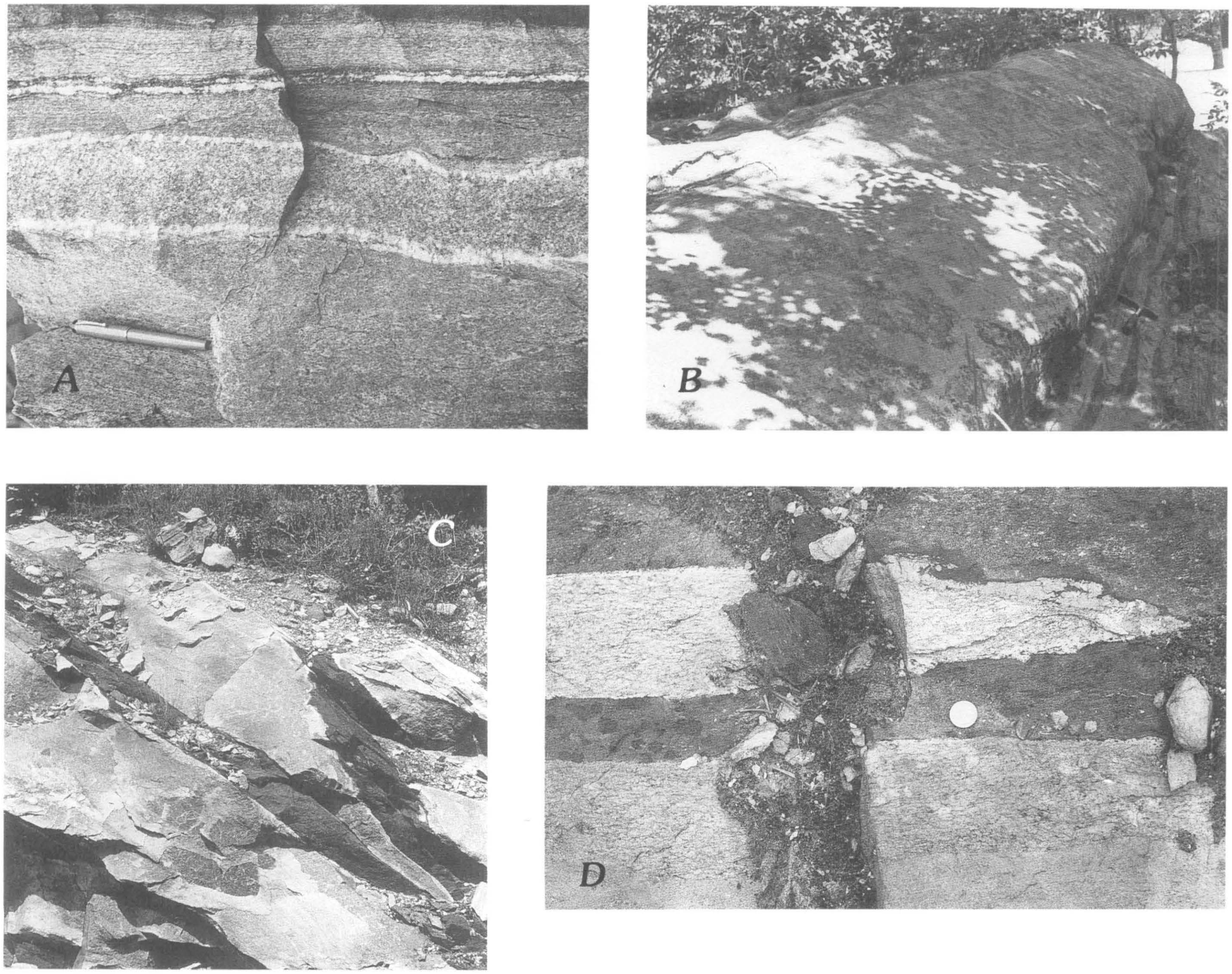


FIGURE 3.—Trondhjemite associated with Ammonoosuc Volcanics, Berlin area of New Hampshire. *A*, Slightly crosscutting trondhjemite sill in felsic Ammonoosuc Volcanics. Western edge of Berlin, 6th Avenue at Madigan Street (fig. 2, loc. 398). Pen gives scale. *B*, One-meter trondhjemite sill intruding layered mafic and felsic Ammonoosuc (under hammer). First Avenue near Hill Street, Berlin (fig. 2, loc. 388). *C*, Slabs of amphibolite enclosed by trondhjemite plug. Brown Company aeration plant, southern edge of Berlin, eastern side of Androscoggin River (fig. 2, loc. 384). Photograph shows a section 2 m across at the bottom. *D*, Trondhjemite sills (coarser texture) intruding interlayered mafic (center and top) and felsic (bottom) Ammonoosuc. Power line southwest of Bean Brook, 2.7 km northeast of the center of Berlin (fig. 2, loc. 411).

reliably related to primary crystallization ages. Available Rb-Sr whole-rock data published between 1965 and 1985 (cited by Zartman and Leo, 1985) on the Ammonoosuc and equivalent rocks in Massachusetts and Connecticut yield ages ranging from about 450 to 430 Ma. Recent state-of-the-art U-Pb determinations using abraded zircons (Tucker and Robinson, 1990) have yielded significantly more accurate results.

The Ammonoosuc Volcanics were designated as Upper Ordovician by Billings (1937) on the basis of unconformably overlying, fossiliferous Upper Silurian Fitch Formation. Subsequently, the Ammonoosuc was considered to be Middle Ordovician on the basis of graptolites in a black shale (equivalent to the Partridge Formation) interpreted to overlie similar volcanics in the Cupsuptic 15-min quadrangle of west-central Maine (Harwood and Berry, 1967). Reexamination of this critical locality (R.H. Moench, written commun., 1982) now shows the black shale to lie within rather than above the Ammonoosuc. The graptolite assemblage there correlates with zone 12 (Berry, 1968) or, more specifically, with the lower part of that zone (S.C. Finney, oral commun.,

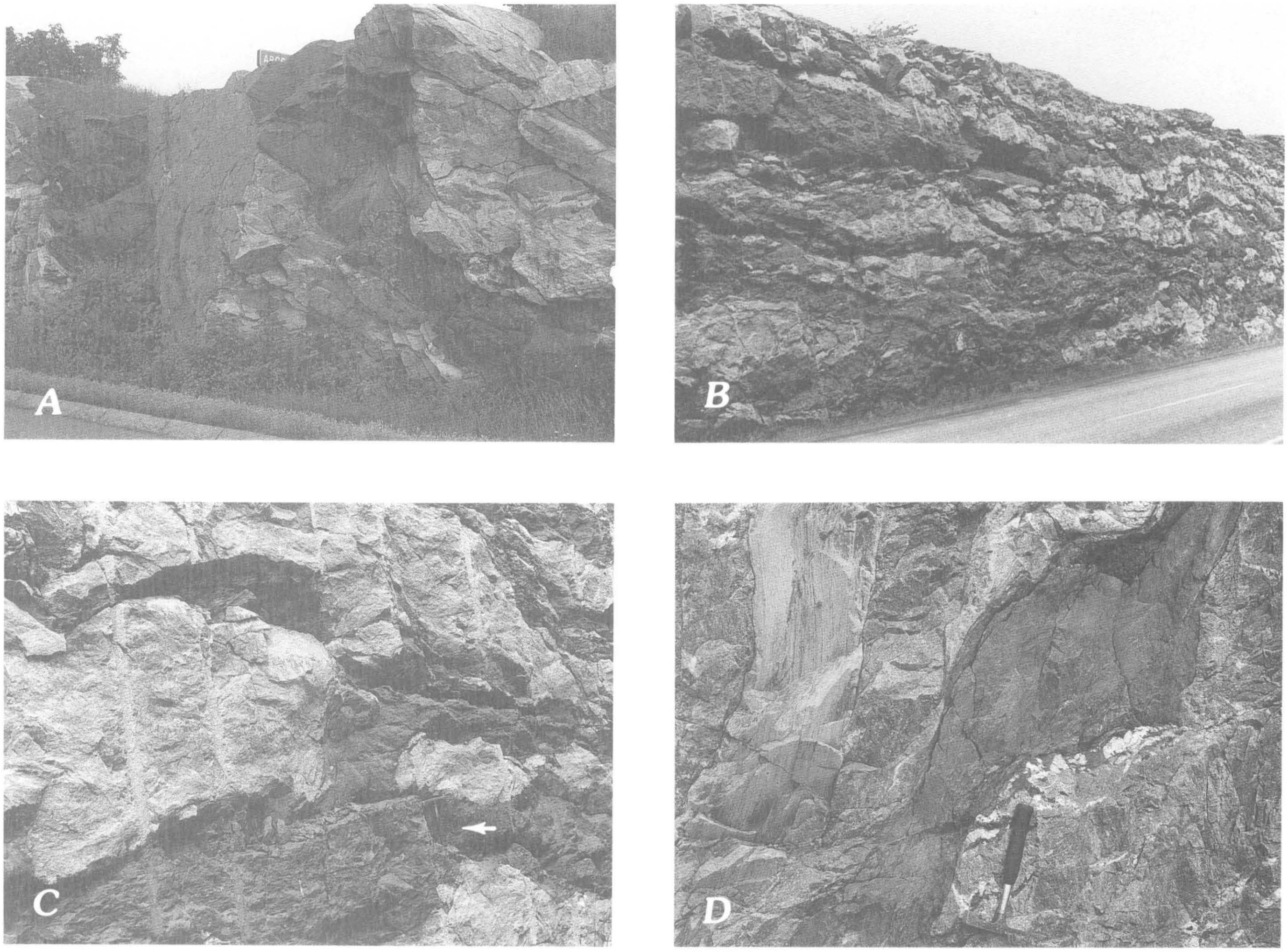


FIGURE 4.—Trondhjemite-amphibolite relationships near West Lebanon, N.H., and White River Junction, Vt. (see fig. 10). *A*, Trondhjemitic gneiss (light gray) cutting Ammonoosuc amphibolite. Western side of interchange between Interstate 89 and New Hampshire Route 12A south of West Lebanon. *B*, Ammonoosuc Volcanics injected by trondhjemite (white). Cut on Interstate 91 about 2 km north of White River Junction. Height of cut approximately 10 m. Extremely shattered aspect may be related to post-Acadian movement on the Ammonoosuc fault approximately 0.5 km to the east. *C*, Detail of preceding exposure. The lensoid, boudinaged appearance of both trondhjemite and the amphibolite matrix indicates a plastic condition. Hammer (right center) gives scale. *D*, Plastically deformed trondhjemite (left) and tonalite (right) dikes in a mostly trondhjemite matrix. Cut on Interstate 91 south of White River, about 1 km northwest of White River Junction.

1982). Recent evaluation of the Ordovician time scale on the basis of $^{40}Ar/^{39}Ar$ age spectrum dating (Kunk and Sutter, 1984; M.J. Kunk, oral commun., 1982) suggests a corresponding isotopic age having a minimum value of 454±3 Ma. This age, corresponding to early Late Ordovician (Caredocian) (DNAG Geologic Time Scale, 1983), is here regarded as the best estimate for the black shale horizon in the Cupsuptic area and is in excellent accord with a recent U-Pb zircon age determination on quartz-phyric rhyolite (Ammonoosuc) of 453±2 Ma (Tucker and Robinson, 1990) and is also in accord with U-Pb ages in the range of 444±8 Ma on rocks of the Oliverian Plutonic Suite that widely intrude Ammonoosuc Volcanics on the Oliverian domes (Zartman and Leo, 1985).

Recent mapping by R.H. Moench (unpub. map, 1989) and Moench and others (1987) has demonstrated lithologic correlation between the Ammonoosuc Volcanics of the New Hampshire section and the Ammonoosuc section of western Maine (Old Speck Mountain 15-min quadrangle) (Milton, 1961). In the latter area, rocks very similar to the Ammonoosuc Volcanics in New Hampshire overlie the Lower Ordovician Dead River Formation (formerly the Albee Formation) and underlie the Upper Ordovician Quimby Formation. The Ammonoosuc in this area is intruded by gabbro, tonalite, and sheeted diabase

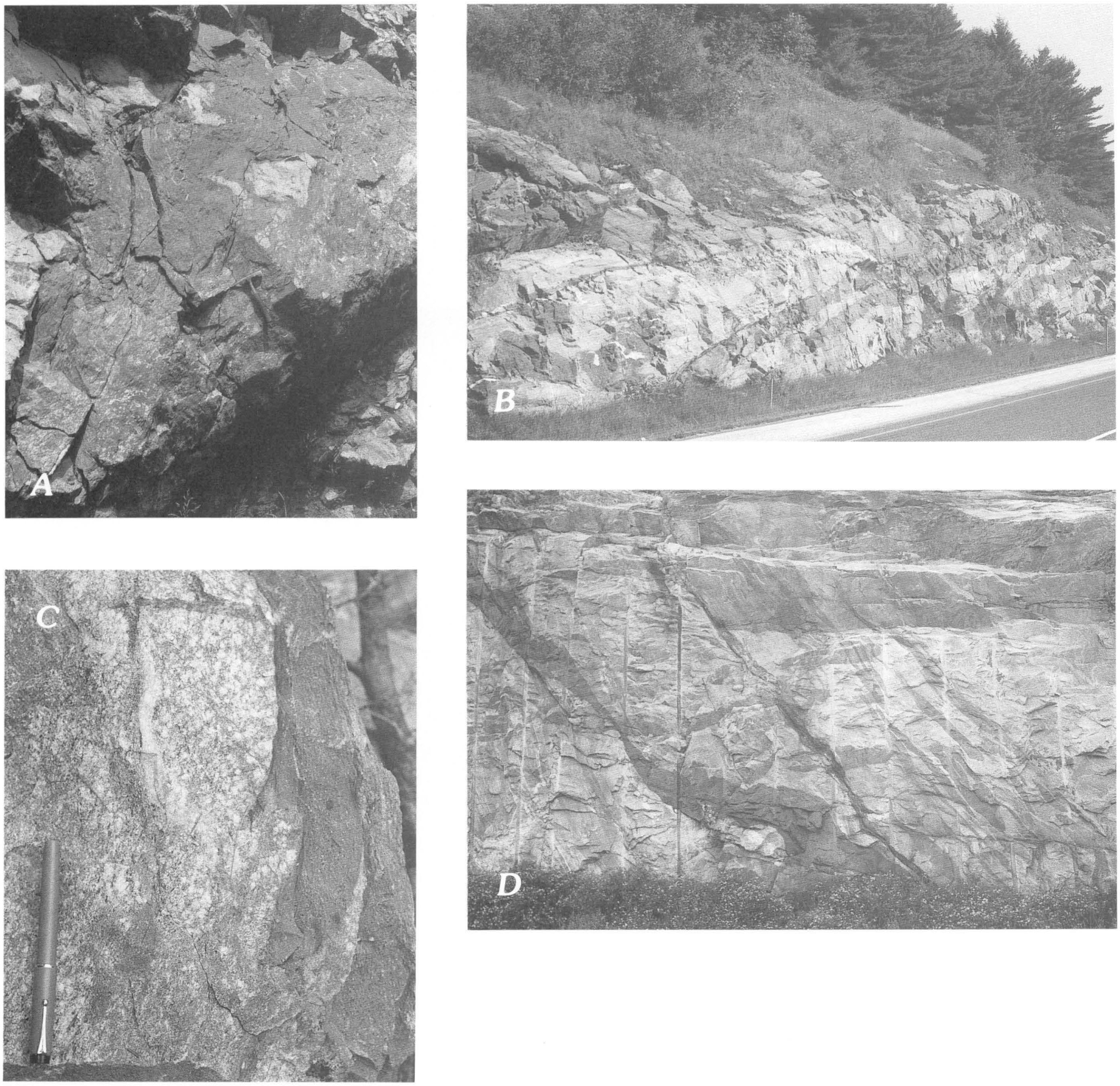


FIGURE 5.—Trondhjemite-amphibolite relationships near West Lebanon, N.H., and White River Junction, Vt., and elsewhere in western New Hampshire (see fig. 10). *A*, Angular trondhjemite blocks in matrix of amphibolite; basalt protolith of amphibolite was the intrusive phase. Interstate 91, 2 km north of White River Junction. *B*, Amphibolite sills (dark) in trondhjemite gneiss. Interstate 91, 11 km north of Norwich exit (3 km north of Ompompanoosuc River). *C*, Amphibolite fragments in metatonalite (Plainfield gneiss of Lyons (1955)). Pen gives scale. Porter Road, about 5.8 km northeast of Plainfield (Hanover 15-min quadrangle of New Hampshire). *D*, Shadowy tabular inclusions of Ammonoosuc amphibolite in trondhjemitic gneiss. Northern end of Croydon dome, roadcut on western side of Interstate 89, approximately 1 km west of North Grantham (Mascoma 15-min quadrangle of New Hampshire) (see fig. 10).

as well as by Oliverian granitic gneiss and can be traced west and southwest in the vicinity of Milan and Berlin, N.H. Tonalite intruding the Ammonoosuc Volcanics (Chickwolnepy tonalite) yields a U-Pb zircon age of 465±4 Ma (Aleinikoff and Moench, 1987), which puts a younger limit on the age of the Ammonoosuc in western Maine. Recent U-Pb determinations on rhyolite tuffs of the Partridge Formation (449±3 Ma) and Ammonoosuc

Volcanics (453±2 Ma) from northern Massachusetts have been reported (Tucker and Robinson, 1990). No reliable U-Pb ages on Ammonoosuc keratophyre or on associated trondhjemite have been determined in central to northern New Hampshire as yet.

Along the Bronson Hill anticlinorium in central Massachusetts and south into Connecticut, the Ammonoosuc Volcanics structurally overlie the Monson Gneiss, a massively layered quartz-plagioclase gneiss, and associated plagioclase gneisses, including the Fourmile, Swanzey, and Pauchaug Gneisses. Earlier, somewhat discordant $^{207}Pb/^{206}Pb$ age values spanning an approximate range of 439 to 431 Ma (average age, 435±6 Ma; hence, earliest Silurian) were obtained on the Monson Gneiss (R.E. Zartman, as cited by Leo and others, 1985). New and probably more accurate U-Pb age determinations on these gneisses (Tucker and Robinson, 1990) span the approximate range of 454 to 442 Ma. Contacts between the Ammonoosuc Volcanics and the plagioclase gneisses—notably the Monson Gneiss—have heretofore been regarded as unconformable (Robinson and Hall, 1980; Hall and Robinson, 1982) or gradational (Peper, 1966, p. 33–35). In view of the virtual overlap of the new age determinations on the Ammonoosuc Volcanics and plagioclase gneisses, the unconformity hypothesis has been abandoned (P. Robinson and others, written commun., 1989). Nevertheless, given the field relationships that led to the identification of unconformable contacts in the first place, some unconformable and gradational contacts are likely to be valid. They may reflect relatively short and repeated intervals of erosion and redeposition within the Ammonoosuc outcrop areas instead of, as previously assumed, one major erosional hiatus between the Ammonoosuc and the gneisses. The temporal relationships between the Ammonoosuc Volcanics and underlying calc-alkaline Oliverian plutons along the Bronson Hill anticlinorium to the north are not affected by the new data, because, as mentioned earlier, some (if not all) of the plutons are younger than the associated volcanics. Intrusive contacts between the Ammonoosuc Volcanics and Oliverian plutons are therefore to be expected and are locally mappable and (or) exposed along the Bronson Hill anticlinorium. The new U-Pb data on plagioclase gneisses indicate that they, too, must be intrusive into the Ammonoosuc, at least in part.

It remains to emphasize the seemingly significant age disparity between the Ammonoosuc section in northern Massachusetts and that in central to northern New Hampshire. The U-Pb age of 465±4 Ma for the Chickwolnepy tonalite (Aleinikoff and Moench, 1987), which intrudes the lower member of the Ammonoosuc east of Milan, N.H. (R.H. Moench, written commun., 1988), defines a minimum age of the Ammonoosuc about 12 m.y. older than that of the recently dated Massachusetts sample (Tucker and Robinson, 1990). Additional dating of representative samples of Ammonoosuc Volcanics and stratigraphically or structurally adjacent units throughout the Bronson Hill anticlinorium will be required to establish a reliable and consistent geochronologic basis for the correlation, or perhaps lack thereof, between the Ammonoosuc sections in various parts of the region. The recent advent of high-precision U-Pb dating gives reason to hope that such determinations are not far in the future.

OLIVERIAN PLUTONIC SUITE AND OTHER ROCKS IN CORES OF DOMES

The gneissic rocks in the interiors of Oliverian domes are the major focus of this paper. There are four distinct types of gneisses, although only the first type is Oliverian in the strict sense:

1. Compositionally homogeneous, intrusive plutons displaying slight to strong foliation are typically granite but include subordinate syenite, granodiorite, and minor tonalite. Examples of these plutons occur in the Jefferson and Owls Head domes.
2. Trondhjemite related to the Ammonoosuc Volcanics, which is almost certainly not comagmatic with the granite plutons.
3. Thickly layered to nearly homogeneous quartz-plagioclase gneisses (the plagioclase gneisses of Thompson and others (1968)), are probably mostly of volcanic origin. The major representatives are the Monson, Fourmile, and Swanzey Gneisses. Such gneisses locally resemble the felsic phase of the Ammonoosuc Volcanics but are typically coarser grained, include more amphibolite, and have a higher proportion of rocks of intermediate composition. Given their apparent isotopic ages (see preceding section), the Monson and related gneisses are likely to intrude Ammonoosuc, but few such contacts have been identified. Unconformable and (or) gradational contacts with Ammonoosuc have been observed locally.
4. Layered gneisses, including paragneisses, quartzite, and calcareous granofels in addition to metavolcanic rocks, are at least in part of Late Proterozoic age. This lithology is seen in the Pelham dome (Ashenden, 1973), which is not generally included with the Oliverian domes and is not discussed further in this paper. Finally, felsic to mafic, evidently high-level plutons yielding Ordovician ages constitute the Highlandcroft Plutonic Suite. These rocks, exposed only on the northwestern side of the Ammonoosuc fault, are chemically distinct from the Oliverian Plutonic Suite and probably are not comagmatic. The Highlandcroft

plutons are not related to domal structures, but they extensively intrude the Dead River (formerly Albee) Formation and the Ammonoosuc Volcanics west of the axis of the Oliverian domes (see Naylor, 1968). Both the Oliverian and the Highlandcroft plutons are nonconformably overlain by near-shore and on-shore Silurian and Lower Devonian rocks (Clough Quartzite and overlying rocks) (see fig. 1).

TECTONIC DEVELOPMENT

Early studies of rocks in the Oliverian domes have variously described the petrology and field relationships (Balk, 1956; Billings, 1937; Billings and Keevil, 1946; Billings and others, 1946; Billings and Rabbit, 1947; Chapman, 1939, 1942; Chapman and others, 1944; Chapman, 1949; Hadley, 1942,; Kruger, 1946; Lyons, 1955; Moore, 1949b). Until about 1950, the gneissic cores of the domes were regarded as simple plutons that had domed the overlying strata by the force of their intrusion. Because the youngest deformed layers are as young as Early Devonian (Littleton Formation), the Oliverian plutons were then regarded as post-Early Devonian. Intrusive contacts with mantling Ordovician rocks were mapped, or assumed, in all the domes. Contacts with Silurian rocks were tacitly assumed to be intrusive but were never satisfactorily documented (for example, the Mascoma dome) (Chapman, 1939). The post-Early Devonian age of the Oliverian plutons has been disproved by Naylor (1969), Foland and Loiselle (1981), Aleinikoff and Moench (1985), and Zartman and Leo (1985). A U-Pb age of 435±3 Ma (earliest Silurian) has recently been obtained on an outlier of the Moody Ledge pluton, but, because the sample was strongly sheared, this apparent age cannot be regarded as fully reliable (J.N. Aleinikoff, oral commun., 1990). Recognition of the dominantly Late Ordovician age of the plutons compels the conclusion that the development of the domes was a two-stage process, initiated by intrusion of the central plutons in the Ordovician and followed by the actual doming, in the Devonian, of both the core gneisses and the mantling strata, in some areas accompanied by the formation of giant nappes (Thompson and others, 1968, and references therein). The doming was probably a response to (1) the moderate to intense deformation of the Acadian orogeny and (2) the density contrast between the plutons and the mantling rocks, which caused the former to rise like bubbles (Thompson, 1950; Thompson and others, 1968; Robinson and Hall, 1980). As mentioned earlier, investigation of contact relationships has revealed that the picture of simple and ubiquitous intrusion of the Ammonoosuc Volcanics by Oliverian plutons assumed in some earlier studies requires modification.

DESCRIPTIONS OF INDIVIDUAL DOMES AND PLUTONS

Descriptions of individual Oliverian domes, emphasizing their interior gneisses, follow. The domes are described generally from north to south. Lithology and contact relationships are summarized in table 1. Chemical data for dome gneisses are given in tables 2 and 3. Sample characterizations and locations are in the appendix.

Field coverage of some domes was not comprehensive, particularly for the Jefferson dome, which was studied only in selected areas of good exposures. Smaller domes were typically sampled in several traverses. The Swanzey and Monson Gneisses and the Highlandcroft Plutonic Suite were sampled only locally to get a representative impression of their characters. Additional data on the Monson Gneiss in Massachusetts and Connecticut have been presented elsewhere (Leo and others, 1984; Hollocher and Lent, 1987). The Croydon dome was studied only in roadcuts in its northeastern exposure because access to most of the dome is restricted.

JEFFERSON DOME AND BATHOLITH

The large Jefferson dome, the northeasternmost of the Oliverian domes, extends from southwest of Littleton, N.H., to beyond Milan, N.H., for a distance of some 70 km (pl. 1). Its maximum width is approximately 20 km. The granitic core of the dome has been named Jefferson batholith by Moench (1984).

The Jefferson dome lies mainly within the Littleton (Billings, 1937), Whitefield (R.H. Arndt, unpub. data, 1946), Mt. Washington (Billings and others, 1946), and Gorham (Billings and Fowler-Billings, 1975) 15-min quadrangles. Small parts of the dome are in the Franconia (Williams and Billings, 1938) and Percy (Chapman, 1949) 15-min quadrangles. The Milan quadrangle, which contains the northeastern end of the dome, is included on Moench's (1984) geologic map.

Field investigations in the Jefferson dome were limited to detailed reconnaissance in the Berlin and Whitefield areas, where exposures and variety of rock types are especially good, plus brief reconnaissance and sampling in other parts of the dome.

BERLIN AREA OF NEW HAMPSHIRE

Gneiss of the Oliverian Plutonic Suite

Oliverian gneiss in the Berlin area of New Hampshire[4] is of two general types. The predominant type, here

[4] The Berlin area as here defined is equivalent to the Berlin-Randolph area, tables 2 and 3. The town of Randolph is located approximately 13 km (8 mi) southwest of Berlin (see pl. 1).

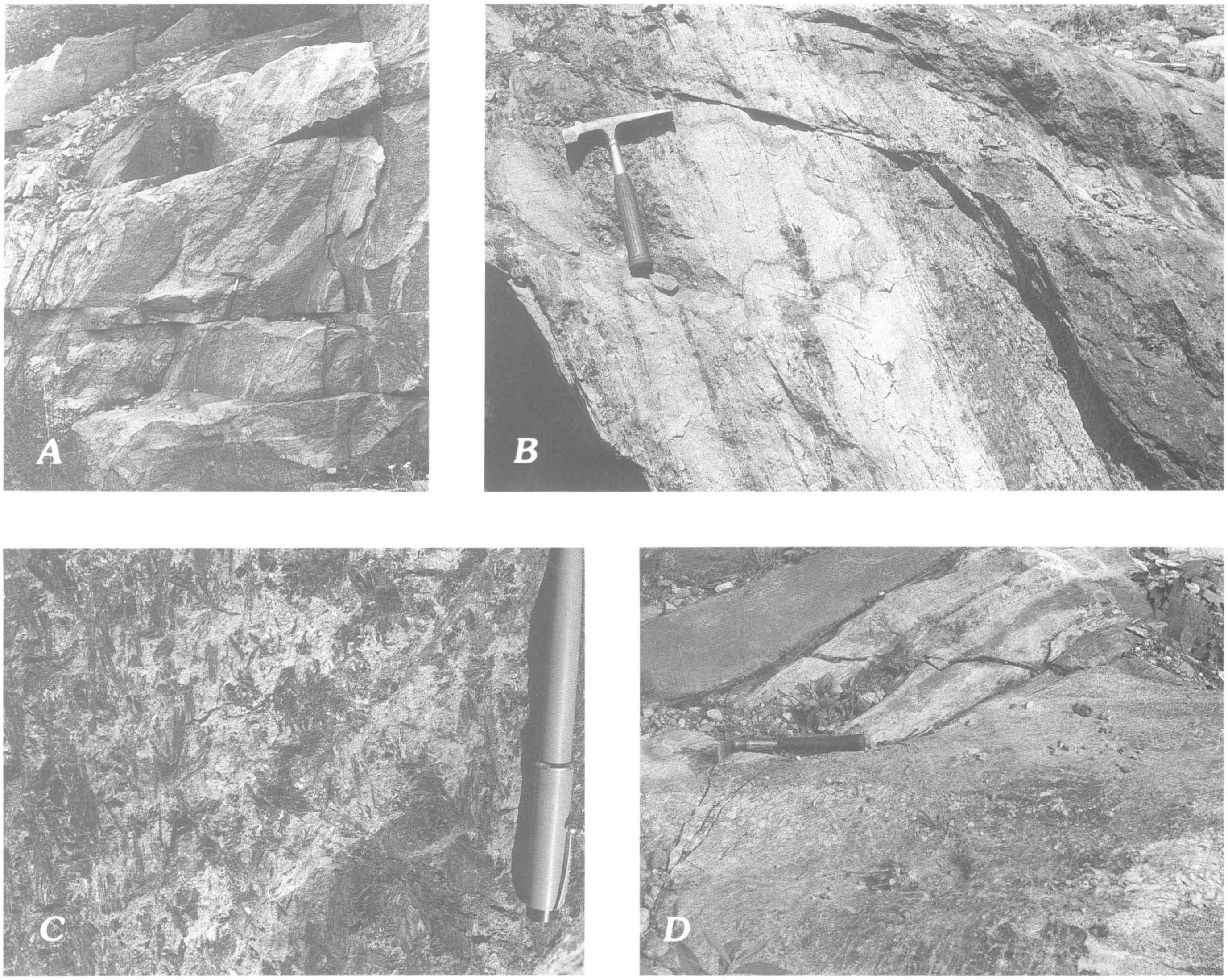


FIGURE 6.—Oliverian gneiss and Ammonoosuc Volcanics in the Berlin area of New Hampshire. *A*, Oliverian gneiss along New Hampshire Route 16 south of Berlin (fig. 2, loc. 53), showing sharply bounded to indistinct pegmatites. *B*, Mafic and felsic gedrite-bearing Ammonoosuc Volcanics. Hammer gives scale. Western side of Berlin High School (fig. 2, loc. 402). *C*, Coarse prisms of gedrite in mafic to intermediate Ammonoosuc Volcanics (detail of fig. 6*B*). Pen gives scale. *D*, Ammonoosuc Volcanics (top of picture) truncated by Oliverian gneiss (below hammer), indicative of an intrusive contact. Northern side of Berlin High School (fig. 2, loc. 402).

referred to informally as pink Berlin gneiss, is medium- to coarse-grained, typically well-foliated granitic gneiss that is well exposed in cuts on New Hampshire Route 16 south of Berlin (fig. 2, locs. 52, 53). This gneiss is typically pink but locally grades over short distances to gray and mottled pink and gray. It carries abundant pegmatites having a mineralogy similar to that of the gneiss but containing a higher proportion of K-feldspar. The pegmatites are generally tabular, occur in swarms, and are concordant to semiconcordant to the regional northeastern foliation. Contacts are mostly gradational, blurred, or smeared out, indicative of comagmatic intrusion (fig. 6*A*). However, some pegmatite contacts are sharp and crosscutting. The concordant, indistinctly bounded pegmatites probably represent a late Oliverian phase comagmatic with the pink gneiss. The crosscutting, sharply bounded pegmatites could be Devonian (New Hampshire Plutonic Suite) or even younger (Billings and Fowler-Billings, 1975, p. 15).

The other major type of Oliverian gneiss in the Berlin area, hereafter referred to informally as gray Berlin gneiss, is a light-gray, well-foliated, conspicuously biotitic rock apparently equivalent to Chapman's (1949) gd unit. The biotite forms blotchy aggregates that define the strong northeastern foliation. The gray gneiss is similar texturally to the pink phase but contains much less pegmatite.

The chemical composition of the gray gneiss ranges from trondhjemite to tonalite or granodiorite (table 2, anals. 4–6). Limited data indicate that it is less potassic than the pink gneiss but more potassic than the Ammonoosuc trondhjemite (table 2, anals. 110–127). Contacts between pink and gray gneiss are poorly exposed, so their mutual relationship is uncertain. In roadcuts along New Hampshire Route 110 northwest of Berlin, the gray gneiss is intruded along sharp to diffuse contacts by faintly foliated pink aplitic granite that may or may not be comagmatic with the coarser pink Oliverian gneiss. In any case, the gray gneiss, which displays a strong northeast-trending foliation, is almost certainly an Oliverian phase. It has been mapped as a major trondhjemite pluton by Moench (1984). On the basis of the available chemical data discussed earlier, the designation of trondhjemite may be inappropriate, and the gray gneiss is certainly distinct from the Ammonoosuc trondhjemite. An age of 454±9 Ma reported by Aleinikoff and Moench (1987) is somewhat older than the presently accepted composite age of the Oliverian Plutonic Suite (444±8 Ma) (Zartman and Leo, 1985).

Structural Relationship to the Ammonoosuc Volcanics

Recognition of the contacts between Oliverian gneiss and the Ammonoosuc Volcanics is complicated by widespread Ammonoosuc trondhjemite. Before the trondhjemite was recognized as distinct from gneiss of the Oliverian Plutonic Suite, it seemed self-evident that Oliverian gneiss intrudes the Ammonoosuc. Billings and Fowler-Billings (1975, p. 35–38) described and sketched several examples of such contacts in the Berlin area. Although the precise exposures described by Billings and Fowler-Billings were not relocated (in one instance because a house had been built on the site), numerous other intrusive contacts were observed; most of these subsequently proved to be trondhjemite instead of calc-alkaline Oliverian gneiss. A few contacts between Oliverian gneiss and Ammonoosuc Volcanics were located. However, apart from a few significant exceptions, intrusive contacts are on a local scale and seem to represent relatively minor features along regionally subparallel contacts.

This conclusion partly agrees with that reached by Billings and Fowler-Billings (1975). They, however, regarded the Oliverian gneiss as "a gigantic sill [injected] some thousands of feet below the top of the Ammonoosuc Volcanics" (Billings and Fowler-Billings, 1975, p. 34). This interpretation appears unlikely for two reasons:

1. The lithologic variety and complexity of the Oliverian gneisses from dome to dome and even within individual domes make a single sill unlikely.
2. The variation in erosion levels among the various domes, including some spatially contiguous ones such as the Jefferson and the Sugar Hill and related plutons, implies differential thicknesses of some of the Oliverian plutons that are basically incompatible with the concept of a sill. The possibility exists that the plutons are laccoliths.

Contacts between Oliverian gneiss and the Ammonoosuc Volcanics are particularly well exposed at the following three localities:

1. Southwest of New Hampshire Route 110 approximately 12 km northwest of Berlin, a concordant, northeast-trending contact between mafic Ammonoosuc Volcanics and pink Oliverian gneiss is intermittently exposed for about 300 m. One hundred and fifty meters to the southeast along the same contact, aplitic gneiss cuts the Ammonoosuc Volcanics.
2. At the northwestern corner of Berlin High School (fig. 2, loc. 402), Oliverian gneiss has a lobate contact against the Ammonoosuc; reentrants into the Ammonoosuc cut across the foliation (fig. 6*D*).
3. In cuts on the western side of New Hampshire Route 16, 1.4 km south of the Traveler Motel in Berlin (fig. 2, loc. 191), gneiss intrudes Ammonoosuc amphibolite and granofels. Tabular amphibolite inclusions in Oliverian gneiss are exposed locally—for example, in extensive outcrops in the bed of the Androscoggin River.

Straight-walled tabular amphibolite dikes, 0.5 to 4 m wide and showing northeast-trending foliation and well-preserved chilled margins, cut Oliverian gneiss in the Berlin area. Such dikes could be of Ammonoosuc age, but this determination cannot be made from available exposures, and the dikes could be alternatively Silurian or Early Devonian. Swarms of metamorphosed mafic dikes occur in the Sherbrooke-Lewiston area (R.H. Moench, written commun., 1988).

WHITEFIELD AREA OF NEW HAMPSHIRE

Rocks in the Whitefield 15-min quadrangle (Arndt, 1949) include the Whitefield Gneiss, several(?) other Oliverian granitic units, and rocks of the Highlandcroft Plutonic Suite ("Lost Nation group" of Chapman (1948)), discussed in a later section.

The Whitefield Gneiss of Billings (1956) is a strongly foliated, relatively mafic rock ranging in composition from granodiorite to granite and showing a variety of textures. The color varies from pinkish gray to dark gray. Textures range from fine grained and closely laminated, to medium grained and displaying a crenulated, curviplanar foliation, to mylonitic. The mafic constituents (biotite, hornblende, accessory titanite and epidote) range in total abundance from approximately 10 to 25 percent. The chemistry of three samples (table 2, anals. 14–16) reflects the compositional spread, which is actually less in bulk composition than the varied mineralogy would suggest. The development of both foliation and mylonitization increases toward the Ammonoosuc fault. As a result, the gneiss in the vicinity of the fault appears darker, but this darker appearance does not seem to be related to any changes in bulk composition. The Whitefield gneiss bears some resemblance to the Highlandcroft Plutonic Suite except for the lower grade of metamorphism of the latter.

The Bray granite of Arndt (1949) is a quartz syenite in composition and is hereafter referred to informally as Bray syenite. The syenite is mapped as an equant pluton about 2 km in diameter that underlies Bray Hill and adjoining areas about 7 km northeast of Whitefield. The Bray syenite has a distinct northeast-trending foliation, although it is much less pronounced than that of the Whitefield Gneiss. An analysis of the Bray syenite shows about 61 percent SiO_2 and 6 percent K_2O (table 2, anal. 11). Thus, the syenite may be related to Oliverian syenite eastward in the Jefferson dome (Foland and Loiselle, 1981). The Whitefield Gneiss is intruded by Bray syenite(?) in the Israel River about 6 km southeast of Lancaster, N.H. A possible intrusive contact between the Whitefield Gneiss and the Ordovician Dead River (formerly the Albee) Formation is exposed on the southeastern slope of Eustis Hill, 1.5 km south of Littleton, N.H. Other well-exposed intrusive contacts between the Dead River Formation and pink biotite granite (presumed equivalent to pink Berlin gneiss in the Berlin area) were reported by R.H. Moench (written commun., 1988) in the central and eastern part of the Milan 15-min quadrangle.

The Highlandcroft Plutonic Suite, dated at 443 to 453 Ma (Lyons and others, 1986a), extensively intrudes the Dead River (Albee) Formation and Ammonoosuc Volcanics west of the Ammonoosuc fault. Within analytical error, the Highlandcroft and Oliverian Plutonic Suites are of the same age.

OWLS HEAD GROUP OF PLUTONS

The term "Owls Head group of plutons" is here applied to six small plutons located between the Jefferson and Smarts Mountain domes (pl. 1)—that is, between Black Mountain and Mount Cube. From north to south, they are the Sugar Hill pluton, the Landaff pluton, the northern and southern Moody Ledge plutons, the Owls Head pluton, and the Baker Pond pluton. The four northern plutons fall within the Moosilauke 15-min quadrangle, where they were described by Billings (1937) as Sugar Hill quartz monzonite, Landaff granite, and Moody Ledge granite, respectively. The geographical names are retained here, but the informal term "pluton" is substituted for the formal petrographic designations, which, in any case, are not consistently appropriate. In his original study, Billings regarded the Sugar Hill and Moody Ledge plutons as belonging to the New Hampshire magma series (New Hampshire Plutonic Suite) and the Landaff pluton as being part of the White Mountain Plutonic-Volcanic Suite; in his later synthesis, Billings (1955) assigned all of these plutons to the Oliverian Plutonic Suite. As indicated earlier, a composite Late Ordovician age (448±8 Ma) has been established for six Oliverian plutons that include the Owls Head and Sugar Hill plutons (Zartman and Leo, 1985). An Early Silurian age of 435±3 Ma has been reported recently by J.N. Aleinikoff for an outlier of the southern Moody Ledge pluton, but, as stated earlier, this determination is suspect. An age of 454±14 Ma has been determined recently on the Landaff pluton (J.N. Aleinikoff, oral commun., 1988).

The four northern plutons show marked similarities in texture and composition. All four are, for the most part, fine-grained granites, and at least two of them have an associated hypabyssal or eruptive phase. Given these similarities, it would be reasonable to suggest that the four plutons may represent relatively high level cupolas of a single, larger pluton at depth. However, the disparities in their isotopic ages, especially those of the Landaff and Moody Ledge plutons, seem to indicate several distinct magmatic episodes over a period of about 20 Ma (454–435(?) Ma), during which the magma source remained essentially unchanged. Their different ages notwithstanding, the four plutons were emplaced at shallow depths and are exposed at a higher level of erosion relative to the Jefferson and Owls Head domes. These four plutons, as well as the Owls Head, show some evidence of intrusive contacts with Ammonoosuc Volcanics.

The sizes, compositional ranges, and textural variations of the Owls Head and Baker Pond plutons are greater than those of the northern four, but they show relatively little scatter on Harker diagrams and thus may represent a single comagmatic pluton. All six plutons are described chemically and petrologically as one group (tables 2, 3, anals. 17–32, and related plots).

SUGAR HILL PLUTON

The Sugar Hill pluton, the smallest of the four northern plutons of the Owls Head group of plutons, is located approximately 2.5 km southeast of the village of Sugar Hill, N.H. (Sugar Hill 7½-min quadrangle). The pluton comprises an elliptical plug approximately 0.7 by 0.5 km and a broad south-southwest-trending sill some 0.7 km long underlying parts of Ore Hill (fig. 7).

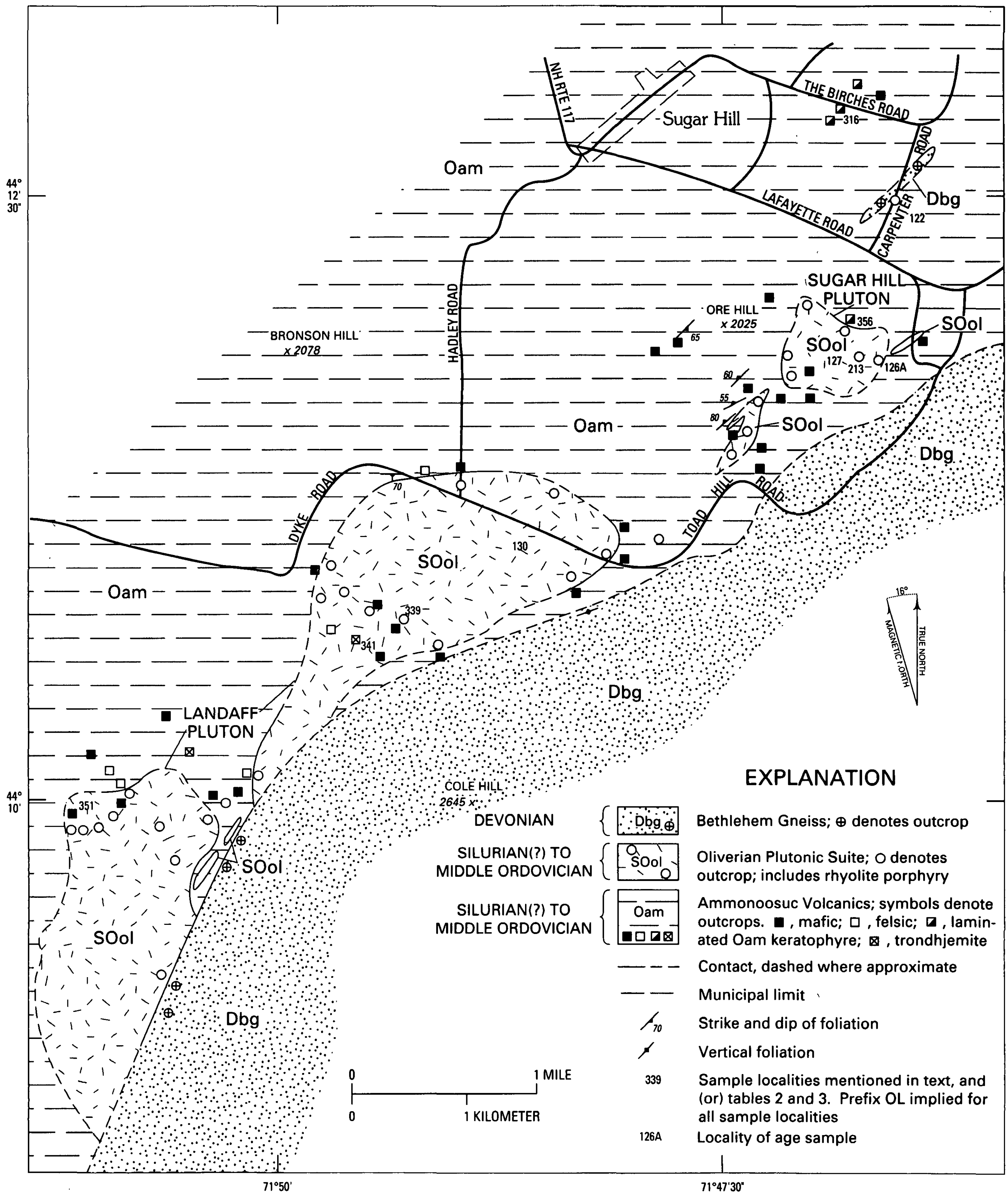


FIGURE 7.—Geology of the Sugar Hill and Landaff plutons (Sugar Hill 7½-min quadrangle of New Hampshire).

The Sugar Hill pluton (Sugar Hill quartz monzonite of Billings (1937, p. 508)) is of two distinct textural types: fine-grained granite and rhyolite porphyry (table 1) having fairly similar compositions (table 2, anals. 17–19). The two phases probably are comagmatic, and contact relationships between them could not be determined. Quite possibly, they are transitional.

Two varieties of Ammonoosuc Volcanics are exposed in the Sugar Hill area. North of the Sugar Hill pluton are scattered large blocks of quartz keratophyre (table 2, anals. 91–92) that are judged to be close to their bedrock source. This keratophyre differs from the finely granular, sugary-textured keratophyre of the Berlin area in being tougher and more coherent and in having a laminated structure along mutually intersecting planes that suggest shearing.

Other than the enigmatic keratophyre, the major Ammonoosuc type is hornblende-(biotite)-plagioclase amphibolite, which underlies most of Ore Hill to the west, southwest, and south of the pluton (see below).

A wedge-shaped, essentially sill-like apophysis of the Sugar Hill cuts Ammonoosuc amphibolite on the southwestern side of the southern peak of Ore Hill (fig. 7). Much of the outcrop area is defined by heavy float only, but the northwestern contact is well controlled for most of its extent and is exposed locally. The contact is sharp; slabs of amphibolite are enclosed in granite near the contact, and dense, dark-green epidote-hornblende-biotite hornfels is developed locally. Northwest of the sill, significant quantities of magnetite occur along several horizons trending northeast parallel to the regional foliation and primary layering. Several trenches have been excavated over a distance of several hundred meters northwest of the granite sill. The largest of these trenches is approximately 30 m deep and extends 150 to 200 m southeast of the visible end of the western branch of the sill, which appears to pinch out at this point. Thus, the distribution of magnetite coincides only partly with the location of the sill. A genetic relationship between the granite and the magnetite deposits is possible but cannot be established without additional detailed studies. In view of the low iron content (approximately 1 percent Fe) in the Sugar Hill gneiss, the latter is an unlikely source of iron. Instead, iron from the amphibolite itself may have become remobilized, partly or wholly in response to the intrusion of the sill, followed by its redeposition as magnetite. Annis (1982) implied that the magnetite is part of a volcanogenic iron formation but cited no evidence other than relict volcanic textures.

LANDAFF PLUTON

The Landaff pluton, actually two distinct outcrop areas separated by Ammonoosuc Volcanics, trends north-northeast to northeast for a distance of about 6 km and has a maximum width of 1.3 km (fig. 7). Most of the Landaff is pink and fine grained and has an average composition of granodiorite (Billings, 1937, table 10 and p. 511) (see table 2, anal. 20). Thus, this rock is somewhat less potassic than the Sugar Hill granite and also appears to lack a hypabyssal phase. Another granitic phase of the Landaff pluton, of unknown abundance and relationship to the above granite, contains approximately 5 percent green-brown biotite and 0 to 2 percent green hastingsitic(?) hornblende, as well as accessory titanite and magnetite (table 2, anal. 21). A detailed description of the Landaff petrography was given by Billings (1937, p. 511).

Amphibolite inclusions, believed to be Ammonoosuc Volcanics, are abundant within the Landaff pluton. Amphibolite, both within the pluton and in the bordering, more extensive exposures, is black, fine- to medium-grained hornblende-plagioclase rock typical of the mafic Ammonoosuc elsewhere in the region. Where bedrock is more continuous, as it is in the nearly sheer cliffs near the western margin of the pluton (fig. 7, loc. 351), slabby, tabular or lensoid amphibolite inclusions in granite are up to 1 m wide and several meters long.

Cream-colored, fine- to medium-grained trondhjemite of less than 1 percent alkali feldspar and only 0.26 percent K_2O (table 2, anal. 113) crops out sporadically within the pluton. The nature of the contacts is unknown. Chemically, this trondhjemite is similar to Ammonoosuc-related trondhjemite and is tentatively regarded as such. On the other hand, it contains accessory minerals (chloritized biotite, titanite, magnetite, and green hornblende) similar to the varietal and accessory minerals of the hornblende-bearing Landaff Granite. Thus, it is possible that this trondhjemite was produced by hydrothermal alteration of granite.

MOODY LEDGE PLUTONS

The term "Moody Ledge granite" was applied to two small plutons north and south of the Wild Ammonoosuc River, the name being taken from a peak that underlies the one to the north (Billings, 1937). The northern pluton, as mapped by Billings, measures 3.7 km long and 1.3 km wide, and the southern pluton measures approximately 3.3×2.5 km. Moench (1984) has remapped the two bodies as a single pluton.

The Moody Ledge plutons are composed of a tan to brownish-gray, fine-grained, weakly foliated to unfoliated granite generally similar to the gneissic granite of the Sugar Hill pluton and the felsic phase of the Landaff pluton (table 1). A hypabyssal phase exhibiting a well-preserved volcanic texture identical to that of the Sugar Hill rhyolite porphyry crops out locally.

Billings (1937, p. 509–510) drew attention to conspicuous contact aureoles around these two plutons, which he interpreted as resulting from extensive potassium metasomatism of bordering Ammonoosuc Volcanics. The present reconnaissance has confirmed the effects of some K-metasomatism, although no attempt was made to retrace the aureoles throughout their entire extent.

The Ammonoosuc Volcanics near the Moody Ledge plutons are K-poor felsic granofels and hornblende-plagioclase-(quartz-biotite) amphibolite. Felsic Ammonoosuc, cropping out fairly continuously from west of Cobble Hill to the Wild Ammonoosuc River (pl. 1), appears to be the phase most affected by K-metasomatism. Unmetasomatized granofels contains the usual quartz-plagioclase assemblage and as much as 20 percent biotite. Locally abundant magnetite accentuates foliation. Metasomatic introduction of K-feldspar can render felsic Ammonoosuc and Moody Ledge Granite very similar, the felsic Ammonoosuc being distinguished in this case mainly by its grayer color and well-defined foliation. Good exposures of the granofels are found in Dearth Brook approximately 2 km north of New Hampshire Route 112 and in the Wild Ammonoosuc River west of the former Woodsville Reservoir (Mt. Moosilauke 7½-min quadrangle) (not shown on pl. 1).

Amphibolite crops out mainly east of the belt of felsic granofels. Conspicuous interlayering of the two types of Ammonoosuc Volcanics, as seen in the Berlin area, was not observed. No Ca-poor amphiboles were found in this area.

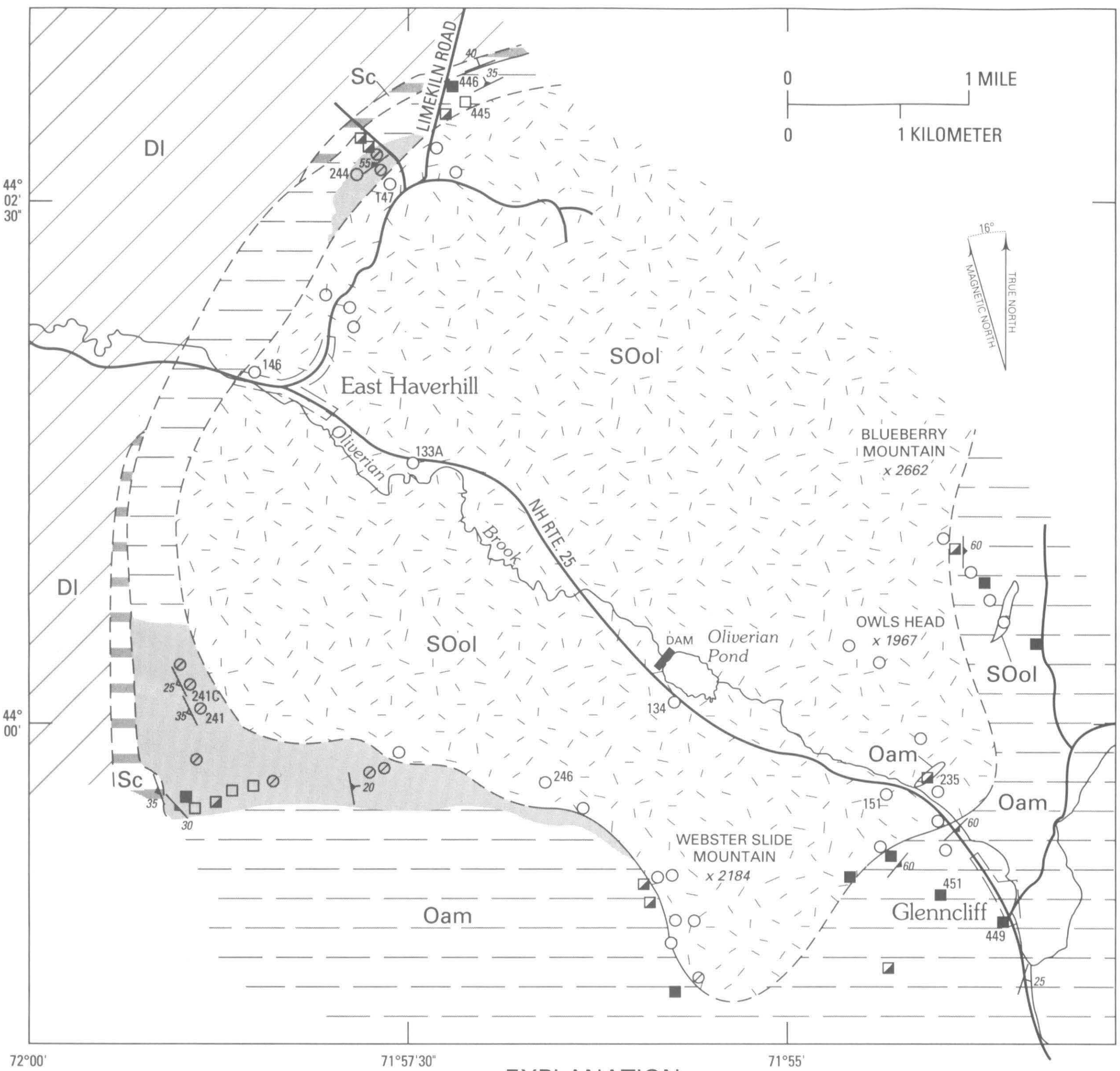
The contact between the northern Moody Ledge pluton and Ammonoosuc Volcanics, as Billings (1937) noted, is gradational through a zone of injection by granite dikes, some on a scale of millimeters. The effect of this metasomatism is evident in pavement outcrops along Cobble Hill trail east of Moody Ledge. Along the trail 2 to 3 km north of New Hampshire Route 112, one passes imperceptibly from the typical fine-grained, pink microgranite to gray, equally granular, massive and brittle rocks differing subtly from granite in texture and mineralogy, as mentioned previously, but containing about the same amount of disseminated K-feldspar. Some outcrops within this zone are normal-appearing Ammonoosuc granofels devoid of K-feldspar, whereas westward, up Moody Ledge, there is unequivocal granite. In Dearth Brook, south of the granite contact, well-layered gray Ammonoosuc granofels varies over short distances from K-feldspar bearing to K-feldspar free. A few sharply bounded granite sills are also exposed there. Similar rocks crop out some 200 m west of the small dam at the former Woodsville Reservoir (Mt. Moosilauke 7½-min quadrangle, 1.2 km from the western edge of the sheet on New Hampshire Route 112), but most of the Ammonoosuc eastward to the dam and beyond is unmetasomatized. A similar contact between granite and felsic Ammonoosuc was noted at the northeastern margin of the southern Moody Ledge pluton. Current observations tend to agree with those of Billings (1937) rather than with those of R.H. Moench (written commun., 1988), who interpreted the potassic granofels as mylonitized Moody Ledge Granite instead of as metasomatized Ammonoosuc Volcanics.

OWLS HEAD DOME AND PLUTON

The Owls Head dome has a nearly circular outline, measuring about 8 km north-south and 7 km east-west (pl. 1, fig. 8). Most of the dome is in the Moosilauke 15-min quadrangle (Billings, 1937), and the remainder is in the Rumney 15-min quadrangle to the south (Page, 1940). The lithology and structure of the Owls Head dome and the associated pluton were described in some detail by Billings (1937, p. 501–502, 535–536), who designated the pluton as Owls Head granite, after the prominent Owls Head cliff 5.5 km southeast of the village of East Haverhill (fig. 8), a name that is retained here. The Owls Head granite is light pinkish gray and gneissic. It has a rather broad, fine-grained border phase on the southern, western, and northwestern margins; in its central and southeastern exposures, the rock is medium grained. The contact between the fine-grained border phase granite and mantling Ammonoosuc Volcanics along most of the southwestern margin is marked by a zone of metasomatism comparable to the one found in the northern Moody Ledge pluton, which renders the contact transitional and locally imperceptible.

The fine-grained marginal phase is distinctly coarser than the gneissic granite of Sugar Hill and lacks the relict volcanic textures. This fact, along with the larger size of the pluton and the coarser grained interior, supports the idea that the Owls Head is exposed at an erosion level deeper than that of the four plutons to the north.

Contact relationships are of two kinds. The first is a progressive K-metasomatism that affects the Ammonoosuc in a zone of variable width along parts of the margin, and the second is sporadic and poorly exposed granitic dikes that cut the Ammonoosuc Volcanics, mostly in the eastern and southeastern parts of the dome. The major evidence for an intrusive contact lies in the broad but irregular contact metasomatic zones. The most extensive of these zones, as much as 1 km wide, is developed at the southwestern side of the Owls Head pluton (fig. 8) and affects virtually all the Ammonoosuc between the pluton and the overlying Clough Quartzite. Another zone about 300 m wide is exposed along a north-trending power line west of Limekiln Road (fig. 8). In outcrop, the metasomatized rock is distinctively pinkish gray and conspicuously massive, showing none of the



EXPLANATION

DEVONIAN	DI	Littleton Formation (from Billings, 1937)
SILURIAN	Sc	Clough Quartzite
SILURIAN(?) TO MIDDLE ORDOVICIAN	SOol	Oliverian Plutonic Suite; ○ denotes outcrop
SILURIAN(?) TO MIDDLE ORDOVICIAN	Oam	Ammonoosuc Volcanics; symbols denote outcrops. ■ , mafic; □ , felsic; ◪ , associated mafic and felsic; ⊘ , metasomatized (mostly felsic); shaded, metasomatized zones

— — — Contact, dashed where approximate

60 Strike and dip of bedding

60 Strike and dip of foliation

60 Combined bedding and foliation

246 Sample localities mentioned in text, and (or) tables 2 and 3, and figure 9*A*. Prefix OL implied for all sample localities

133A Locality of age sample

— — Municipal limit

FIGURE 8.—Geology of part of the Owls Head dome area (East Haverhill and Warren 7½-min quadrangles of New Hampshire).

characteristic friability of the normal felsic granofels. This rock differs from the marginal granite in lacking foliation (as distinct from lamination), in having a grayer color, and in displaying the slabby layering that is characteristic of the unaltered Ammonoosuc. Veins and dikes of pink granite on a scale of centimeters are developed locally (fig. 9*A*). In thin section, the relict clastic texture of the granofels is distinct from the hypidiomorphic-cataclastic texture of the granite. The additional significant distinction between normal and metasomatized granofels is the presence in the latter of 5 to 30 percent K-feldspar, which tends to form crosscutting veins or to be enriched along certain layers and to be absent from adjacent layers. The K_2O content of the metasomatized Ammonoosuc is significantly higher than that of normal Ammonoosuc quartz keratophyre (table 2, anals. 101–103), and it is somewhat lower than the average K_2O content for the Owls Head granite.

Reconnaissance traverses of the granite-Ammonoosuc contact in the Rumney quadrangle suggest that the contact as shown on the published map (Page, 1940) is essentially correct and that the attenuation of the Owls Head pluton in the Rumney quadrangle is real and not an artifact of different identifications of the Ammonoosuc lithologies (notably, the presence or absence of "stratified core gneiss" in the Rumney and Moosilauke (Billings, 1937) 15-min quadrangles). Stratified core gneiss as defined by Naylor (1969) for the Mascoma dome appears to be absent from the Owls Head dome and from the domes to the north.

METASOMATISM VERSUS PRIMARY POTASSIC COMPOSITION

The possibility must be considered that some, if not all, of the K-feldspar-bearing Ammonoosuc granofelses simply reflect primary potassic compositions and have nothing to do with metasomatism. Perhaps the strongest case for this possibility can be made for homogeneous granular rocks in which K-feldspar is evenly disseminated rather than forming veinlets or dikes. However, although it is true that any such sample in isolation can prove nothing about the origin of the K-feldspar, the cumulative evidence in the Owls Head pluton (and, to a lesser extent, in the Moody Ledge pluton) supports a metasomatic origin for the K-feldspar. The principal lines of evidence can be summarized as follows: (1) the irregular form of the aureole, broad only in the southwest, negligible or absent almost everywhere else (possibly reflecting a gentle dip of the pluton on its southwestern side); (2) the local granitic dikelets, occasionally reflected in thin section as concentrations of K-feldspar in otherwise K-feldspar-poor rock; (3) the appearance of K-feldspar in some but not all samples of crystal-lithic tuff on the northwestern margin as well as in the more common Ammonoosuc granofels; (4) the mineralogical and textural similarity of more potassic and less potassic granofelses except for the K-feldspar content of the former; (5) the resemblance of non-K-feldspar bearing granofels to felsic Ammonoosuc granofels elsewhere; and (6) the general sparsity of K-feldspar in any Ammonoosuc lithology away from this area.

SOUTHERN NEW HAMPSHIRE AND NORTHERN MASSACHUSETTS PLUTONS

BAKER POND PLUTON AND ASSOCIATED ROCKS

The Baker Pond pluton, approximately 15 km southwest of the Owls Head pluton (pl. 1), is located mostly in the Rumney 15-min quadrangle (Page, 1940). Its western edge is in the Mt. Cube 15-min quadrangle (Hadley, 1942).

Although it has the characteristics of other Oliverian domes, the Baker Pond pluton and its mantling rocks are not traditionally referred to as a separate dome. Instead, this assemblage has been regarded, at least tacitly, as the southwestern extension of the Owls Head dome, an interpretation accepted in the present study. The terminology for subdivisions of the Baker Pond Gneiss used in this study and summarized in table 1 is that of Page (1940).

The Baker Pond pluton consists of a nonporphyritic facies of light-gray, well-foliated granite gneiss (table 2, anal. 31) similar to the Owls Head granite; a border facies of relatively mafic rock containing hornblende and biotite (table 2, anal. 32); and a porphyritic facies marked by poorly developed microcline porphyroblasts (table 2, anal. 30).

The border facies of the pluton constitutes an early crystallized, more mafic part of the Baker Pond pluton (granodiorite to quartz monzodiorite). The porphyritic and nonporphyritic facies of the pluton are chemically similar, and both are slightly more mafic than the Owls Head granite.

Ammonoosuc Volcanics in the Baker Pond area are represented mostly by even-textured, fine-grained felsic granofels locally interlayered with mafic amphibolite. Massively layered granofels containing 10 percent (total) green hornblende±epidote±garnet±titanite crops out along New Hampshire Route 25A opposite the center of Lower Baker Pond (Warren 7½-min quadrangle of New Hampshire). Similarly layered quartz-plagioclase-biotite±K-feldspar granofels is present in abundant blocks along the western margin of the Baker Pond Gneiss near Clay Hollow Pond (Mt. Cube 15-min quadrangle). These massively layered rocks are comparable to some of the rocks in the Smarts Mountain dome and in the lower part of the Holts Ledge volcanic sequence of the Mascoma dome, described below. Further mapping

FIGURE 9.—Contact features in the Owls Head and Lebanon plutons. *A*, K-metasomatism at macroscopic scale. Lenticles and stringers of Oliverian granite (above pen) along subparallel foliation and bedding planes of the Ammonoosuc Volcanics. Northwestern side of the Owls Head dome (fig. 8, loc. 244). *B*, Coarse granite of the inner part of the Lebanon pluton ("Lebanon granite") showing narrow aplitic dike (right of hammer). Cut in New Hampshire Route 120, approximately 3 km north of junction with Interstate 89. *C*, Contact between Lebanon border gneiss (light outcrops, left) and the Partridge Formation (in shadow, right). Southern side of Interstate 89, West Lebanon, N.H., 0.3 km east of Poverty Lane overpass. *D*, Detail of contact, northern side of Interstate 89. Chisel edge of hammer rests on sharp contact that shows no sign of contact metamorphism or metasomatism and no indication of an unconformity. As exposed, the contact is ambiguous, but it appears more likely to be intrusive than an unconformity.

is needed to confirm (or disprove) the position of these rocks at the base of the Ammonoosuc Volcanics.

Contacts between the Baker Pond Gneiss and Ammonoosuc Volcanics are poorly exposed, and none were seen. Granite sills "in the Ammonoosuc Formation near the border of the body" cited by Hadley (1942, p. 137) were not found. Moreover, no trace of a metasomatic border zone comparable to the one in the Owls Head pluton was found. Thus, although the Baker Pond pluton, as an extension of the Owls Head, may intrude the Ammonoosuc, this supposition cannot be proved on the basis of the present study.

SMARTS MOUNTAIN DOME AND GNEISS

The Smarts Mountain dome is a long, narrow structure trending nearly northward (fig. 10). Most of the dome is located in the southeastern part of the Mt. Cube 15-min quadrangle (Hadley, 1942), and most of the remainder is in the northeastern corner of the Mascoma 15-min quadrangle (Chapman, 1939). A small part of the southeastern end of the dome is in the Cardigan 15-min quadrangle (Fowler-Billings, 1942).

The interior gneiss of the dome, which may or may not be a pluton in the strict sense, is about 18 km long and 3 km wide at its widest point. The relatively long and narrow shape contrasts with the more elliptical forms of most of the other domes, notably the Mascoma and the Owls Head. The peculiar shape of the Smarts Mountain gneiss body has been commented on by Hadley (1942, p. 162), who regarded it and other Oliverian plutons as syntectonic phacoliths. Naylor (1968) proposed that the long, narrow domes such as the Smarts Mountain might be cored by stratified metavolcanic rocks rather than by plutons and hence were more easily deformed. The present reconnaissance suggests that this proposition is true for at least the southern part of the dome. Reconnaissance of the Smarts Mountain dome included traverses to the Smarts Mountain summit along the Appalachian trail and up Pollard Hill in the southern part of the dome (Mascoma 15-min quadrangle) and some partial traverses along roads.

The Oliverian "gneiss" in the Smarts Mountain area is a light-gray, fine- to medium-grained granofels of notably uniform texture and composition. Along the trail to the Smarts Mountain summit, where almost continuous pavement crops out over a distance of approximately 2 km and 380 vertical meters, the granofels appears essentially structureless except for faint and variable foliation and for some local jointing and rare tabular amphibolite layers, both parallel to the foliation. The rock consists of a granoblastic quartz-feldspar mosaic that contrasts with the relict hypidiomorphic texture of most other Oliverian gneisses and may represent a massive, well-sorted tuff protolith. The estimated proportion of plagioclase (An_{16-20} zoned to An_{5-7} margins) to K-feldspar varies between 3:1 and 1:1. Varietal and accessory minerals constitute less than 7 percent and include deep olive-brown biotite, magnetite, garnet, and epidote locally intergrown with allanite. Several analyses of samples at different elevations show a generally progressive increase in K_2O from approximately 1.6 to 3.0 percent over a vertical (stratigraphic?) interval estimated at 280 m (table 4, fig. 11). The increasing K_2O contents downsection are comparable to a similar trend in the Holts Ledge volcanic sequence of the Mascoma dome. Contacts between Smarts Mountain granofels and amphibolite west of the summit of Smarts Mountain appear fairly sharp, but an intrusive contact cannot be established. Regional relationships suggest the possibility of an unconformity (Naylor, 1969, p. 418–419), but the nature of the contact between the Ammonoosuc Volcanics and the underlying volcanic sequence on Smarts Mountain remains undetermined (see fig. 11).

The Pollard Hill area near the southeastern end of the Smarts Mountain dome (Mascoma 15-min quadrangle) (Chapman, 1939) is underlain by interlayered felsic granofels and amphibolites locally rich in epidote. Texturally, these rocks are coarser than the Ammonoosuc but generally comparable to the Holts Ledge volcanic sequence in the northwestern part of the Mascoma dome.

MASCOMA DOME AND PLUTON

The Mascoma dome was originally mapped by Chapman (1939) and Hadley (1942) and was subsequently restudied in some detail by Naylor (1968, 1969), who regarded it as a model for all Oliverian domes (fig. 10). Naylor described the major rock types and their mutual relationships, and he established the radiometric age of the dome as Middle to Late Ordovician.

The Mascoma is one of the largest of the Oliverian domes. Oliverian granitic rocks (Mascoma pluton) underlie an elliptical, north-south trending area about 29 km long and 10 km wide. The inner part of the Mascoma pluton is pink, relatively coarse grained, faintly foliated to nonfoliated biotite-muscovite granite, here informally termed Mascoma granite. This rock approximately corresponds to the mgr unit of Hadley (1942) and is the "unstratified core gneiss" of Naylor (1968, 1969).

Holts Ledge Volcanic Sequence

Overlying the Mascoma granite but underlying the Ammonoosuc Volcanics is a unit consisting predominantly of quartz keratophyre (the "stratified core gneiss" of Naylor (1969), recently changed to the informal designation Holts Ledge Gneiss (Naylor, 1987)). At Holts Ledge (figs. 10, 11; table 2, anals. 104–109), this quartz

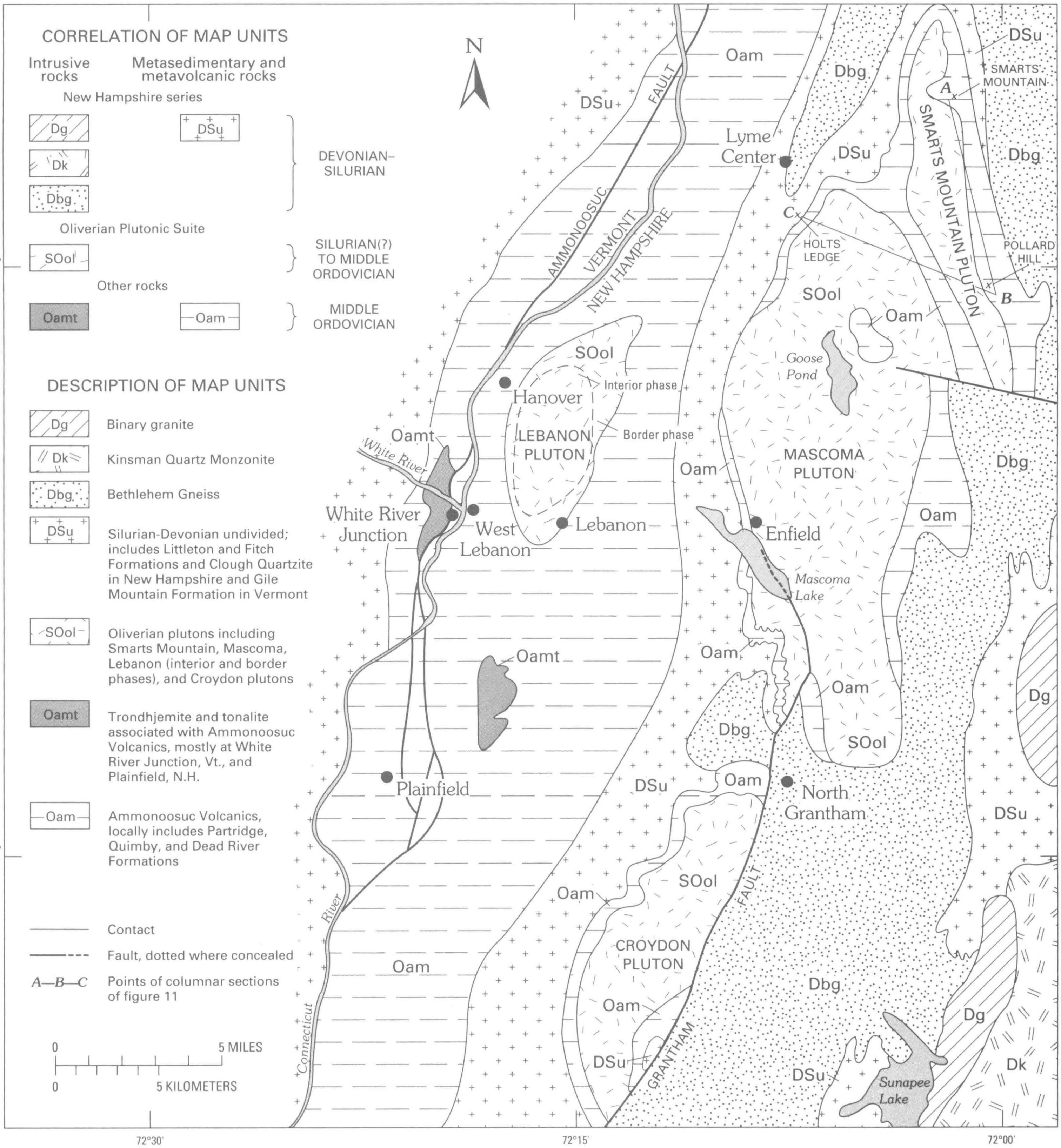


FIGURE 10.—Geology of the Smarts Mountain, Mascoma, Lebanon, and Croydon plutons, west-central New Hampshire. After Billings (1955) and Doll and others (1961).

TABLE 4.—*Vertical variations in K_2O in the Smarts Mountain gneiss*
[Traverse along Appalachian Trail. Rapid-rock analyses by F. Brown, U.S. Geological Survey; X-ray fluorescence analyses by R.G. Johnson, U.S. Geological Survey]

Elevation (ft)[1]	Sample no.	K_2O (percent)	Remarks
2900 (890)	OL46	1.9	Rapid rock.
	OL261	1.57	XRF (same location).
2600 (800)	OL47	4.5	Rapid rock.
2500 (760)	OL26A	2.67	XRF.
2350 (710)	OL467	2.73	XRF.
2250 (690)	OL468	3.06	XRF.
2000 (610)	OL313	3.01	XRF

[1] Meters in parentheses.

keratophyre is exposed in cliffy and continuous outcrops over a vertical distance of 200+ m. According to Naylor (1969), the width of the outcrop belt of quartz keratophyre is about 1 km near Holts Ledge and as much as 5 km on the eastern side of the dome. Naylor (1969) estimated the volume of the Holts Ledge section to constitute two-thirds of the entire dome. Because of the volcanic origin and nongneissic character of these rocks, the informal name Holts ledge volcanic sequence is here proposed.

The Holts Ledge volcanic sequence correlates with Chapman's (1939) and Hadley's (1942) mqd (Mascoma quartz diorite) near the top of the section, but, toward the dome interior, they correlate also with parts of their mgd (Mascoma granodiorite) and mqm (Mascoma quartz monzonite). The remarkably uniform unit, originally regarded as the marginal phase of the central pluton (Chapman, 1939; Hadley, 1942), was reinterpreted by Naylor (1968, 1969) as volcanic strata underlying the Ammonoosuc Volcanics. Naylor's evidence for this reinterpretation included (1) various features indicative of layering, such as subtle compositional and textural variations across strike, flattened inclusions, and bedding planes emphasized by cavernous weathering; (2) lateral continuity of individual layers; and (3) the absence of crosscutting relationships with the overlying Ammonoosuc Volcanics (although Naylor did not exclude the possibility of an unconformity). This study confirms Naylor's observations and suggests the additional criteria of a uniformly fine grained and sugary texture, similar to that of the overlying felsic Ammonoosuc Volcanics, and the distinctive friability of the rock even in fresh exposures. Both of these features contrast sharply with the Mascoma granite (and other Oliverian granites), as do the mineralogical and chemical compositions of the granites and the stratified volcanic rocks. R.H. Moench (written commun., 1988) interpreted the Holts Ledge volcanic sequence as a sill or laccolith that became foliated, sheared, and "stratified" during doming. Nevertheless, because of the evidence discussed earlier, Naylor's volcaniclastic interpretation is strongly preferred here.

The Holts Ledge volcanic sequence (fig. 10) consists of even-grained, granular aggregates of quartz and plagioclase (mostly An_{22-25}, rarely An_{5-8}) and a few percent hornblende, biotite, magnetite and (or) epidote, and, rarely, garnet. Grains are slightly flattened in the direc-

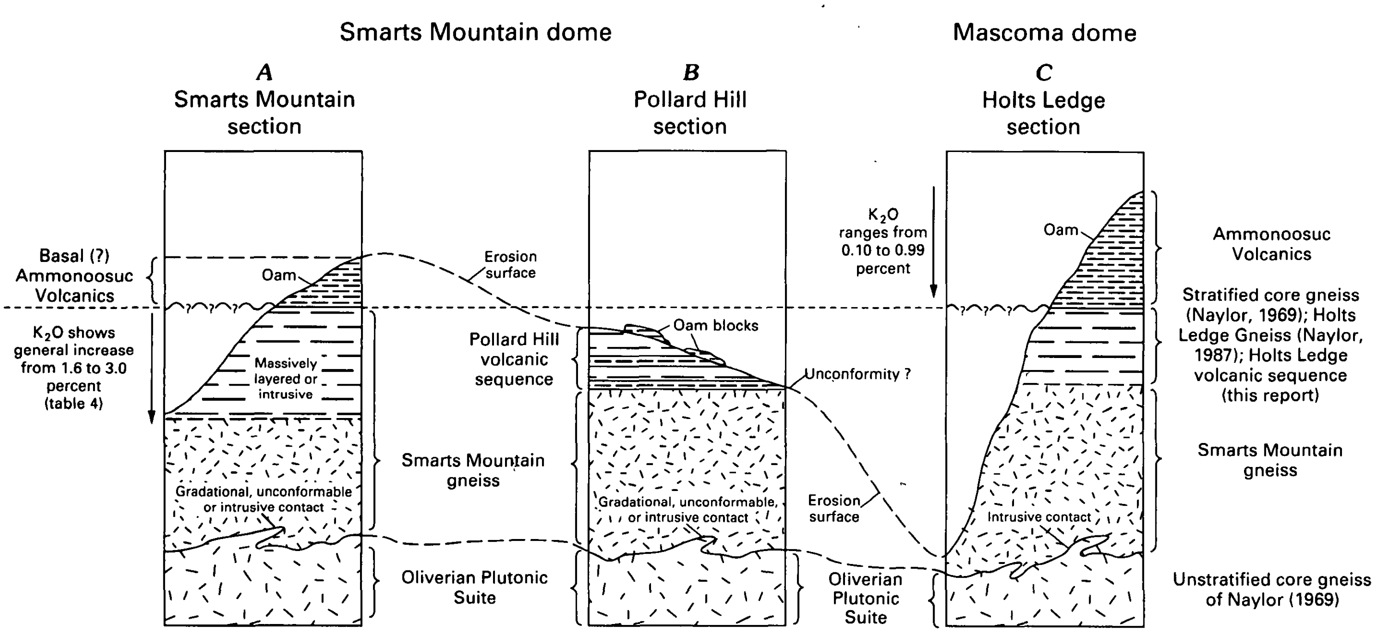


FIGURE 11.—Hypothetical relationship involving the Ammonoosuc Volcanics, the stratified core gneiss of Naylor (1969) (equivalent to the Holts Ledge Gneiss of Naylor (1987), which is equivalent to the Holts Ledge volcanic sequence of this paper), and the Oliverian Plutonic Suite in the Smarts Mountain and Mascoma domes. See figure 10 for locations of columnar sections.

tion of layering. There is no indication of shearing and granulation, possible owing to annealing at high temperature. This granoblastic texture, which retains much of the primary clastic character, is the main reason for preferring the term "granofels" over "gneiss" for these rocks. Most of the granofels at Holts Ledge is high in SiO_2 and low in Al_2O_3 and K_2O and is mineralogically and chemically similar to felsic Ammonoosuc Volcanics (table 2, anals. 106–109). K-feldspar was absent in three of four samples selected by the writer, including a sample of the "metarhyolite" mentioned by Naylor (1969, p. 411; 1987, p. 244) (table 2, anal. 107). The fourth sample (table 2, anal. 109), lowest in the section and an estimated 150 m stratigraphically below the Ammonoosuc Volcanics, contained approximately 3 percent K-feldspar and is the most potassic (about 1.0 percent K_2O) of these conspicuously K-poor rocks. Samples from two outcrops of mgd (Chapman, 1939) from the eastern side of the dome near Canaan Center, N.H. (Mascoma 15-min quadrangle) contain 3 to 6 percent K-feldspar and are megascopically identical to the Smarts Mountain granofels along the Appalachian Trail.

The lower part of the Holts Ledge volcanic sequence was not investigated in detail. In a general way, it corresponds to the subunit mgr (Mascoma granodiorite) of Chapman (1939) and Hadley (1942). Whether these rocks are layered like those in the Holts Ledge sequence or whether parts may be intrusive is not certain. Because some of these rocks resemble the texturally and compositionally ambiguous Smarts Mountain core gneiss, it may be difficult, if not meaningless, to make an unequivocal distinction between "layered" and "intrusive" rocks.

"Stratified Core Gneiss"

Naylor (1968) recognized the Holts Ledge section as a volcaniclastic sequence, and the present investigation confirms and amplifies his interpretation. Naylor chose to designate these rocks as an integral part of the Oliverian lithology, assuming that most of "... the other Oliverian domes consist chiefly of rocks which are similar to the stratified core gneiss of the Mascoma dome..." (Naylor, 1968, p. 234). This interpretation has been tacitly dropped (Naylor, 1987), and the present study supports a volcanogenic origin of the former "Holts Ledge Gneiss." Barring controversial exposures of Ammonoosuc Volcanics such as the interlayered felsic and mafic granofels northeast of Berlin, rocks resembling those on Holts Ledge and underlying strata of the Mascoma dome are found only near the Baker Pond pluton and in the Smarts Mountain and the Warwick domes (the latter to be discussed). Except in the Mascoma dome, moreover, the stratigraphic positions of similar rocks in the overlying Ammonoosuc Volcanics and in the underlying intrusive gneiss are equivocal. The Mascoma is unique among the Oliverian domes in possessing clear-cut, well-exposed, stratified sub-Ammonoosuc rocks. All the Oliverian domes, with the possible exception of the ambiguous Smarts Mountain dome, contain plutons that are in contact, intrusive or otherwise, with Ammonoosuc Volcanics. Therefore, the name "Oliverian Plutonic Suite" is here retained to designate the identifiable plutonic, typically calc-alkaline gneissic rocks of the domes. As Naylor (1987) tacitly did, the term "stratified core gneiss" is here abandoned, inasmuch as it does not denote an integral part of the Oliverian lithology. As stated earlier, the informal term "Holts Ledge volcanic sequence" (to replace the "sub-Ammonoosuc quartz keratophyre" of Leo (1985)) is here proposed for all such rocks underlying the Ammonoosuc Volcanics known mainly at Holts Ledge, Smarts Mountain, and Pollard Hill.

LEBANON DOME AND PLUTON

The Lebanon dome (fig. 10), an ellipsoidal, north-northeast trending structure, lies partly in the Mascoma 15-min quadrangle (Chapman, 1939) and partly in the Hanover 15-min quadrangle (Lyons, 1955). As mapped, the interior pluton consists of two parts—a weakly foliated, interior granitic gneiss and a more strongly foliated, more mafic border gneiss ranging from diorite to quartz diorite. Different workers have regarded the granitic gneiss either as sharply bounded from the border gneiss (Chapman, 1939, p. 135) or as transitional but displaying local mutually intrusive contacts between the two gneisses (Lyons, 1955, p. 118; J.B. Lyons, oral commun., 1977). The present study suggests that the contact is gradational at least in some places and that the Lebanon border gneiss is definitely a metamorphosed plutonic rock. In this respect, it resembles the border gneiss of the Baker Pond pluton but differs from the Holts Ledge volcanic sequence of the Mascoma dome. No evidence was found for a proposed origin of the border gneiss by metasomatism of the adjacent Ammonoosuc Volcanics and the Partridge Formation (Kaiser, 1938).

The interior of the Lebanon pluton is pink to tan, medium-grained, weakly foliated granite that megascopically resembles pink Berlin gneiss and, to a lesser extent, Mascoma and Owls Head granites (table 1). The texture is mylonitic but retains a relict hypidiomorphic fabric. In cuts on New Hampshire Route 120 southeast of Hanover, the granite appears relatively homogeneous except for aplitic dikes, which vary from shadowy and indistinctly bounded (probably synintrusive) to straight walled and clearly postintrusive (fig. 9*B*). Pegmatites are rare.

The border gneiss of the Lebanon pluton is a dark-gray, well-foliated rock having the same mineralogy as the interior granite but containing relatively more biotite, epidote, and plagioclase and less than 5 percent K-feldspar. Its composition is equivalent to diorite-quartz diorite (table 2, anal. 40). Hornblende is absent. Except for a greater degree of granulation and development of mafic-felsic segregation bands (metamorphic differentiation), the texture is similar to that of the granite. Several samples along a traverse from the interior granitic gneiss to the border gneiss show that the texture and mineralogy change in a progressive fashion, the implication being that the Lebanon pluton is a zoned intrusion.

The Lebanon pluton is mantled by the Partridge Formation. On Interstate 89 near Poverty Lane 2.5 km west of West Lebanon, the Lebanon border phase abuts the Partridge along a very sharp, slightly folded contact (fig. 9*C*). This contact shows no signs of metasomatism, contact metamorphism, or granitic dikes or apophyses, nor does it show typical features of an unconformity such as a basal conglomerate or clasts of the border gneiss. Such features might have been partly or entirely removed by faulting. As it is, the contact on Interstate 89 cannot be definitely characterized; the same is true at the base of Lord's Hill (northwestern corner of the Mascoma 15-min quadrangle), where the contact is also fairly well exposed. Along its western border, the Lebanon gneiss contacts the Partridge or the Quimby; thus, it cuts higher in the section than the Ammonoosuc, as presently defined (J.B. Lyons, written commun., 1988).

The most abundant lithologic type of the Ammonoosuc Volcanics in the West Lebanon area is hornblende-plagioclase amphibolite. In the Lebanon-Hanover area, possibly because of alteration of the highly fractured rocks near the Ammonoosuc fault, the mafic phase is generally chlorite schist, locally much silicified (see Lyons, 1955, p. 113). The mafic rocks are extensively intruded by trondhjemite, as described earlier (p. 27). Particularly good exposures are in West Lebanon at the interchange between New Hampshire Route 12 and Interstate 89; along Interstate 91 northeast of White River Junction, Vt. (gneiss at White River Junction of Lyons (1955)); and approximately 5 km northeast of Plainfield, N.H. (gneiss east of Plainfield of Lyons (1955)).

CROYDON DOME AND PLUTON

The Croydon dome is located in the southern part of the Mascoma 15-min quadrangle (Chapman, 1939) and the northwestern corner of the Sunapee 15-min quadrangle (Chapman, 1952) (fig. 10). As mapped, the gneissic core of the dome is 18 km long and 5 km wide at its widest point. The dome is mantled by Ammonoosuc Volcanics everywhere but along its southeastern margin, which is truncated and relatively downdropped to the east along the Grantham fault.

Published descriptions of the Croydon pluton in the core of the dome are very brief (Chapman, 1939, 1952), referring only to the dominantly quartz dioritic composition of the northern end of the dome in the Mascoma quadrangle and to a mainly granitic composition for the remainder of the dome (but see below). The Croydon dome was all but omitted from the present study owing to the difficulty of access to a private hunting preserve that extends over most of the dome. Field reconnaissance was limited to a single traverse near the southern end of the dome and inspection of extensive roadcuts on Interstate 89 at the northern end.

Gneiss from the southern end of the Croydon pluton is medium-grained, pinkish, poorly foliated granite (table 1; table 2, anals. 118, 119). The northern part of the pluton is not quartz diorite but is trondhjemitic in part. Trondhjemite intrudes Ammonoosuc amphibolite in cuts on Interstate 89 near the North Grantham exit, where it contains abundant tabular inclusions (see fig. 5*D*). To the north, Ammonoosuc Volcanics, including amphibolite and granofels locally containing Ca-poor amphiboles, are well exposed.

UNITY DOME AND GNEISS

The Unity dome is composed of two relatively small areas of trondhjemitic gneiss enclosed by a relatively broad belt of Ammonoosuc Volcanics (pl. 1). The Unity dome, like the Croydon dome, is truncated on its eastern side by the Grantham fault. The dome, including mantling Ammonoosuc, is about 15 km long and 4 km wide.

The Unity is the northernmost of three domes (the others being the Alstead and the Vernon) in which the core gneiss appears to be all trondhjemite and a potassic gneiss phase is lacking, at least at the present erosion level. The Unity gneiss is white to pale pink, granular, medium grained, and poorly foliated and generally compares with other trondhjemite associated with the Ammonoosuc Volcanics (table 1; table 2, anals. 120, 121). Associated Ammonoosuc Volcanics include hornblende$\pm$garnet$\pm$gedrite amphibolite.

ALSTEAD DOME AND GNEISS

The Alstead dome (pl. 1) is located in the Bellows Falls 15-min quadrangle (Kruger, 1946). The Alstead is one of the most elongated of the Oliverian domes, extending north-south for 20 km and having a maximum width of only 3 km. The interior felsic gneiss as mapped (Kruger, 1946) has two outcrop areas, a northern one approximately 3 km long and a southern one approximately 15 km long, separated by Ammonoosuc Volcanics. The northern, elliptical gneiss outcrop area is surrounded entirely by Ammonoosuc Volcanics, cut by dikes and sills of trondhjemite (see fig. 13*A*). The southern area is bordered by relatively coarse grained Ammonoosuc containing locally abundant Ca-poor amphibole and is cored by gray trondhjemite gneiss. The overall composition of Alstead dome rocks is among the lowest in K_2O (table 2, anals. 122–124) and thus is distinct from the granitic Oliverian rocks. Kruger's (1946, p. 181) assertion that "the gneiss grades from granite to quartz monzonite but the average is quartz monzonite" does not agree with the present observations.

VERNON DOME AND PLUTON

The Vernon dome is located in the southwestern part of the Brattleboro 15-min quadrangle (Moore, 1949a; Billings, 1955). It straddles the Connecticut River, and its southern part is in Vermont. The dome trends slightly northwest and has an elliptical outline; the central part is approximately 13 km long and 3 to 3.5 km wide. The Vernon dome is located on the western (downthrown) side of the Connecticut Valley border fault, which has a relative vertical offset of about 3,000 m in this area (Thompson and others, 1968, fig. 15–1b); prefault reconstruction shows the Vernon dome to be a northwestward extension of the Warwick dome (P. Robinson, oral commun., 1980).

The gneiss of the Vernon pluton is trondhjemitic, a fact that emerges clearly from Moore's (1949b, p. 1638) modal analyses. In his brief description, however, Moore did not comment on the K-poor composition but appeared more concerned with correlating the Vernon gneiss and the Swanzey Gneiss as parts of the Oliverian Plutonic Suite. In fact, the two gneiss units are not very similar. Hepburn and others (1984) likewise characterized the Vernon trondhjemite gneiss as [Oliverian] quartz diorite gneiss.

The Vernon gneiss is a leucocratic, light-gray to grayish-green, moderately to strongly foliated rock generally similar to other trondhjemites (table 1; table 2, anals. 125–126). Except for variations in the amount of deformation, it is relatively homogeneous throughout and nowhere shows the kind of migmatitic contacts with the Ammonoosuc Volcanics found in the Alstead dome. Exposed contacts are sharp, straight, and parallel to the trace of foliation, as seen on Cannon Hill south of Hinsdale (Keene 15-min quadrangle of New Hampshire).

WARWICK DOME AND PAUCHAUG GNEISS

The Warwick dome is the southernmost of the domes included in this study. Located mostly in Massachusetts (Northfield, Mt. Grace, and Millers Falls 7½-min quadrangles), its northern end extends into New Hampshire (Keene 15-min topographic quadrangle or Keene-Brattleboro geologic sheet) (Moore, 1949a; Hepburn and others, 1984). The Warwick dome has an elliptical outline, trends almost exactly north-south, and has a length (gneissic core only) of about 20 km and a width of 6 km.

The Massachusetts part of the Warwick dome was mapped by Hadley (1949) and Balk (1956), both of whom correlated the core gneiss with the Monson Gneiss. Robinson (1963, 1977) remapped the Orange area, including all of the Warwick dome within Massachusetts. Robinson distinguished the Warwick gneiss from the Monson Gneiss and renamed the former the Pauchaug Gneiss. The following discussion is based on these sources.

The Pauchaug Gneiss includes two distinct phases: (1) a coarser grained, more potassic granitic gneiss and (2) a finer grained, less potassic, more foliated border gneiss. The border phase, which forms a relatively narrow band around the periphery of the pluton and a broader belt across its central part, is megascopically similar to the central granite, differing mainly in being finer grained and more closely foliated. It contains less microcline (estimated 6 percent) and somewhat more epidote. These differences, reflected in chemical analyses (table 2, anals. 42, 43) seem to indicate slight differentiation from the center of the pluton to the margin.

The Ammonoosuc section on the Warwick dome has been mapped in some detail by Schumacher (1988) and has been described briefly in an earlier section of this paper. It remains to emphasize here only the varied lithologies in the northern Massachusetts section, including the presence of rhyolitic rocks in the upper member. The nature of the transition to a simpler bimodal lithology in western New Hampshire has not been investigated. The contact between the Ammonoosuc and the Pauchaug heretofore has been considered to be an unconformity (J.C. Schumacher and P. Robinson, oral commun., 1980), but new isotopic dates, discussed earlier, suggest intrusive relationships at least in part (Tucker and Robinson, 1990).

Reconnaissance mapping by J.C. Schumacher and P. Robinson (oral commun., 1980) in the Notch Mountain area of Massachusetts shows that a volcaniclastic-epiclastic sequence comparable to the Holts Ledge volcanic sequence on Holts Ledge in the Mascoma dome and (or) to rocks on Pollard Hill in the Smarts Mountain dome conformably underlies the Ammonoosuc Volcanics in the northern part of the Warwick dome. These rocks, hereafter informally designated the Notch Mountain sequence, are granular, friable, well sorted and massively bedded or crossbedded and display cavernous weathering very similar to that on Pollard Hill and Holts Ledge. They are clean, equigranular granofelses consist-

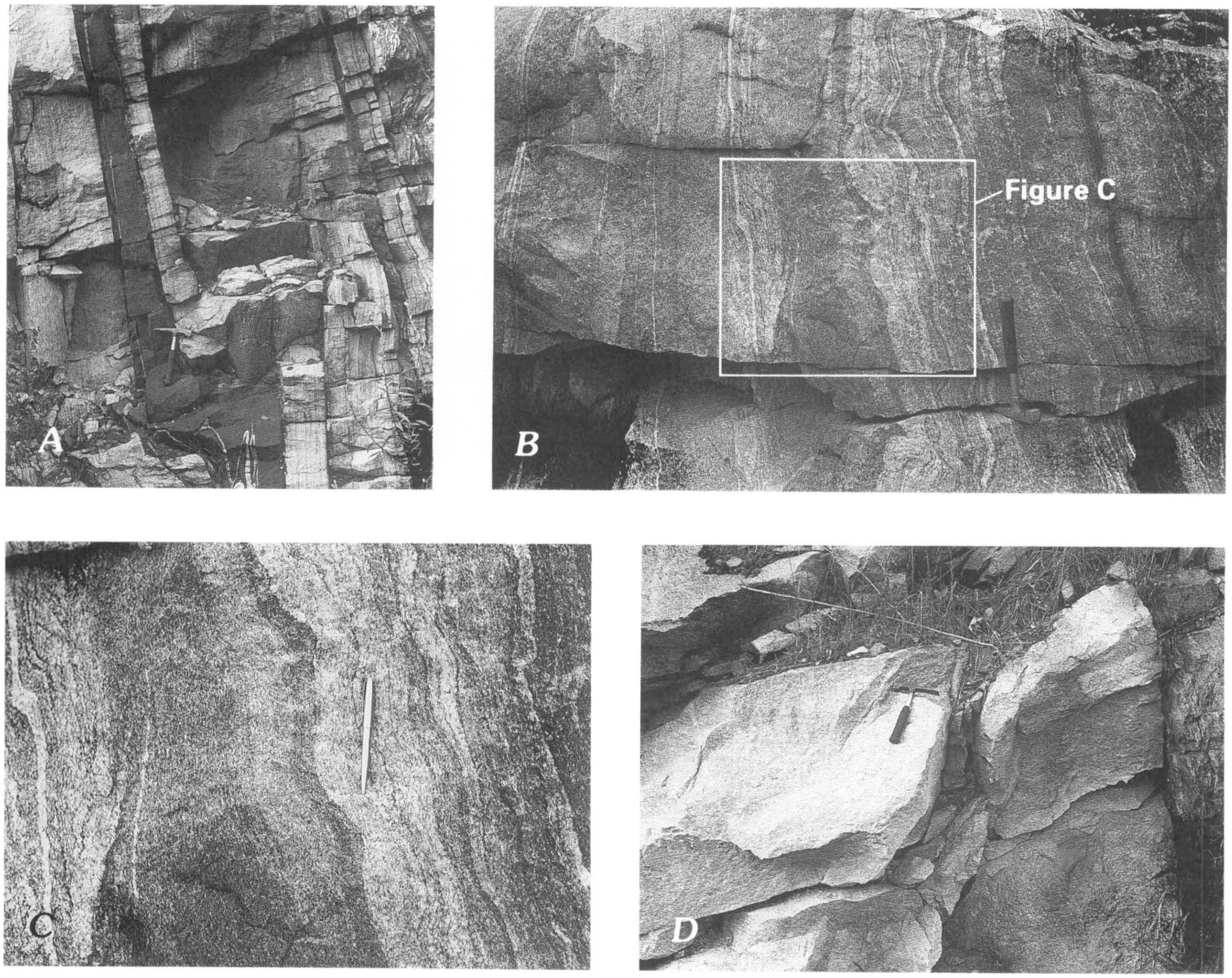


FIGURE 12.—Aspects of the Monson Gneiss. *A*, Banded Monson Gneiss showing amphibolite sill (both folded); axis plunges north and is related to Acadian deformation. The presence of primary layering is uncertain. Northern side of cut in Massachusetts Turnpike (Interstate 90), 2.5 km north-northeast of the center of Palmer, Mass., directly east of the Breckenridge Street overpass (Palmer 7½-min quadrangle of Massachusetts). *B*, Monson Gneiss showing swirled banding and local felsic segregations indicative of incipient anatexis. Massachusetts Route 2, southwestern ramp of Orange exit, 3.3 km south-southeast of the center of Orange, Mass. (Orange 7½-min quadrangle of Massachusetts). *C*, Detail of *B* (indicated rectangle). Pen gives scale. *D*, Gradational transition from banded Monson Gneiss (right side of photograph) to weakly foliated but unlayered rock (under hammer). This aspect is the nearest the Monson comes to looking like a magmatic granitoid. Same location as *A*.

ing dominantly of quartz and plagioclase, (An_{12-15}), 10 to 15 percent green hornblende, and conspicuous titanite (2–3 percent). K-feldspar is absent. This composition corresponds in a general way to parts of both the Holts Ledge and the Pollard Hill outcrops, although the Notch Mountain compositions have lower SiO_2 and higher ferromagnesian components than the usual felsic granofelses do. Available data imply that the Notch Mountain sequence should not be correlated with the Pauchaug Gneiss or with any other Oliverian lithologies. Rather, like the Holts Ledge sequence, it appears to be a volcaniclastic unit underlying the Ammonoosuc. Only a tentative correlation with the Holts Ledge volcanic sequence is justified at this time.

MONSON GNEISS AND SWANZEY GNEISS OF THE KEENE DOME

The Monson Gneiss (pl. 1; fig. 12; table 1; table 2, anals. 48–54) and the Swanzey Gneiss (Robinson, 1967) (equivalent to the Swanzey Gneiss of the Keene dome (Zartman and Leo, 1985)) (pl. 1; figs. 12, 13; table 1; table 2, anals. 44–47) are similar rocks that form several large

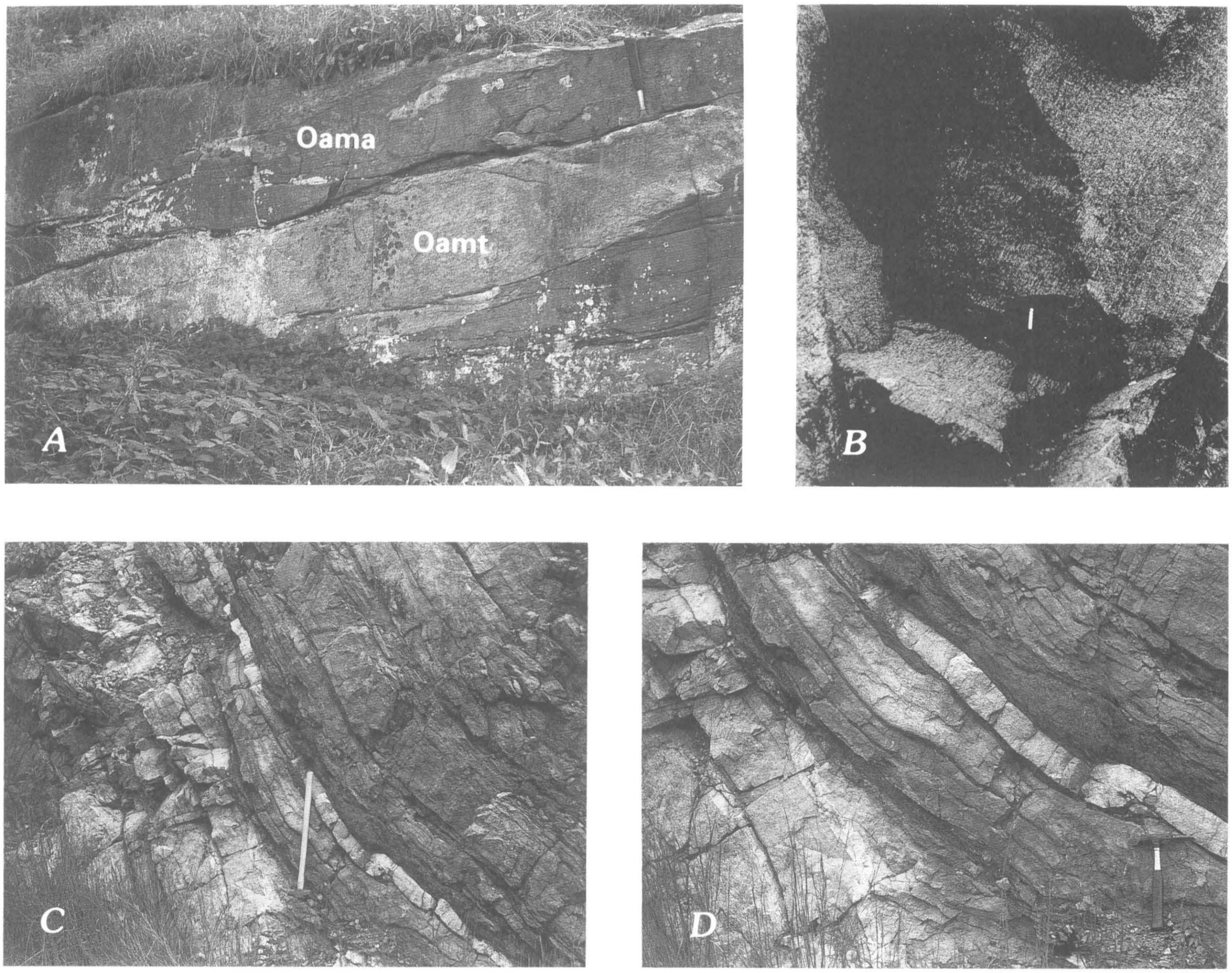


FIGURE 13.—Contact relationships in the Alstead and Keene domes. *A*, Ammonoosuc amphibolite (Oama) cut by trondhjemite dike (Oamt), northern part of Alstead dome. New Hampshire Route 123A, approximately 5 km northwest of Alstead (Bellows Falls 15-min quadrangle of New Hampshire and Vermont). *B*, Laminated, relatively homogeneous Swanzey Gneiss in a roadcut on New Hampshire Route 12, approximately 8 km southeast of Keene, N.H. Hammer gives scale. *C*, Head of sledge hammer rests on sharp contact between the Swanzey Gneiss (left) (a few meters from *B*) and the Ammonoosuc Volcanics. End of sledge hammer rests on a felsic layer that may be either a sill of the Swanzey Gneiss or a layer of Ammonoosuc quartz keratophyre. Ammonoosuc amphibolite continues above the felsic layer. Contact may be intrusive or (more probably) unconformable. *D*, Detail of *C*. Hammer head below the felsic layer.

domes in southwestern New Hampshire and north-central Massachusetts. They are not regarded as units of the Oliverian Plutonic Suite for reasons discussed below. The Monson Gneiss, as a much attenuated belt, trends southward through Massachusetts and Connecticut (Leo and others, 1984) to the end of the Bronson Hill anticlinorium, where it terminates in the Killingworth dome (Webster and Wintsch, 1987). The extent and wide distribution of nominal Monson Gneiss have caused problems in identification and correlation, discussion of which is beyond the scope of this paper (Robinson, 1963; Thompson and others, 1968; Leo and others, 1984; Hollocher and Lent, 1987; Hollocher, 1988). In the context of the Oliverian domes, the major question concerning these two gneiss units is why, given their structural-stratigraphic position analogous to both the Oliverian plutons and the sub-Ammonoosuc volcanic rocks, the gneisses are so different from these rocks as to preclude specific correlations. The following sections describe typical exposures of the two gneiss units and their contact relationships with the Ammonoosuc Volcanics. The contact relationships are summarized in table 1.

MONSON GNEISS

The Monson Gneiss typically is light to dark gray and medium to coarse grained and has a distinctive planar fabric. The gneiss can be classified by megascopic appearance into the following types (divisions are arbitrary, and the types are mutually gradational):

1. Rocks in which layering is clearly defined by relatively sharp contacts separating more mafic compositions from more felsic compositions. Such layering may be primary in part but may also be produced by transposition. The layering is enhanced by sharply bounded, generally concordant amphibolite bands, most likely sills (fig. 12*A*).
2. Gneiss possessing a streaky, indistinct foliation involving compositional and textural variations across strike but not readily relatable to any primary layering. This aspect of the Monson is probably the most characteristic (fig. 12*B*, *C*).
3. Relatively homogeneous gneiss displaying regular but typically crenulated foliation produced by subparallel aggregates of mafic minerals constituting 10 to 25 percent of the rock.
4. Homogeneous, massive gray rock retaining a planar structure but lacking streaks and folia (fig. 12*D*). This type of Monson Gneiss most closely resembles a magmatic granitoid. Small anatectic(?) Acadian intrusions within the Monson Gneiss have been identified locally (Hollocher, 1988).

Most of the Monson Gneiss has the appearance of a primary layered rock (for example, a thickly bedded tuff sequence in which the layering has been modified, obliterated, or transposed through deformation and (or) metamorphic differentiation and recrystallization, in places under conditions of plastic flow (see Leo and others, 1984)). Thus, the Monson differs significantly from the relatively homogeneous Oliverian plutons; its K_2O content is also consistently lower (table 2).

Although there are broad similarities between the Monson Gneiss and rocks of the sub-Ammonoosuc layered sequences of the Mascoma, Smarts Mountain, and Warwick domes, they are more notable for their textural differences. The Monson Gneiss is mostly hard, dense, thoroughly recrystallized, and commonly highly deformed, whereas the rocks of Holts Ledge and analogous rocks are granular, friable, poorly consolidated, and, except for compaction and thinning, virtually undeformed. Microscopic textures further emphasize these differences. The Holts Ledge type of granofels, described earlier, has an even-grained, well-sorted, noninterlocking fabric of subrounded, obviously clastic grains, a fabric only slightly modified by metamorphic recrystallization. The Monson, by contrast, has seriate, interlocking textures and mylonitic zones reminiscent of some of the more deformed Oliverian rocks such as the Lebanon pluton. Plagioclase is typically tabular and sharply twinned, and its composition ranges from An_{22} in felsic rocks to An_{27-37} in hornblende-bearing ones. Mafic constituents include biotite with or without hornblende or epidote, and the K-feldspar content varies from 0 to about 10 percent. Thus, the Monson, although generally comparable to other K-poor rocks of the region, is more variable in composition and, on the average, more calcic and is distinct from the fine-grained, relatively homogeneous, and obviously intrusive trondhjemites.

The above textural distinctions between the Monson and the types of granofels at Holts Ledge and Notch Mountain preclude a simple correlation. The more strongly recrystallized fabric, together with local mylonitization in the Monson, indicates a distinctive tectonic regime, even though the metamorphic grade based on mineral assemblages is about the same in the two units. One may speculate concerning the Monson Gneiss's relatively greater involvement in Acadian doming and nappe formation in comparison with the Warwick domes, but such a distinction is not supported by interpretations of the doming process in this area (Robinson, 1979). The fact remains that the Monson Gneiss and the Notch Mountain layered sequence are separated by only a few kilometers in the Orange area of Massachusetts. Available isotopic age determinations do not help to distinguish the above-described differences in these rocks, inasmuch as the Monson Gneiss, as discussed earlier, yields a range of U-Pb zircon ages of approximately 454 to 442 Ma (Middle to Late Ordovician). No reliable age has been obtained on the Holts Ledge volcanic sequence. Thus, a satisfactory explanation for the marked textural differences between these structurally analogous rocks remains to be found.

The Monson Gneiss has exposed contacts with the Ammonoosuc in several localities, most strikingly in the Quabbin Reservoir area, where the contact can be traced with few breaks over hundreds of meters (P. Robinson, oral commun., 1986). A less well exposed contact, defined by a thin quartz-pebble conglomerate, can be observed on McGoo Hill in the Orange 7½-min quadrangle of Massachusetts (Robinson, 1979, p. 137). On the eastern slope of an unnamed hill 1 km west of Palmer Center, Mass. (near the center of the Palmer 7½-min quadrangle of Massachusetts) (Peper, 1976), dark schistose Ammonoosuc Volcanics unconformably overlie the Monson Gneiss along a sharp contact. The nature of these contacts, formerly regarded as unconformities, is now in doubt owing to newly determined, nearly overlapping isotopic ages on the Ammonoosuc Volcanics and the Monson Gneiss, mentioned earlier (Tucker and Robinson, 1990).

SWANZEY GNEISS

A brief reconnaissance of the Swanzey Gneiss east of the Connecticut Valley border fault (pl. 1; table 2, anals. 44–47) [5] suggests a general similarity to the Monson Gneiss. Fairly detailed petrographic descriptions have been provided by Moore (1949b, p. 1635–1636). The Swanzey Gneiss has a swirled foliation, local layering, amphibolite inclusions, and an overall texture and composition similar to those of the Monson Gneiss. The Swanzey Gneiss appears to be more homogeneous (fig. 13*B*) and to contain less hornblende than the Monson, but this observation is based on a few exposures only. Therefore, the Swanzey is tentatively regarded as having a source and tectonic history similar to those of the Monson. It contrasts with the Oliverian Plutonic Suite and the Holts Ledge volcanic sequence, as does the Monson.

The Swanzey Gneiss has amphibolite inclusions at Surrey dam that could be Ammonoosuc but have not been proven to be so. A sharp contact (fig. 13*C–D*) on New Hampshire Route 12 approximately 8 km southeast of Keene, N.H., may be intrusive but suffers from the same ambiguities as the contact between Lebanon border gneiss and the Partridge Formation in West Lebanon, described above.

HIGHLANDCROFT PLUTONIC SUITE

The Highlandcroft Plutonic Suite ("Lost Nation group" of Chapman (1948)) comprises seven plutons exposed between Littleton, N.H. (pl. 1), and the Chain Lakes massif (not shown on pl. 1). The Highlandcroft plutons are not associated with geometric domes. The Highlandcroft Plutonic Suite has a range of isotopic U-Pb ages of about 453 to 443 Ma (Lyons and others, 1986a). Compositionally, this suite ranges from granite to tonalite (Pogorzelski, 1983). A significant component of gabbro also has been identified (table 2, anals. 59, 60). Modal and chemical data, including trace elements on 28 samples (Pogorzelski, 1983), indicate a general similarity with rocks of the Oliverian Plutonic Suite. *Q*-mode factor analysis confirms the similarity between the two suites and also supports a model for the genesis of both the Highlandcroft and the Oliverian Plutonic Suites by differentiation of a mafic magma; the Highlandcroft is unlikely to have formed by anatexis (Pogorzelski, 1983).

It was not the purpose of the present study to deal to any large extent with the Highlandcroft Plutonic Suite. Analytical data on four samples are presented (table 2, anals. 55, 56, 59, 60) from the Highlandcroft pluton. Analyses from the Fairlee pluton (see Lyons and others (1986b) for location) turn out to be invalid, inasmuch as the Fairlee pluton has been recognized to be retrograded Devonian Bethlehem Gneiss and not part of the Highlandcroft Plutonic Suite (Moench and Aleinikoff, 1987; R.H. Moench, written commun., 1988). Therefore, the Fairlee analyses (originally anals. 57 and 58 in table 2) have been deleted, and the Lost Nation analyses are presented but have been excluded from plots because they are insufficiently representative of the total Highlandcroft.

Highlandcroft rocks are described as intruding the Albee (now Dead River) Formation in the southwestern part of the Percy 7½-min quadrangle (Chapman, 1949). An extensive contact zone between the Highlandcroft and the Albee, involving abundant dikes and xenoliths, is exposed in the Guildhall area of eastern Vermont (Johansson, 1963). Less information is available on Highlandcroft-Ammonoosuc contacts. The two units are in contact for several kilometers in the Littleton area (Billings, 1937), and the contact is shown as schematically intrusive in cross sections. Actual descriptions of intrusive contacts are lacking, but R.H. Moench (written commun., 1988) stated that the Lost Nation does intrude Ammonoosuc Volcanics in this area. The Highlandcroft is reported to be unconformably overlain by the Upper Silurian Fitch Formation (Billings, 1937; Harris and others, 1983).

GEOCHEMISTRY

METHODS

Major-element and trace-element compositions of the Oliverian gneisses and associated Ammonoosuc Volcanics are listed in tables 2 and 3, respectively. Accompanying triangular diagrams were generated on a volatile-free basis by the Graphic Normative Analysis Program of the U.S. Geological Survey (USGS) (Bowen, 1971; Stuckless and Van Trump, 1979; T.L. Wright, oral commun., 1983). Major-element oxides for most samples and water and CO_2 for all samples were determined by rapid-rock analysis methods, described by Shapiro (1975). Some major-element analyses were obtained by X-ray spectroscopy, as were Rb, Sr, Ba, Nb, Zr, and Y. Rapid-rock analyses were done by F. Brown, N. Skinner, Z. Brown, and H. Smith (USGS); X-ray spectroscopy analyses were done by H.J. Rose, Jr., G. Sellers, P. Hearn, J. Lindsay, B. McCall, S. Wango, and R. Johnson (USGS). Th, Cr, Hf, Ta, and rare-earth elements were determined by instrumental neutron activation (INA) by C.A. Palmer, G.A. Wandless, P.A. Baedecker, and L.J.

[5] That is, the relatively uplifted and more deeply eroded part of the gneiss that is directly comparable to the Monson Gneiss. The part of the Swanzey Gneiss at a higher erosional level west of the fault was not studied.

Schwarz (USGS) (epithermal INA for mafic samples) (Baedecker and others, 1977). Rare-earth elements for five amphibolite samples (table 3, anals. 66, 67, 72, 79, 80) were determined by isotope-dilution mass spectrometry by L. Peter Gromet (Brown University).

GNEISSES OF THE OLIVERIAN PLUTONIC SUITE AND RELATED ROCKS

MAJOR ELEMENTS

Figures 14 through 17 show a series of Harker diagrams for gneisses from the Oliverian domes. Data for the gneisses from the Unity, Alstead, and Vernon domes, which are cored by Ammonoosuc trondhjemite, are plotted in other diagrams.

The fourfold grouping of gneisses in figures 14 through 17, which also is used for triangular diagrams and some other plots, is based as much on convenience of display as on petrologic affinities. The gneisses of the Jefferson batholith (fig. 14), for example, show considerable scatter, notably for Al_2O_3, CaO, and K_2O, reflecting the compositional varieties of granite, quartz monzonite, syenite, and trondhjemite and the variations in the Whitefield Gneiss. Rocks of the Owls Head group of plutons (fig. 15) are more homogeneous in their major-element characteristics, especially in Al_2O_3, FeO*, MgO, and CaO, whereas alkalies show some scatter (which may be caused by the migration of mobile elements). The relative linearity of the Harker patterns of Owls Head rocks is in accord with the similarity of these rocks in the field.

A more pronounced linearity of data points is seen in the southern New Hampshire and northern Massachusetts plutons (fig. 16). Especially notable is the small range of SiO_2 (72–75 percent) in these rocks, the sole exception being the border phase of the Lebanon pluton. The data points for the southern New Hampshire and northern Massachusetts plutons in figure 16 largely overlap those for the Owls Head group of plutons in figure 15.

Points plotted for the Swanzey Gneiss and the Monson Gneiss (fig. 17) are less linear than those plotted for the Oliverian Plutonic Suite. The relative scatter of the Swanzey and Monson points suggests relatively incomplete differentiation, owing to either contamination, assimilation of wall rocks, or compositionally variable source materials in a volcanic pile. The last scenario is supported by the layered aspect and the lack of intrusive contacts, especially in the Monson Gneiss.

Peacock plots (fig. 18) for the two data sets that showed relatively less scatter on Harker diagrams (figs. 15, 16) show that points for the Owls Head group of plutons plot approximately on the calc-alkaline and alkali-calcic boundary, whereas the points for the southern New Hampshire and northern Massachusetts plutons fall farther into the alkali-calcic field. Neither determination, although reasonable, is very reliable, given the Na_2O+K_2O scatter and the low slope of the lines through them.

Normative Q-Ab-Or diagrams (figs. 19–22) show in particular the range of Or between the syenites and granites of the Jefferson batholith, the essentially granitic Owls Head and southern New Hampshire and northern Massachusetts plutons, and the contrastingly Or-poor Monson and Swanzey Gneisses.

Plotting of all data points for Oliverian gneisses and related rocks on an An-Ab-Or diagram (fig. 23) emphasizes the ranges of bulk compositions displayed by these rocks. The plot confirms that the Jefferson, Owls Head, and southern New Hampshire and northern Massachusetts plutonic bodies are predominantly granite (some compositions falling in the granodiorite field), whereas the Monson Gneiss and, to a lesser degree, the Swanzey Gneiss are mostly trondhjemite and tonalite. In general, the compositional fields for the various groups can be individually defined in figure 23, but several show mutual overlap.

The same points plotted on an AFM diagram (fig. 24) fall largely in Ringwood's (1974) calc-alkaline (CA) field, and all but one Swanzey Gneiss point plot in the CA field of Irvine and Baragar (1971). On the basis of the analyzed samples, therefore, all of the Oliverian gneisses and related rocks are calc-alkaline.

TRACE ELEMENTS OTHER THAN RARE EARTHS

Trace-element discrimination diagrams for gneissic rocks are shown in figures 25 through 30. These diagrams, based on the parameters of Pearce and others (1984), compare 10 trace elements, notably those that behave incompatibly during fractionation of mid-ocean ridge basalt (MORB) to siliceous compositions. Together with K_2O, these elements are normalized to a hypothetical "ocean ridge granite" (ORG). The term "granite" as used by Pearce and others (1984) encompasses the entire spectrum of igneous intrusive rocks containing more than 5 percent modal quartz. Their intention was to demonstrate regularity in the patterns or groups of patterns of several major granite types on the basis of paleotectonic environment.

Because of the variable and somewhat unpredictable scatter in patterns of minor-element abundances, data are shown for individual samples in table 3 without any attempt at averaging. Most samples for which data are available in table 3 have been plotted on figures 25 through 30. To avoid clutter, data for a few samples having patterns virtually identical to other patterns are not plotted.

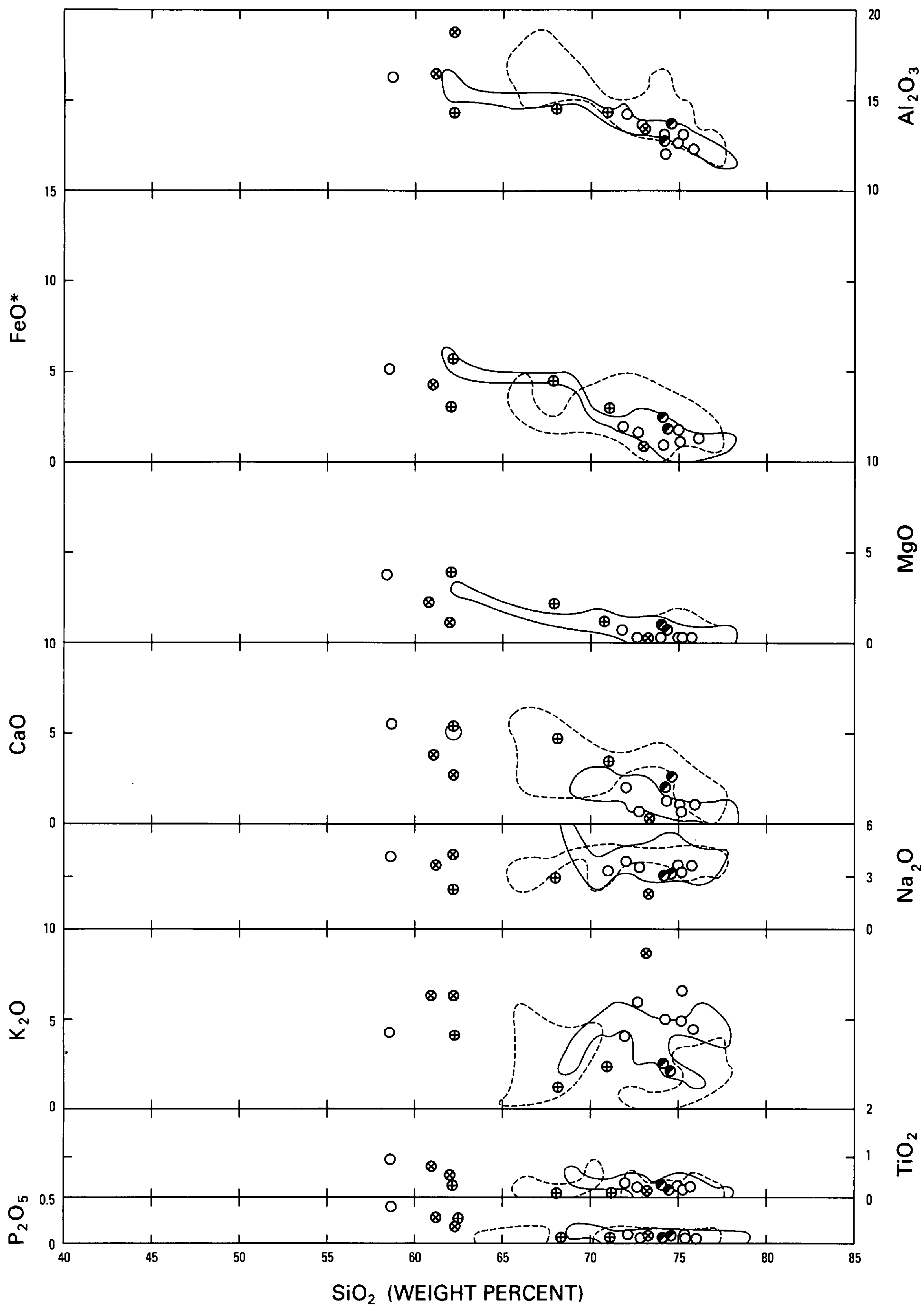


FIGURE 14.—Harker diagrams for the Jefferson batholith. Al_2O_3, FeO^* (total iron as FeO), MgO, CaO, Na_2O, K_2O, TiO_2, and P_2O_5 versus SiO_2. Composition in weight percent, calculated on a water-free basis. ○, pink Berlin gneiss; ⊗, syenitic rocks; ◐, gray Berlin gneiss (trondhjemitic); ⊕, Whitefield Gneiss; ⬭, fields of Owls Head group of plutons and of southern New Hampshire and northern Massachusets plutons (Smarts Mountain, Mascoma, Lebanon, Croydon, and Warwick); ⬭ (dashed), fields of Monson and Swanzey Gneisses. The scatter of data points is relatively large, reflecting the variety of rock types in this pluton. The pronounced scatter of K_2O points suggests that alteration may also be a factor.

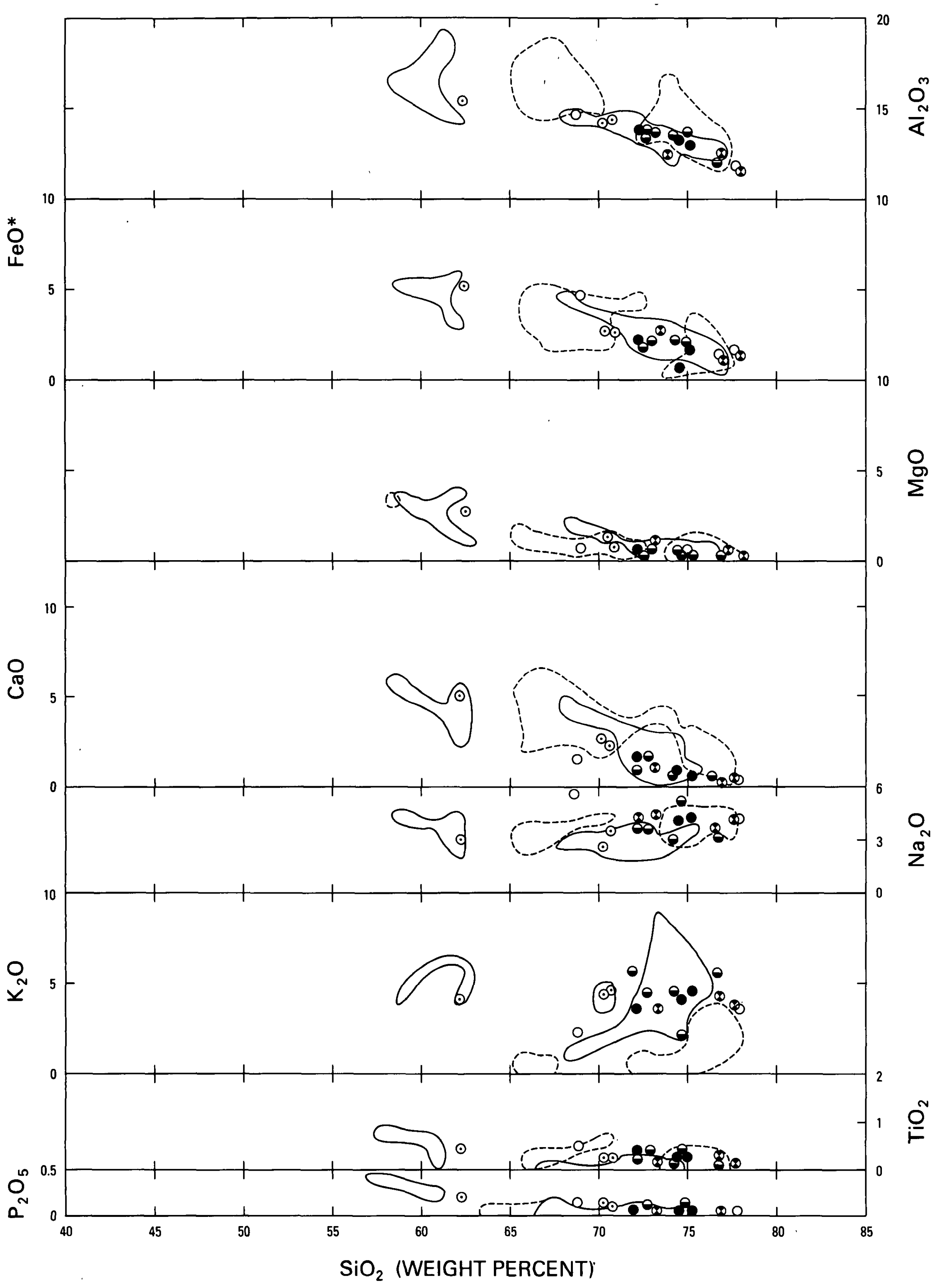


FIGURE 15.—Harker diagrams for the Owls Head group of plutons. Al_2O_3, FeO* (total iron as FeO), MgO, CaO, Na_2O, K_2O, TiO_2, and P_2O_5 versus SiO_2. Composition in weight percent, calculated on a water-free basis. ⦶, Sugar Hill pluton; ○, Landaff pluton; ●, Moody Ledge plutons; ◒, Owls Head pluton; ⊙, Baker Pond pluton; ⬭, fields of Jefferson batholith and of southern New Hampshire and northern Massachusetts plutons; ⬭ (dashed), fields of Monson and Swanzey Gneisses. There is relatively little scatter of data points except for Na_2O and K_2O. Several data points are not plotted because they overlap adjacent points.

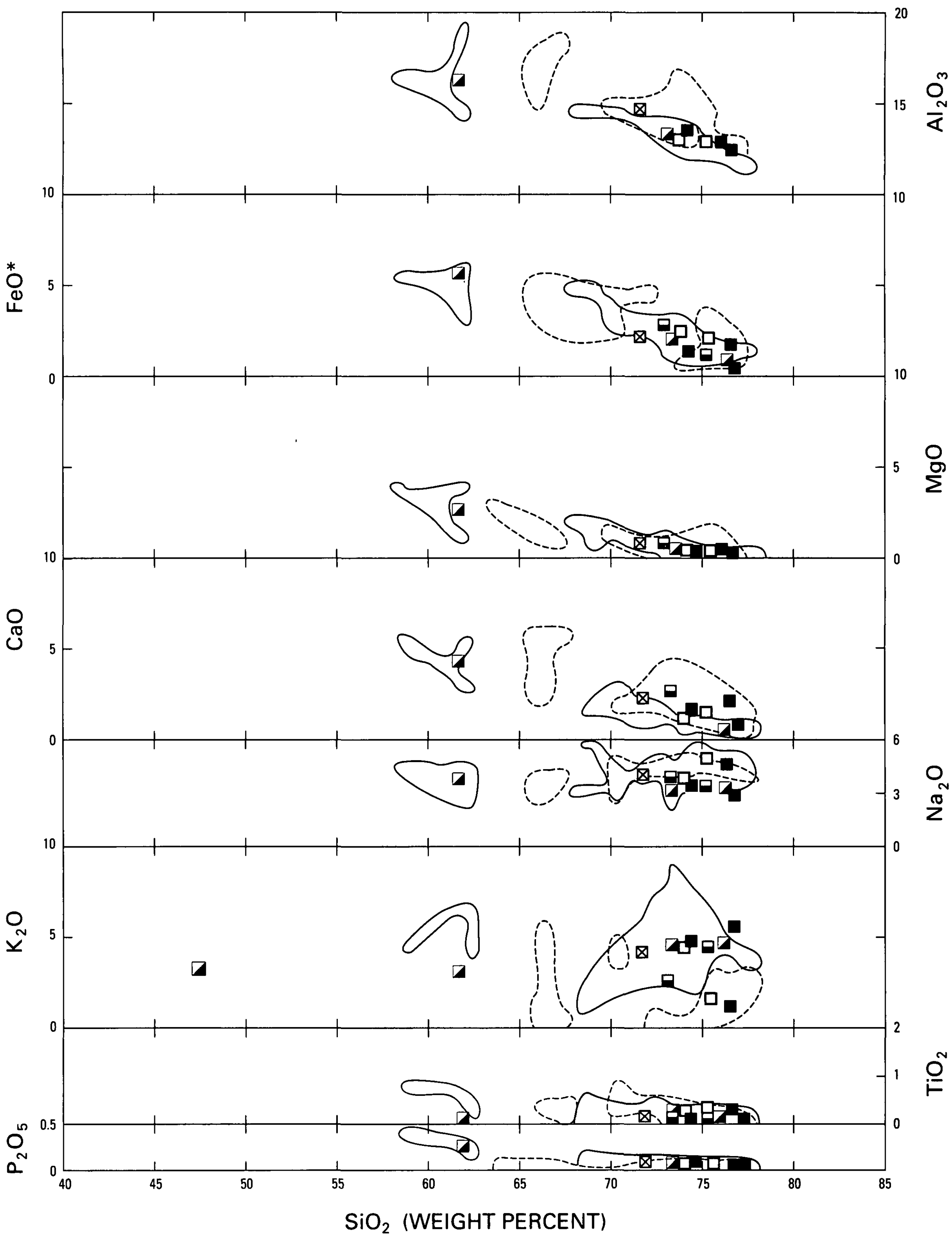


FIGURE 16.—Harker diagrams for the Smarts Mountain, Mascoma, Lebanon, Croydon, and Warwick plutons (southern New Hampshire and northern Massachusetts). Al_2O_3, FeO* (total iron as FeO), MgO, CaO, Na_2O, K_2O, TiO_2, and P_2O_5 versus SiO_2. Composition in weight percent, calculated on a water-free basis. □, Smarts Mountain pluton; ■, Mascoma pluton; ◪, Lebanon pluton; ⊠, Croydon pluton; ⊟, Warwick pluton; ◯, fields of Jefferson batholith and Owls Head group of plutons; ⬭ (dashed), fields of Monson and Swanzey Gneisses.

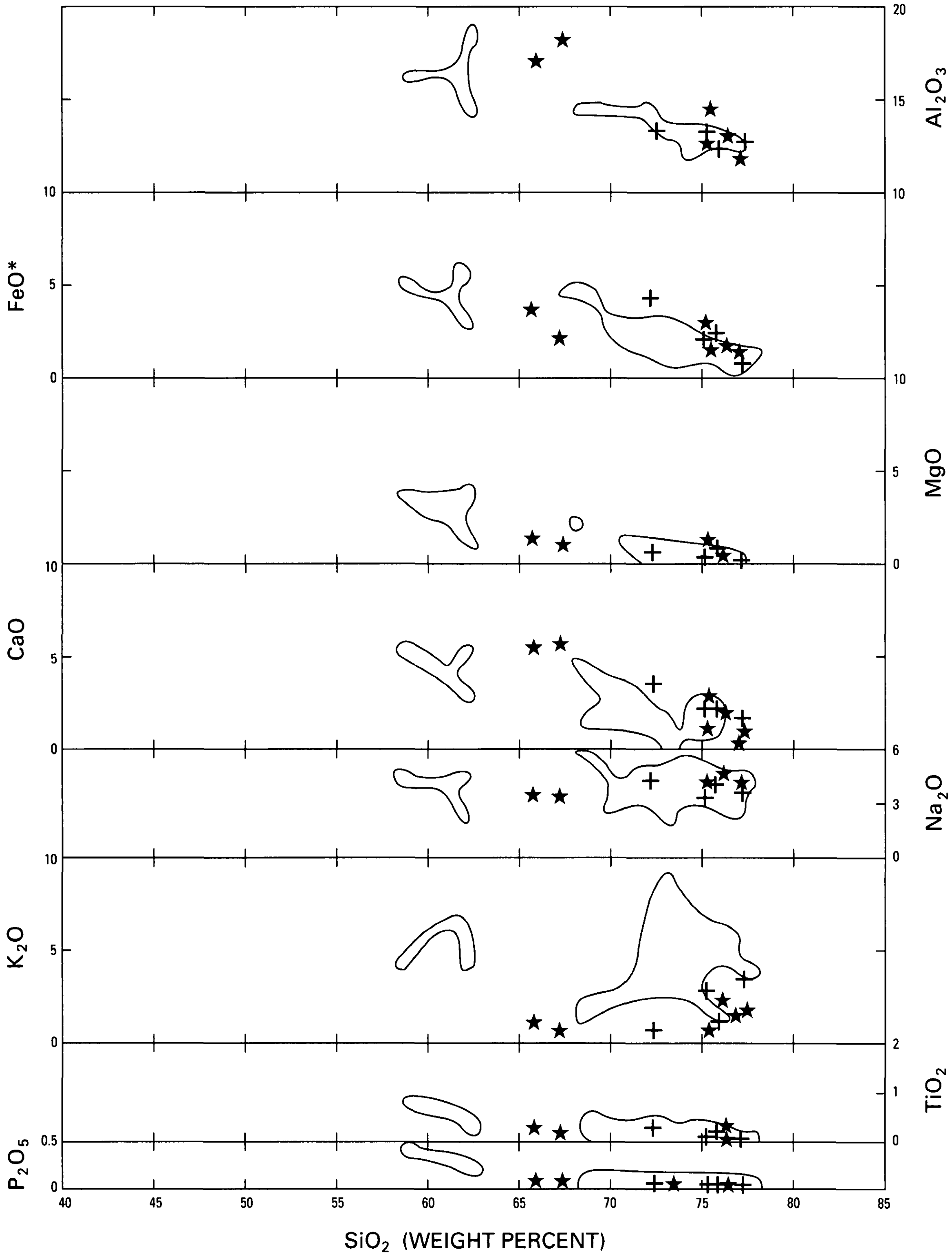


FIGURE 17.—Harker diagrams for the Monson and Swanzey Gneisses. Al_2O_3, FeO* (total iron as FeO), MgO, CaO, Na_2O, K_2O, TiO_2, and P_2O_5 versus SiO_2. Composition in weight percent, calculated on a water-free basis. ★, Monson Gneiss; +, Swanzey Gneiss; ⬭, fields of Jefferson batholith, Owls Head group of plutons, and southern New Hampshire and northern Massachusetts plutons.

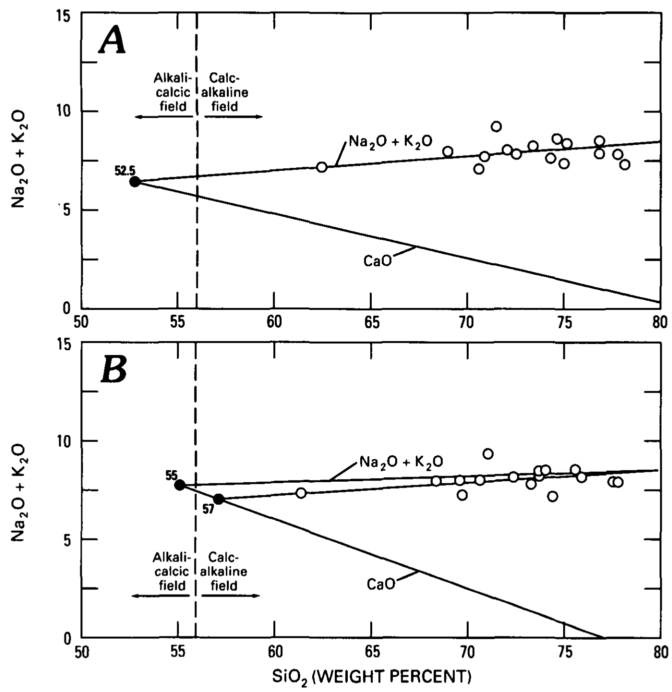


FIGURE 18.—Peacock plots for (*A*) the Smarts Mountain, Mascoma, Lebanon, Croydon, and Warwick plutons (southern New Hampshire and northern Massachusetts) and for (*B*) the Owls Head group of plutons. Compositions in weight percent, calculated on a water-free basis. Open circles indicate Na_2O+K_2O versus SiO_2; lines having a negative slope show CaO (data points not shown) versus SiO_2. Solid circles show estimated intersection of $NaO+K_2O$ and CaO. Lines visually fitted from figures 15 and 16. See text for discussion.

The scatter in the patterns for the Oliverian Plutonic Suite and related gneisses, especially the Jefferson batholith (fig. 25) and the Monson Gneiss (figs. 29, 30), suggests a mixed source area. Samples of the Owls Head group of plutons (fig. 26) and of the southern New Hampshire and northern Massachusetts plutons (fig. 27), by contrast, have much more regular and consistent patterns, which may reflect a relatively homogeneous source. Among volcanic arc granites (the expected correlation for Oliverian gneisses), the only reasonable match (high Rb and Th, low Ba) is with Andean granites from Chile, which lack the pronounced positive Ta peak found in the Oliverian gneisses. Approximately equally good matches are found in several of the patterns for all the paleotectonic granite types identified by Pearce and others (1984). These comparisons are therefore ambiguous.

The irregular patterns of the Monson Gneiss (figs. 29, 30) may reflect inhomogeneous sources. The relative enrichment of Sm-(Y)-Yb in several patterns in contrast to the depletion in other patterns is a feature also seen in Monson REE patterns (Leo and others, 1984, fig. 2).

A Ta-Yb diagram for all plutonic felsites, including Ammonoosuc trondhjemite and the northern and southern Glastonbury Gneiss (Leo and others, 1984), is shown in figure 31. This diagram, based on the work of Pearce and others (1984, fig. 3), is a different attempt to discriminate between several genetic granite types. Whereas the reliability of this scheme and the related compositional fields cannot be judged, most of the data points fall into the field of volcanic arc granites. This distribution reflects a relatively narrow range of Ta and Yb contents in Oliverian samples that appears to have statistical significance and suggests a meaningful correlation. The significance of the 11 samples falling outside this field cannot be evaluated, inasmuch as the deviations are not systematic, involving 6 of the 9 categories of Oliverian and related rocks. Two possible explanations, neither of which is satisfactory, are that (1) analytical error, especially for high Yb values in excess of 5, has caused nonsystematic scatter or (2) the system of Pearce and others (1984) is not appropriate for these samples.

RARE-EARTH ELEMENTS

Chondrite-normalized REE plots for Oliverian granitic rocks are shown in figures 32 through 38. As in the ORG-normalized diagrams, the diversity of REE patterns suggests a variety of source areas for some of these plutons, whereas other plutons show relatively consistent patterns suggesting a single source. Samples having similar trace-element variation patterns tend to have similar REE patterns, and vice versa (compare figs. 26 and 34 with figs. 28 and 37, respectively).

Samples from the Jefferson batholith (fig. 32) show at least two distinct REE trends. The first is exemplified by sample 1 (granitic gneiss extensively exposed near Berlin) and by sample 9 (syenite from the Pliny area) (tables 2, 3) (Foland and Loiselle, 1981). This trend is characterized by strongly fractionated light rare-earth elements (LREE's) and heavy rare-earth elements (HREE's) (Ce/Yb_n=78.3–12.9) and negligible to small negative Eu anomalies (Eu/Eu^*_n=1.33–0.73). These features suggest a significant component of garnet and (or) hornblende as well as plagioclase in the source area. This suggestion has important implications for the depth of origin of the gneiss at Berlin. A hornblende residue implies a depth of generation less than about 60 km, whereas a garnet residue suggests a depth of more than 60 km, where hornblende is unstable (Arth and Barker, 1976). The distinction cannot be made on the basis of available data, but a depth of origin of more than 60 km is also tentatively proposed for the Ammonoosuc Volcanics (Leo, 1985, this study).

Generally similar patterns, although having less depleted HREE and greater overall abundances, are

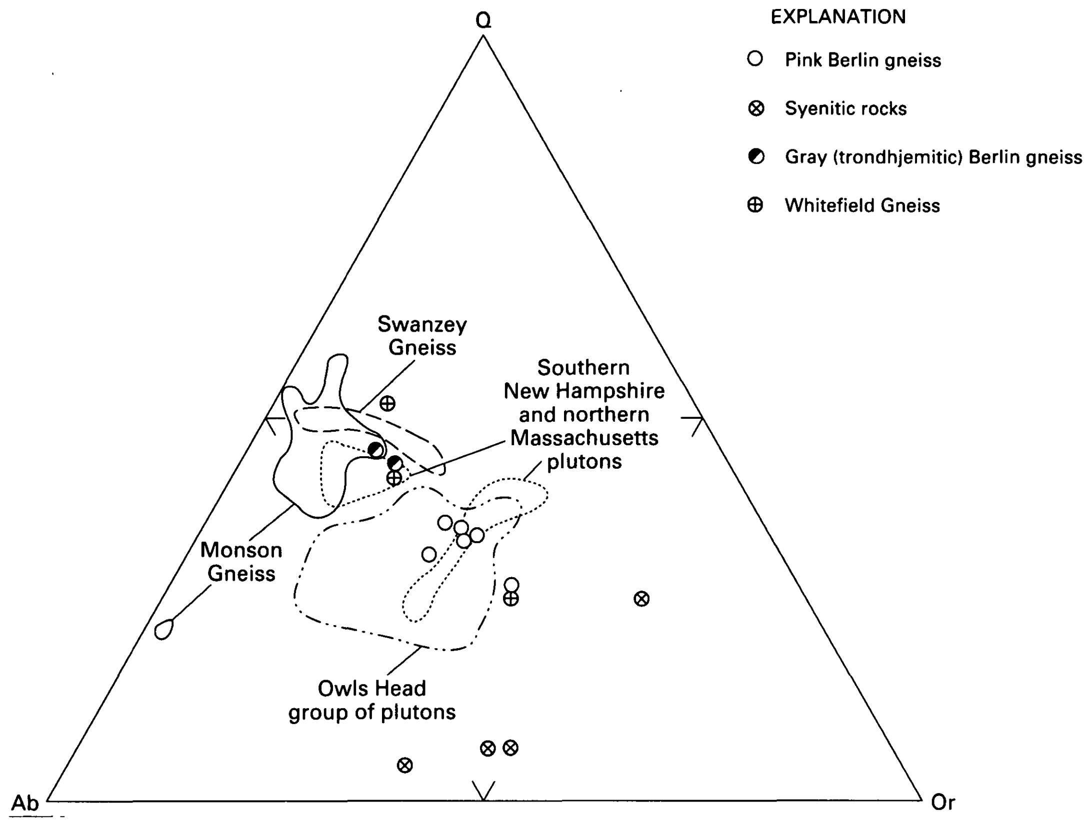


FIGURE 19.—Q-Ab-Or plot for samples from the Jefferson batholith. Remainder of Oliverian and related gneisses shown as fields.

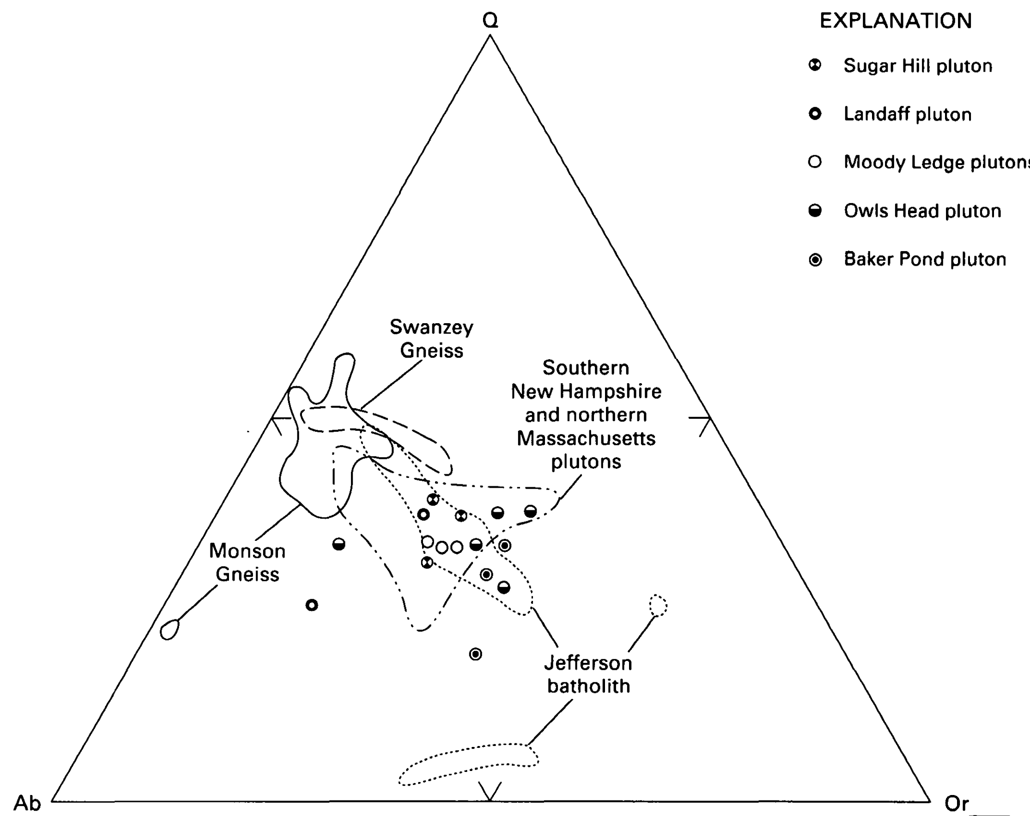


FIGURE 20.—Q-Ab-Or plot for samples from the Owls Head group of plutons. Remainder of Oliverian and related gneisses shown as fields.

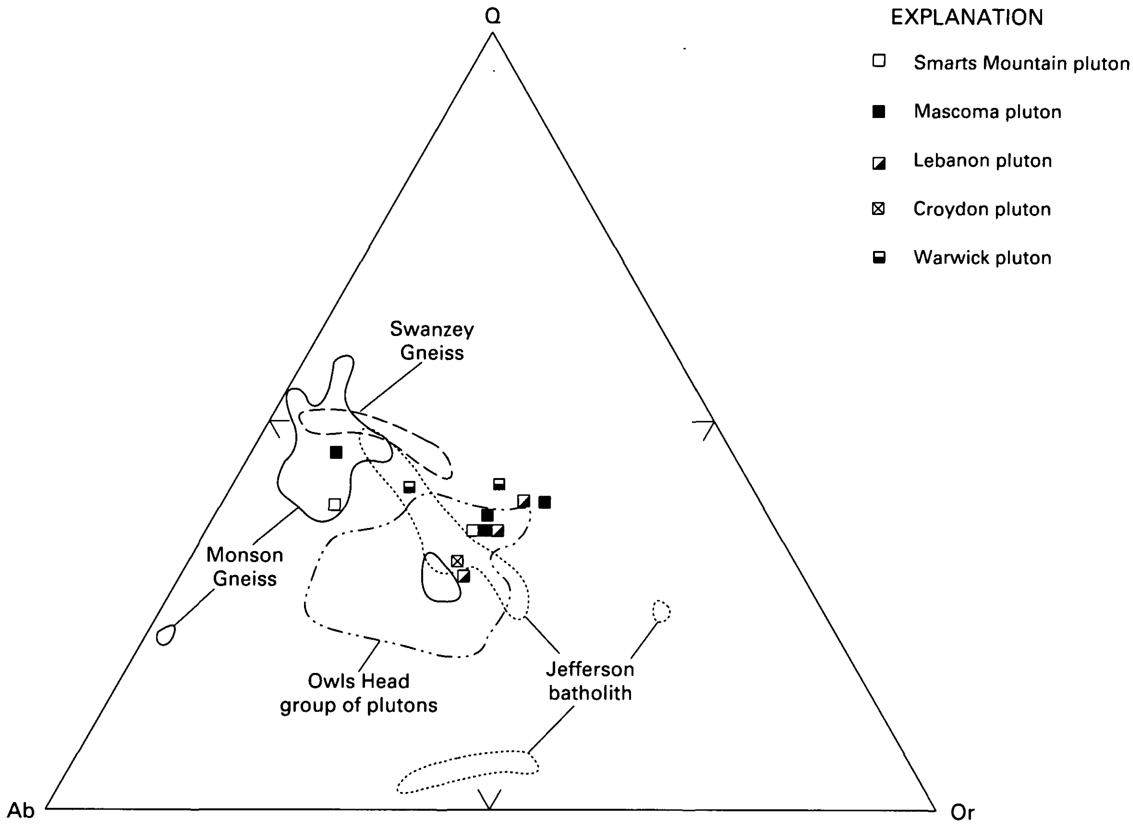


FIGURE 21.—Q-Ab-Or plot for samples from the Smarts Mountain, Mascoma, Lebanon, Croydon, and Warwick plutons (southern New Hampshire and northern Massachusetts). Remainder of Oliverian and related rocks shown as fields.

shown by the Scrag Granite (table 3, anal. 3), the Whitefield Gneiss (table 3, anal. 16), and syenites of the Pliny region (shaded field, fig. 32) (Foland and Loiselle, 1981). The other major trend is shown by K-poor tonalite-trondhjemite (gray Berlin gneiss) intruded by younger Oliverian gneiss (pink Berlin gneiss) (table 2, anals. 3, 4). Patterns of the second type are less fractionated, notably in the HREE's (Ce/Yb_n=4.9–16.2), and show small to moderate negative Eu anomalies (Eu/Eu^*_n=0.62–0.70). The relative flatness of the HREE's suggests a residue in the source area of hornblende but not of garnet (and thus a probable depth of origin of less than 60 km), whereas the Eu anomalies indicate a plagioclase residue.

Patterns for the northern plutons of the Owls Head group (Sugar Hill, Landaff, and Moody Ledge) are shown in figure 33. The patterns are generally similar, displaying moderately fractionated LREE's (Ce/Yb_n= 3.7–7.9), distinct negative Eu anomalies, and nearly flat HREE's, the difference being mainly in total REE abundances. The two patterns (table 3, anals. 17, 19) having distinctly lower abundances are samples of the fine-textured porphyritic Sugar Hill phase regarded as hypabyssal or volcanic. Analysis 18 (table 3) is of the somewhat coarser grained Sugar Hill plutonic phase, which, in turn, is fairly similar to the Landaff pluton (table 3, anal. 20). The single Moody Ledge pluton (table 3, anal. 22) is again more similar to the hypabyssal Sugar Hill phase. Significant residual plagioclase and probable hornblende in their source area are indicated for these samples, which are very likely comagmatic, as was already noted on the basis of other data.

Figure 34 shows three patterns for the Owls Head pluton and two for the Baker Pond pluton. The three Owls Head phases (table 3, anal. 25, interior and coarser; anals. 27 and 28, marginal and finer grained) are quite similar except for slightly lower abundance of LREE's in analysis 28. LREE's are strongly fractionated (Ce/Yb_n= 9.1–16.4), and HREE's are slightly so. The generally higher REE abundances in the Owls Head rocks suggest some evolution relative to the patterns of figure 34.

The Baker Pond patterns (fig. 34) differ somewhat from the Owls Head patterns in having less pronounced Eu anomalies and somewhat more fractionated HREE's (Ce/Yb_n=12.3–17.0). They also resemble some of the Jefferson batholith patterns.

The remaining patterns of rocks in the granitic plutons of southern New Hampshire and northern Massachu-

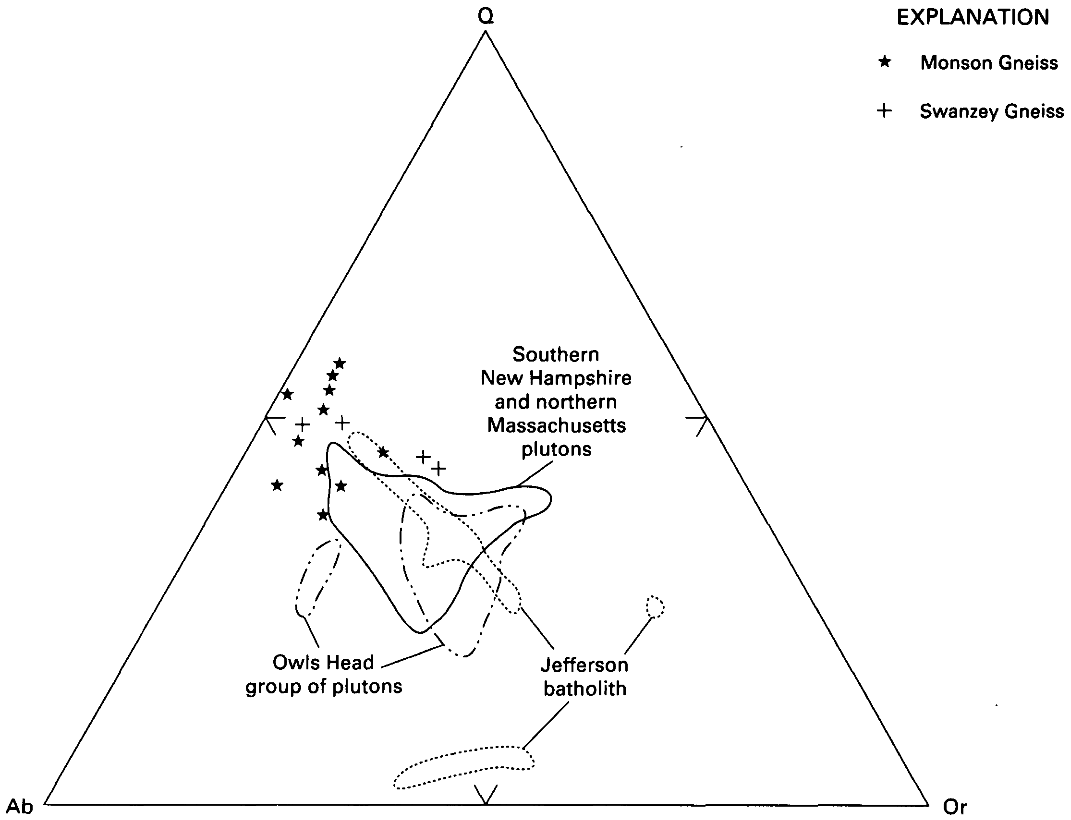


FIGURE 22.—Q-Ab-Or plot for samples from the Monson and Swanzey Gneisses. Remainder of Oliverian and related rocks shown as fields. There is little compositional overlap between the volcanogenic(?) Swanzey and Monson Gneisses and the calc-alkaline plutons.

setts (figs. 35, 36) show variations from the preceding patterns: more or less strongly fractionated LREE's, moderate to pronounced negative Eu anomalies, and HREE's ranging from nearly flat to slightly depleted or slightly enriched. The pattern of the Warwick pluton border phase (table 3, anal. 43) is anomalous in its relatively enriched REE's and resembles some of the Ammonoosuc trondhjemite patterns (table 3, anals. 110–127).

REE patterns of the Swanzey (fig. 37) and Monson (fig. 38) Gneisses have moderately fractionated LREE's, nearly flat HREE's, and moderate to pronounced negative Eu anomalies. These trends are particularly evident in the Monson Gneiss patterns. The irregular patterns of the Swanzey Gneiss (fig. 37) are probably caused in part by INA data (analyzed 1980) that are less accurate than the data for the Monson samples (analyzed 1986). Leo and others (1984, fig. 13*A*) noted two distinct groups of Monson patterns in samples collected on and near the Glastonbury dome. One set resembles the Monson patterns of this paper, whereas the other shows stronger fractionation of HREE's and negligible to moderate positive Eu anomalies, which suggest the presence of garnet and (or) hornblende but not plagioclase in the source area. These findings indicate the probability of more than one environment of genesis (see also Webster and Wintsch, 1987, p. 471).

Most of the Oliverian REE patterns suggest an origin by partial melting or fractional crystallization of a source containing small to significant amounts of plagioclase and hornblende. The main departure from this origin is found in the pattern for syenitic rock from the Pliny area of New Hampshire (fig. 32, no. 9) (Foland and Loiselle, 1981), which indicates garnet but little or no plagioclase in the residue. Foland and Loiselle regarded the source of the syenitic rocks as eclogitic and mantle derived (Cullers and Graf, 1984, p. 296). Other evidence suggests continental crust as a source for most of the Oliverian gneisses (see "Discussion," p. 68).

AMMONOOSUC VOLCANICS AND ASSOCIATED TRONDHJEMITE

MAJOR ELEMENTS

Figure 39 is a Harker diagram of the Ammonoosuc Volcanics, the Holts Ledge volcanic sequence, and associated trondhjemite. Like those of the Oliverian

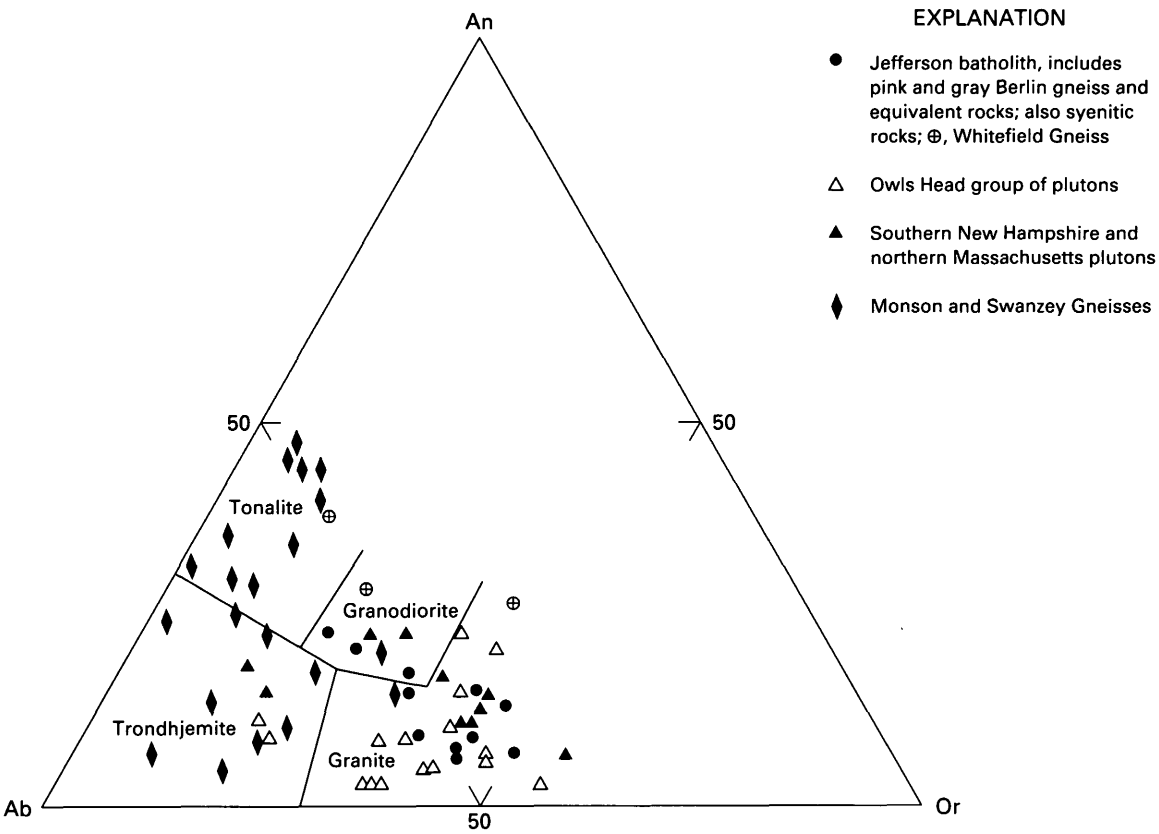


FIGURE 23.—An-Ab-Or plot for samples for all gneissic core rocks except the Unity, Alstead, and Vernon gneisses (see fig. 43). All Monson and most of the Swanzey samples correspond to trondhjemite and tonalite. Compositional fields after O'Connor (1965) as modified by Barker (1979a).

gneisses, Ammonoosuc data points show much scatter. This scatter is more pronounced for the mafic rocks than it is for the felsic ones and may be related to alteration from premetamorphic hydrothermal activity, Paleozoic metamorphism, or both. The Ammonoosuc assemblage is strongly bimodal, showing a gap of 12 percent SiO_2 (58–70 percent) if two not-very-representative samples are omitted. This gap may imply that SiO_2 was not notably mobile. Samples of Ammonoosuc Volcanics containing gedrite and (or) anthophyllite consistently are higher in FeO, MnO (see table 2), and Na_2O and lower in CaO and, to some extent, K_2O than is hornblende-plagioclase amphibolite. Felsic Ammonoosuc data points are a fairly random mixture of quartz keratophyre and trondhjemite, one criterion of comagmatic character. An expanded plot of K_2O-SiO_2 (fig. 40) shows that the majority of Ammonoosuc samples contain less than 2 percent K_2O and that more than half of them contain less than 1 percent, a value corresponding to low-K rhyolite. This feature, which has been discussed by Leo (1985), probably reflects real K-poor primary compositions, although some mobilization and loss of K cannot be ruled out.

A Q-(Ab+An)-Or diagram giving a comparative overview of the Ammonoosuc Volcanics and Oliverian gneisses and related rocks, including the Oliverian Plutonic Suite, is shown in figure 41 (fig. 41*A* shows all the Ammonoosuc and trondhjemite data points, whereas fig. 41*B* shows fields defined by these points). The bimodal character of the Ammonoosuc Volcanics is evident, as is the small degree of overlap between the Ammonoosuc Volcanics and Oliverian gneiss. Trondhjemite and quartz keratophyre show extensive overlap, as they do in Harker diagrams, and the generally K-poor aspect of felsic Ammonoosuc rocks is apparent.

An Ab-An-Or diagram (fig. 42*A*) shows that all felsic Ammonoosuc and trondhjemite fall into the compositional fields of trondhjemite and tonalite. The position of the gedritic amphibolites shows their Ca-poor and Na-rich character, also seen in figure 39. Compositional fields for trondhjemite and dacite in two modern oceanic arcs in the western Pacific (fig. 42*B*) show a large measure of overlap on this diagram, especially so the samples from Fiji (Gill and Stork, 1979).

Finally, an AFM plot (fig. 43) indicates a lack of Fe enrichment and an essentially calc-alkaline character

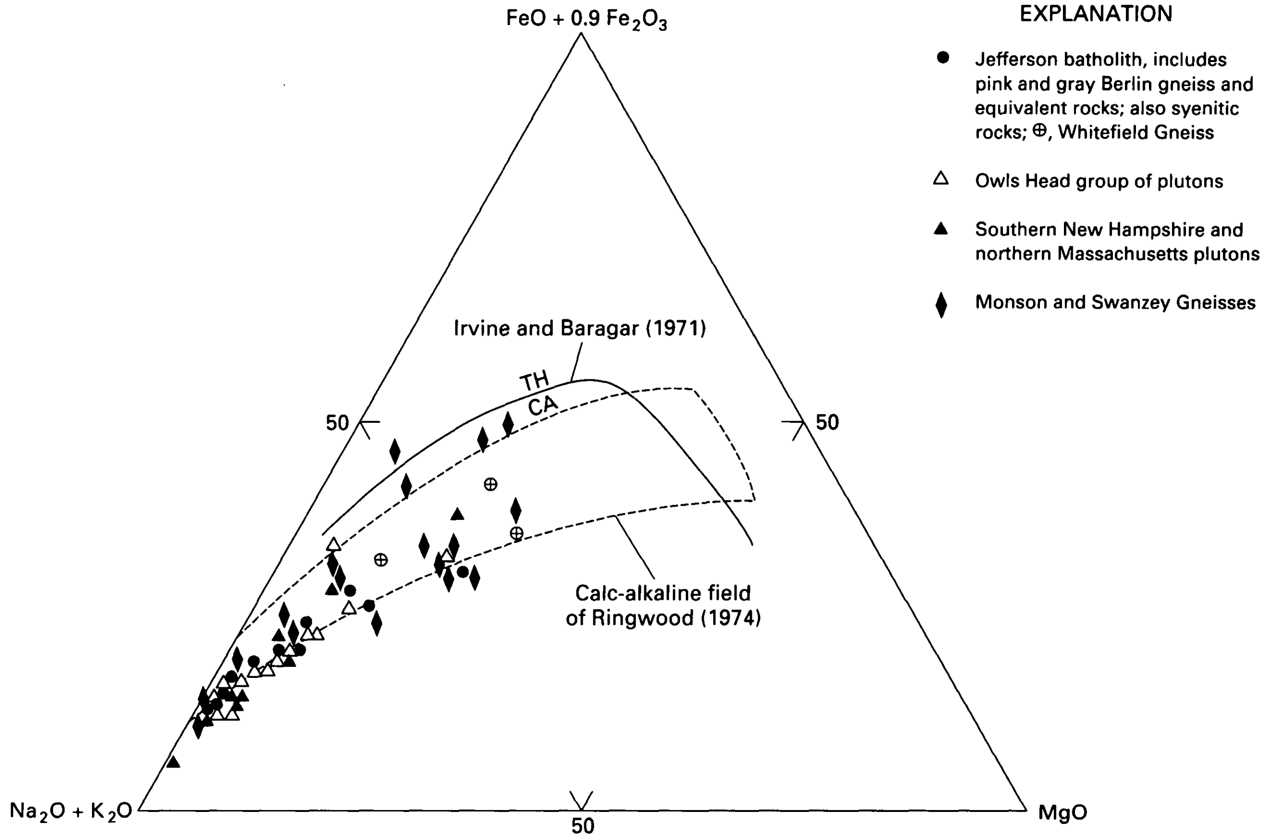


FIGURE 24.—AFM plot for all gneissic core rocks except the Unity, Alstead, and Vernon gneisses (see fig. 43). Nearly all samples plot within or below the calc-alkaline fields of Ringwood (1974) and Irvine and Baragar (1971). CA, calk-alkaline; TH, tholeiitic.

that is not very different from the character of the Oliverian gneisses (see fig. 24). The Irvine and Baragar (1971) tholeiite-calc-alkaline (TH-CA) boundary straddles the field of mafic Ammonoosuc, which could hence be regarded as marginally tholeiitic.

TRACE ELEMENTS OTHER THAN RARE EARTHS

Figure 44*A* and *B* shows an assemblage of trace elements normalized against a standard mid-ocean ridge basalt (MORB), as devised and arranged by Pearce (1983) for basaltic rocks. These diagrams are used here to test the validity of Pearce's (1983) scheme of analysis for the Ammonoosuc Volcanics and related rocks. The array for trace elements differs from the array for granitic rocks (figs. 25–30) and is intended to model the relative proportions of elements supplied by the subduction zone, the subcontinental lithosphere, and the continental crust. The array of trace elements is also intended to model the effects of partial melting and (or) fractional crystallization from a source situated above a downgoing slab of oceanic lithosphere in an active continental margin. Patterns from samples, which, on the basis of geologic considerations, reflect various paleotectonic settings, fall into distinctive groupings and thus provide a potential diagnostic tool. Although it is not the purpose of this paper to reproduce the kind of modeling described by Pearce, it is instructive to compare his patterns with those of the Ammonoosuc Volcanics, and they are thus presented analogously to the comparable scheme for granitic rocks given in the previous section. The mafic Ammonoosuc patterns (fig. 44*A*, *B*) are characterized by generally high but varied concentrations of trace elements Sr, K, Rb, Ba, and Th and low abundances of Ta, Nb, Ce, P, Zr, Hf, Sm, Ti, Y, and Yb (some below the MORB normalizing line, 1.0). Patterns near the MORB line (fig. 44*A*, nos. 70, 72; fig. 44*B*, nos. 77, 80, 84) resemble Pearce's (1983, fig. 4) island-arc tholeiite pattern, whereas patterns above the MORB line (fig. 44*A*, nos. 61, 66, 67) bear a greater resemblance to continental-arc basalts of central Chile (Pearce, 1983, fig. 8). This duality of paleotectonic environments renders the interpretation ambiguous and is improbable. Thus, one can only note a general affinity between mafic Ammonoosuc and Pearce's tholeiitic island-arc patterns.

A Ta-Th-Hf/3 diagram (fig. 45) shows most Ammonoosuc-related data points falling into the field for convergent plate margins of calc-alkaline chemistry.

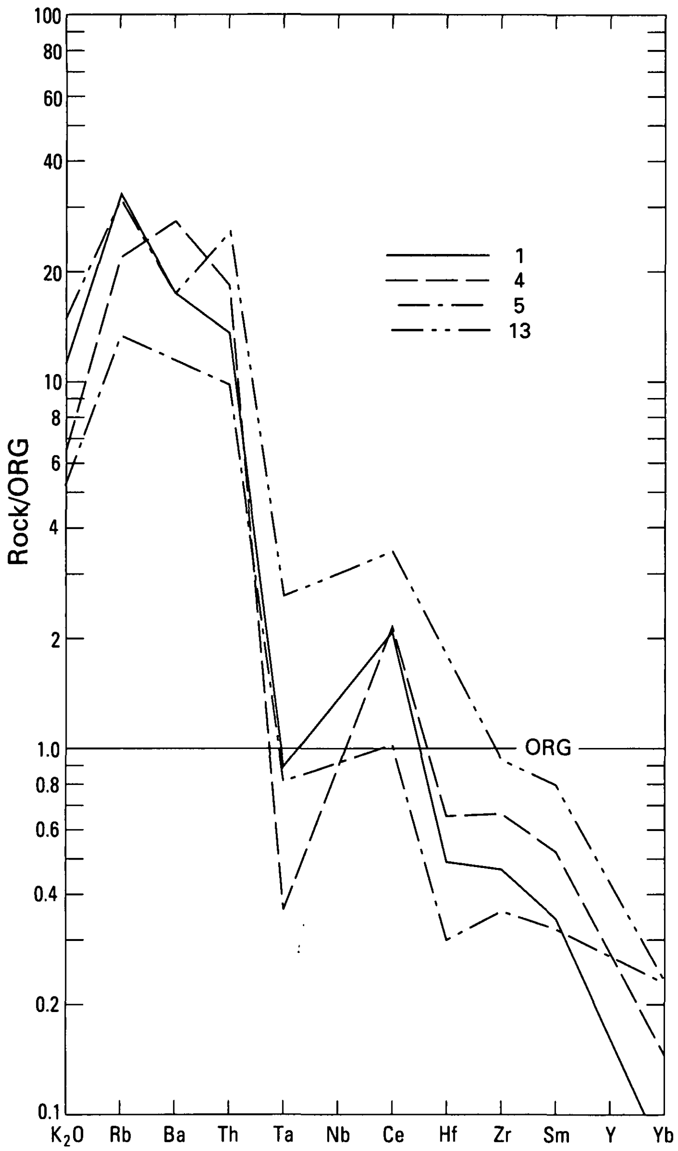


FIGURE 25.—Trace-element abundance normalized to hypothetical ocean ridge granite (ORG) (Pearce and others, 1984, table 4) for samples from the Jefferson batholith. Numbered patterns refer to analysis numbers in table 3. Irregularities suggest a mixed source.

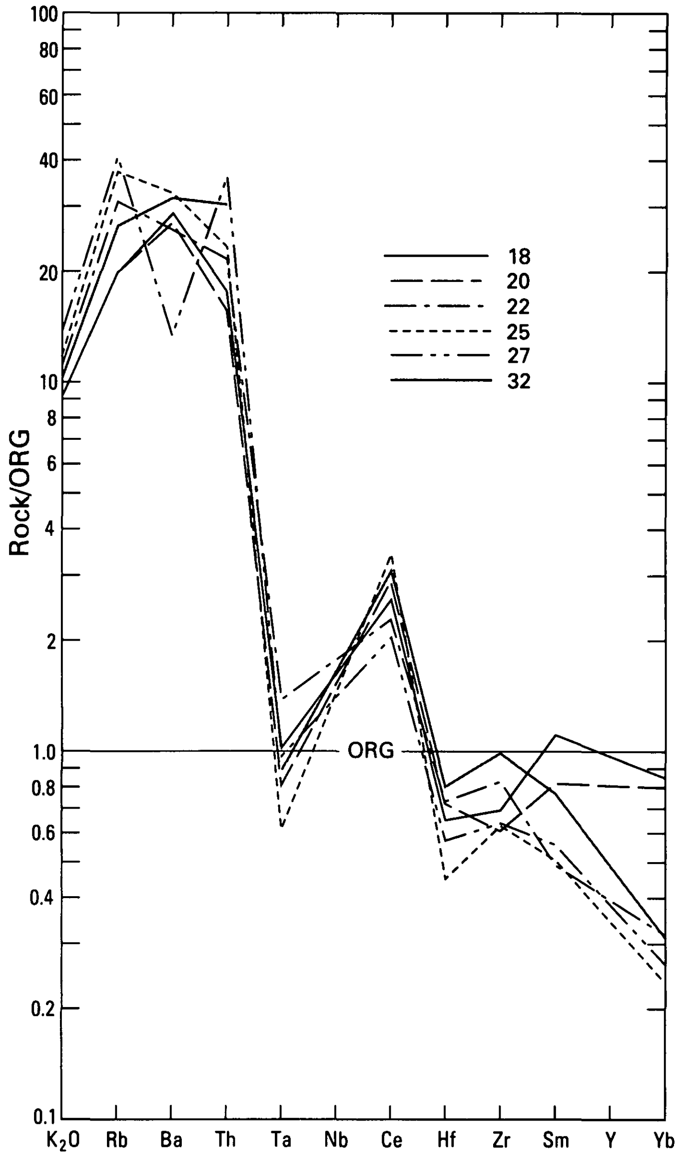


FIGURE 26.—Trace-element abundance normalized to hypothetical ocean ridge granite (ORG) (Pearce and others, 1984) for samples from the Owls Head group of plutons. The fact that the patterns of the Owls Head samples are much more consistent than those of the Jefferson batholith samples suggests a relatively homogeneous source. Numbered patterns refer to analysis numbers in table 3.

Points for Oliverian plutons on the same diagram are tightly clustered near the Th apex. Although the reliability of this diagram is hard to evaluate, the data distribution reflects the generally calc-alkaline character of the Oliverian gneisses and the Ammonoosuc Volcanics, as well as the oceanic-continental plate margin environment suggested by other evidence. Points falling out of the field for calc-alkaline plate margin basalts, mainly amphibolites from the Plainfield-Norwich-Lyme area along the Connecticut River (Aleinikoff, 1977) (see pl. 1), evidently reflect significant, although not consistent, differences in chemistry from the other samples. The significance of the single isolated trondhjemite sample falling in the "alkaline within plate basalts" field is not clear. Thus, the data distributions may have a significance analogous to that of the Yb-Ta plot for volcanic-arc granites (fig. 31).

RARE-EARTH ELEMENTS

REE patterns for mafic and felsic Ammonoosuc and related rocks are shown in figures 46 through 49. Figures 46*A*, 47*A* and 47*B*, 48, and 49, which have been published by Leo (1985) and are reprinted here, are supplemented by additional patterns in figure 46*B*.

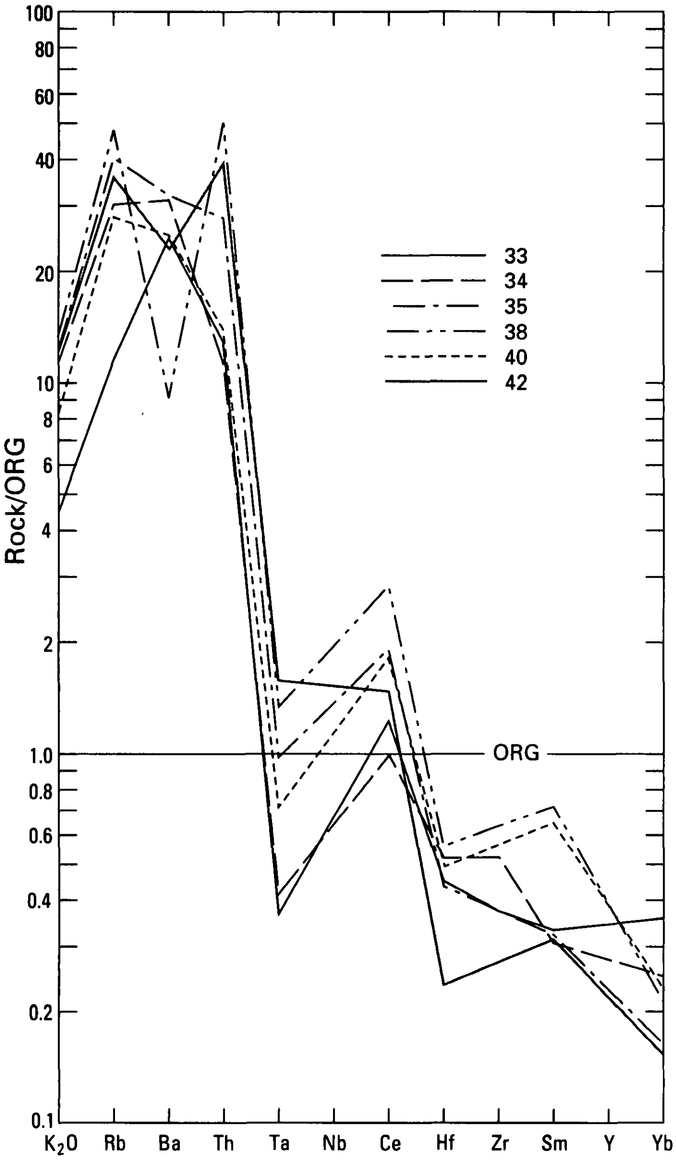


FIGURE 27.—Trace-element abundance normalized to hypothetical ocean ridge granite (ORG) (Pearce and others, 1984) for samples from the Smarts Mountain, Mascoma, Lebanon, Croydon, and Warwick plutons (southern New Hampshire and northern Massachusetts). Numbered patterns refer to analysis numbers in table 3.

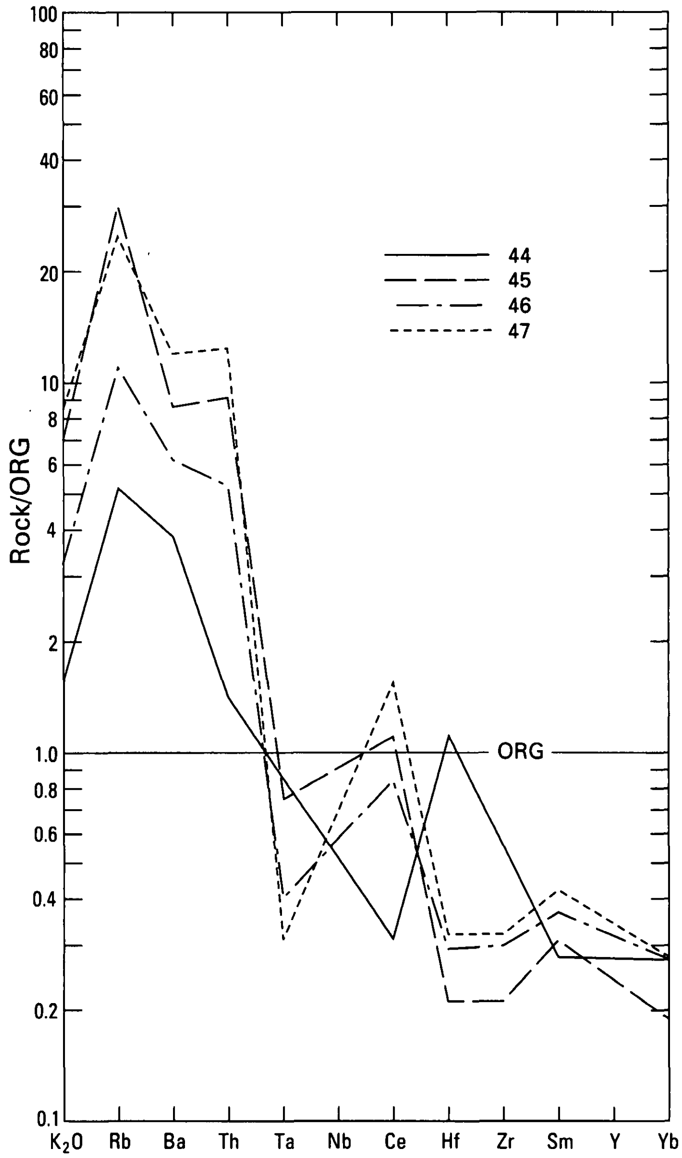


FIGURE 28.—Trace-element abundance normalized to hypothetical ocean ridge granite (ORG) (Pearce and others, 1984) for samples from the Swanzey Gneiss. Note the consistent relative abundances for K_2O, Rb, Ba, and Th. Numbered patterns refer to analysis numbers in table 3.

MAFIC AMMONOOSUC VOLCANICS

REE patterns for mafic Ammonoosuc Volcanics—those determined both by isotope dilution and by INA analysis (fig. 46*A* and *B*, respectively) are flat to slightly fractionated (Ce/Yb_n=1.14–3.65) and have small to negligible Eu anomalies (Eu/Eu^*_n=0.80–1.0). The sole exception (tables 2, 3, anal. 86) is a gedrite-bearing rock of intermediate composition (64.1 percent SiO_2, 2.6 percent CaO) that has a more evolved pattern, characterized by higher total REE's, enriched LREE's, and a distinct negative Eu anomaly. The remaining patterns resemble those of some island-arc tholeiites (for example, see Basaltic Volcanism Study Project, 1982, p. 202, fig. 1.2.7.10; Masuda and others, 1975; Arth, 1981) and also of some low- to medium-K orogenic andesites (Gill, 1981, figs. 5.12 a–b, 1.2). They are conspicuously lacking in the characteristic depleted LREE's associated with normal-type ocean ridge basalts (see Saunders, 1984, ch. 6, especially fig. 6.1). The amphibolite patterns are in good accord with the remaining chemistry of these rocks, notably the straddling of the tholeiite–calc-alkaline boundary (fig. 43). The principal distinction between the amphibolite patterns is the absolute abundance of REE's. The patterns in figure 46*A*, determined by isotope

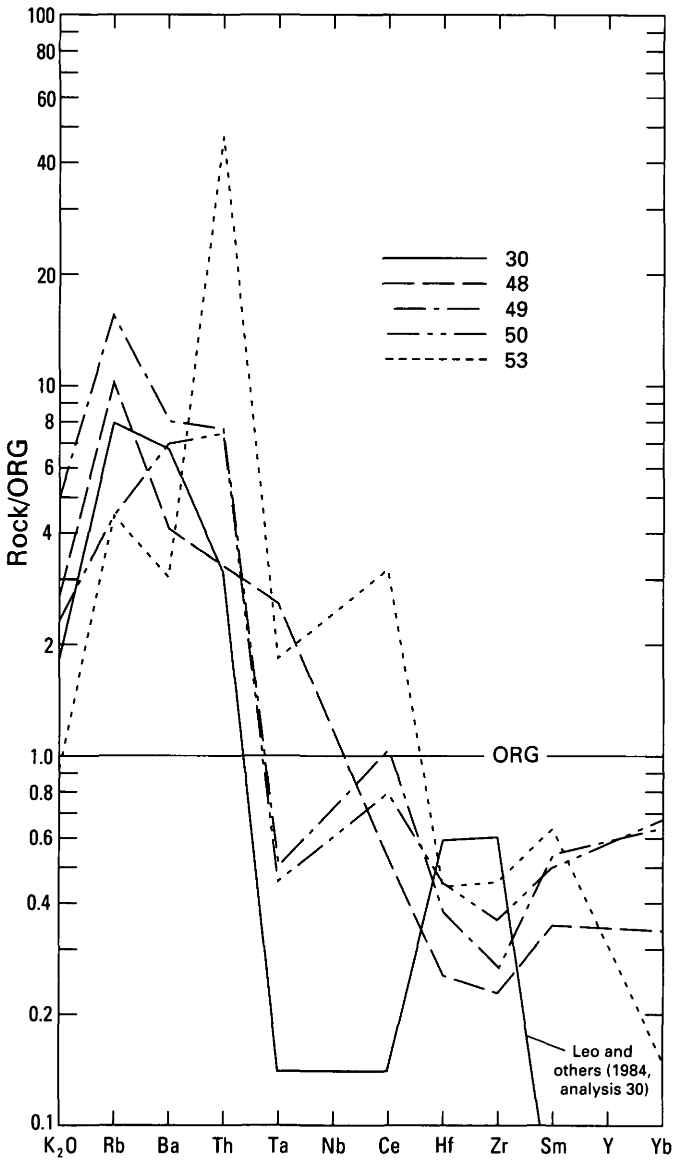


FIGURE 29.—Trace-element abundances normalized to hypothetical ocean ridge granite (ORG) (Pearce and others, 1984) for samples from the Monson Gneiss from this study (table 3, anals. 48, 49, 50, 53) and from Leo and others (1984, tables 1, 2, anal. 30). Marked heterogeneity suggests an inhomogeneous source.

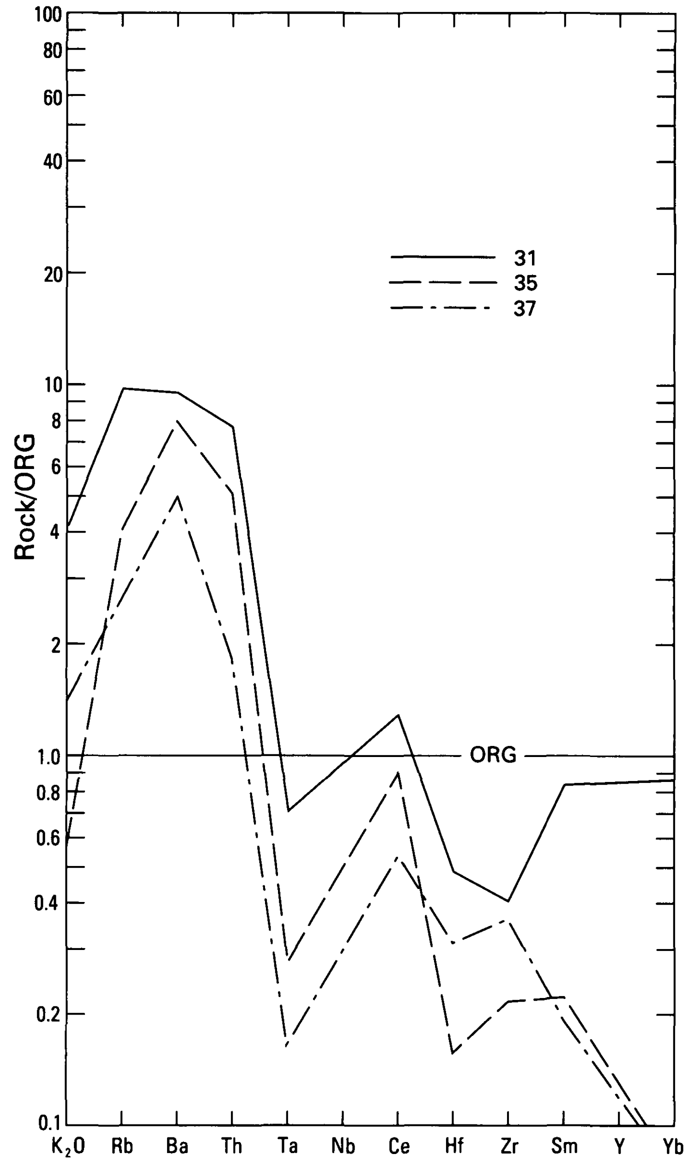


FIGURE 30.—Trace-element abundance normalized to hypothetical ocean ridge granite (ORG) (Pearce and others, 1984) for samples from the Monson Gneiss (Leo and others, 1984, tables 1, 2, anals. 31, 35, 37). Abundances generally are low in comparison with the abundances in Oliverian granites. Large differences in Yb are reflected in distinctive rare-earth element patterns (Leo and others, 1984, fig. 13*A*).

dilution, are probably more reliable than those in figure 46*B*, which represent early (1980–82) state-of-the-art INA analysis.

FELSIC AMMONOOSUC VOLCANICS AND RELATED ROCKS

REE patterns for Ammonoosuc trondhjemite, Ammonoosuc quartz keratophyre, and the Holts Ledge volcanic sequence are shown in figures 47 through 49, with the exception of one sample (table 3, anal. 106) discussed below. The patterns for all three rock types are similar. This similarity and the similar major-element chemistry are the main reasons for regarding them as comagmatic. All the patterns except the one for analysis 106 show slight to moderate fractionation of LREE's, moderate to pronounced negative Eu anomalies, and flat to slightly enriched HREE's. A sample of quartz keratophyre from the southern margin of the Owls Head pluton, regarded as metasomatized (fig. 48; table 3, anal. 102), has a pattern that is more similar to that of Oliverian granites than to that of felsic Ammonoosuc.

The patterns for trondhjemite (fig. 47*A*, *B*) show moderate REE fractionation (Ce/Yb_n=1.33–4.54),

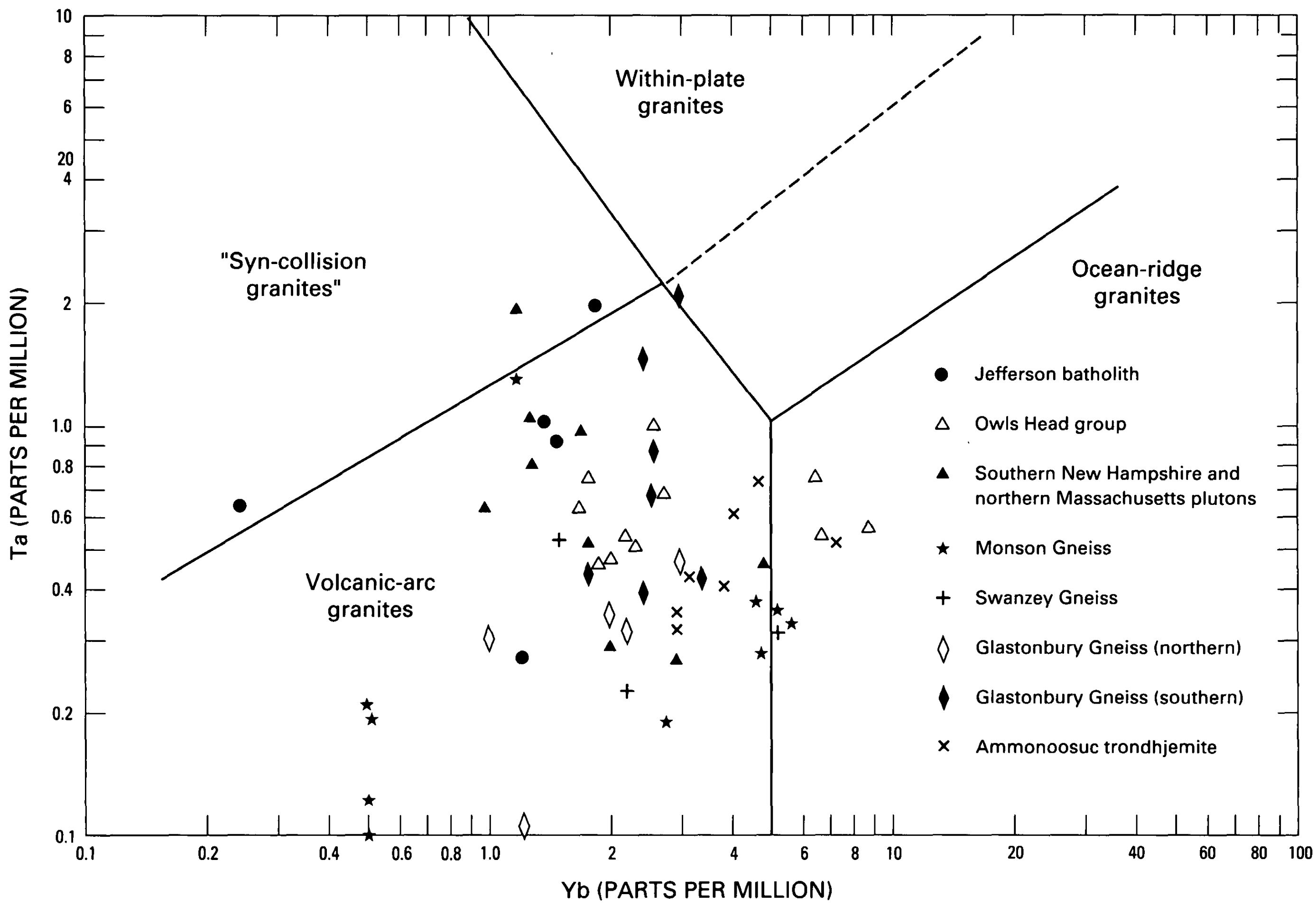


FIGURE 31.—Ta versus Yb (after Pearce and others, 1984, fig. 3) for all felsic plutonic rocks, including Ammonoosuc trondhjemite (table 3) (Leo, 1985, table 1) and the northern and southern Glastonbury Gneiss (Leo and others, 1985).

marked by Ce abundances of approximately 25 to 60× chondrites; moderate to pronounced negative Eu anomalies (Eu/Eu_n*=0.28–0.62); and relatively flat HREE's. These patterns are generally comparable to those of low-Al_2O_3 trondhjemites (Barker and others, 1976) and thus are in accord with the major-element chemistry of these rocks (table 2). The shapes of the trondhjemite patterns, with the exception of sample 11, generally suggest a source material containing plagioclase and pyroxene.

Patterns for four samples of Ammonoosuc quartz keratophyre (fig. 48) are generally similar to Ammonoosuc trondhjemite patterns (shaded field) but have slightly higher abundances of LREE's (Ce_n=30–70× chondrites) and slightly less pronounced Eu anomalies (Eu/Eu_n*=0.45–0.78) than the trondhjemites. LREE fractionation (Ce/Yb_n=1.95–3.61) is slightly less than it is in the trondhjemite patterns. The similarity between the quartz keratophyre and trondhjemite patterns indicates a minimum of either differentiation or of winnowing of heavy accessory minerals during the process of eruption and deposition of the tuff. This similarity constitutes the major basis for regarding the quartz keratophyre composition as close to primary. REE patterns for samples of the Holts Ledge volcanic sequence (fig. 49) differ significantly from one another. Patterns for analyses 105 and 107 (table 3) are comparable to most of the patterns discussed so far (anal. 105: Ce/Yb_n=1.39, Eu/Eu_n*=0.60; anal. 107: Ce/Yb_n=1.77, Eu/Eu_n*=0.47), whereas analysis 106 shows significantly and progressively higher HREE abundances relative to analysis 105. The negative slope of the pattern (Ce/Yb_n=0.61), together with the relative depletion of Ce, suggests that the effect of clinopyroxene in the source area is more pronounced than it is in other silicic rocks. Indeed, analysis 106 (table 3) may reflect a source area other than the overlying Ammonoosuc rocks (Coish and Rogers, 1987, p. 63). It is also noteworthy that the erratic pattern is from one of two samples in the Holts Ledge section, whereas the Baker Pond sample (table 3, anal. 105) resembles the other Holts Ledge pattern. More data would be required to evaluate this situation.

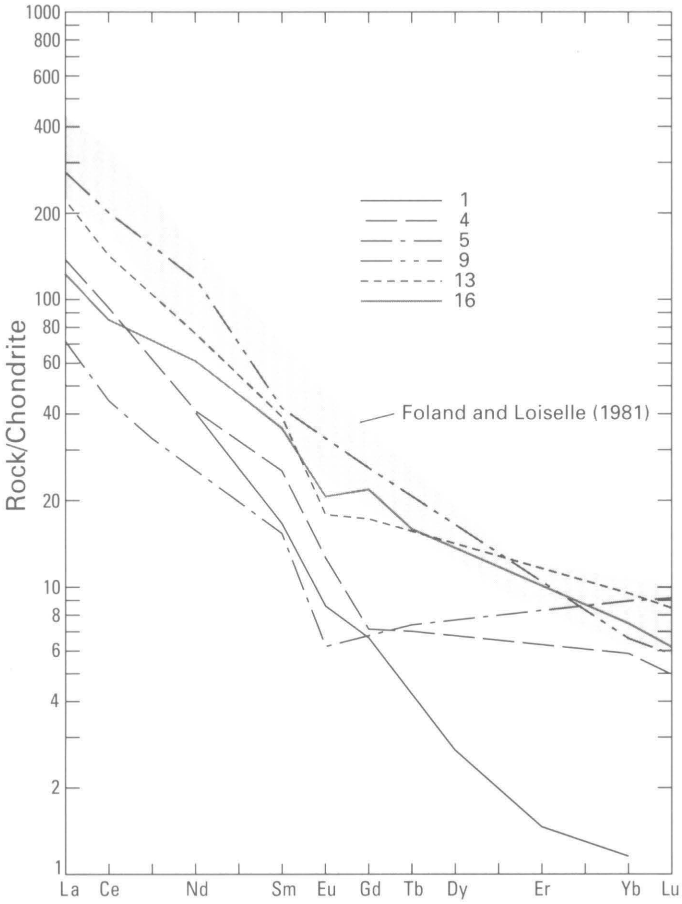


FIGURE 32.—Rare-earth elements of major rock types of the Jefferson batholith. Numbers keyed to analyses in table 3. Shaded area shows syenites from the Pliny area of New Hampshire, north of Jefferson Highland (Foland and Loiselle, 1981) (see pl. 1).

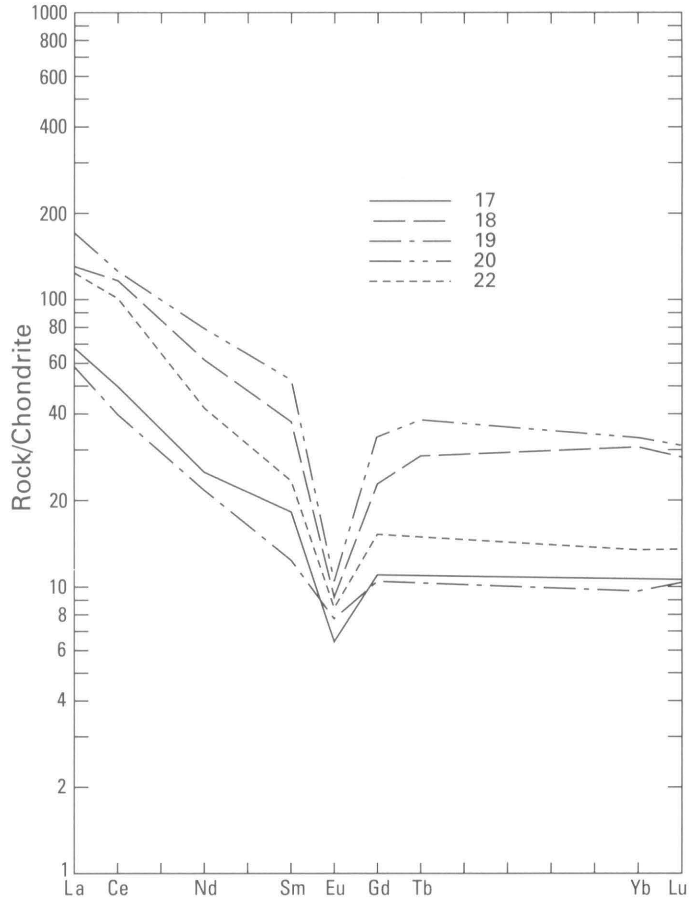


FIGURE 33.—Rare-earth elements of major rock types of the Sugar Hill, Landaff, and Moody Ledge plutons. Numbers keyed to analyses in table 3.

DISCUSSION

The field relationships and geochemistry discussed above provide a basis for evaluating the Bronson Hill lithologies in the context of a magmatic arc. The following discussion attempts to shed some light on the petrogenesis of the somewhat unusual Ammonoosuc Volcanics and to address the question of its relationship to the essentially coeval but chemically distinct Oliverian Plutonic Suite.

AMMONOOSUC VOLCANICS

The Ammonoosuc Volcanics have been studied in some detail (Leo and others, 1984; Leo, 1985; Schumacher, 1988). They are a plausible, if uncommon, volcanic-arc suite (that is, a generally bimodal, low-K, calc-alkaline suite having a high felsic component), derived by partial melting of a basaltic source(s) in the lower crust or upper mantle. The Ammonoosuc-trondhjemite suite of western New Hampshire, moreover, resembles some trondhjemite-amphibolite suites in Newfoundland (for example, Twillingate) not necessarily interpreted as island arcs (Payne and Strong, 1979; Malpas, 1979).

As to analogs with modern arcs, comparisons have been drawn with Fiji (Gill and Stork, 1979) and New Britain (Basaltic Volcanism Study Project, 1982). Concerning such analogs, Leo (1985, p. 1505–1506) commented that an island-arc interpretation for the Ammonoosuc Volcanics is subject to specific constraints imposed by their unusual lithology and geochemistry: (1) the bimodal assemblage, which is disproportionately high in felsic rocks (discussed above); (2) the combination of low K and relative enrichment in incompatible elements (Ba, La, Zr, Th, and, to a lesser extent, Ta) (see tables 2, 3); (3) the moderately fractionated REE patterns (compare with Gill and Stork, 1979, fig. 5); and (4) the generally calc-alkaline trends. This combination of features has no close analog in modern island arcs, whether tholeiitic (oceanic) or calc-alkaline (continental margin). Perhaps the closest analog is the Tertiary volcanic-plutonic assemblage of Fiji in which the relative propor-

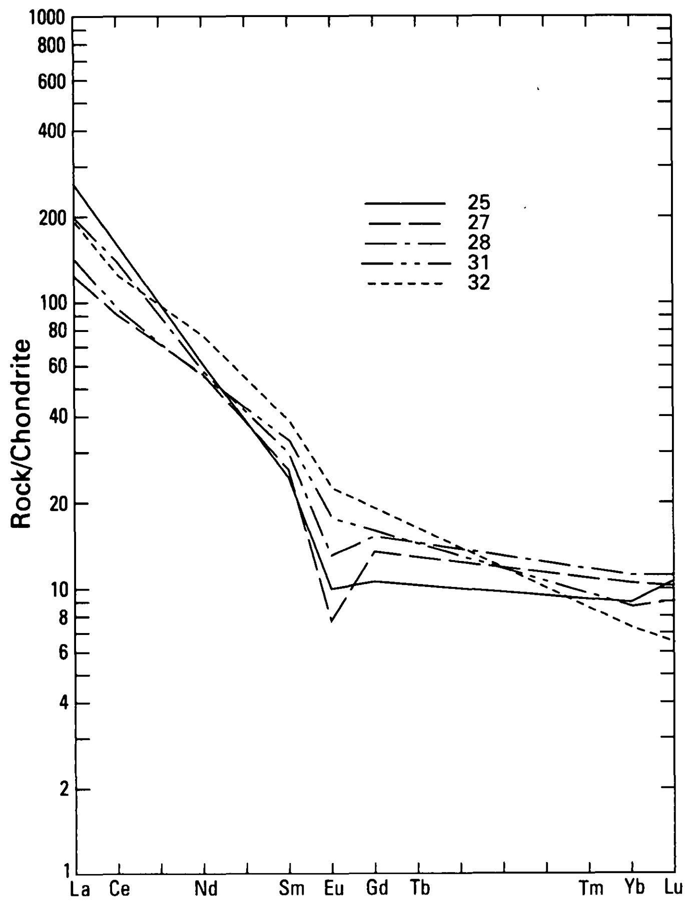


FIGURE 34.—Rare-earth elements of major rock types of the Owls Head and Baker Pond plutons. Numbers keyed to analyses in table 3.

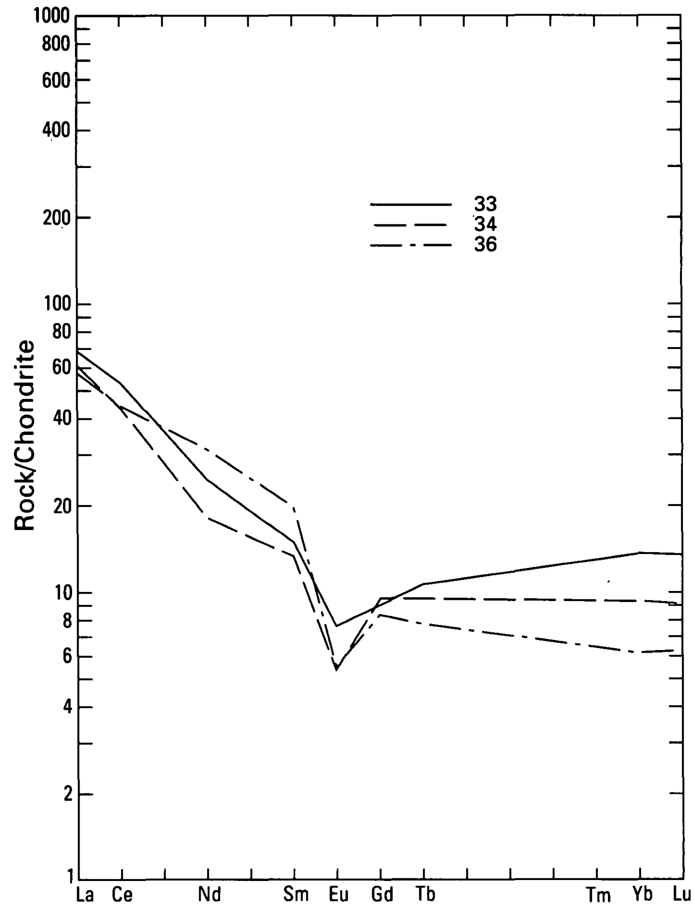


FIGURE 35.—Rare-earth elements of major rock types of the Smarts Mountain and Mascoma plutons. Numbers keyed to analyses in table 3. A representative Mascoma granite—sample 30-1 (anal. 35)—was not plotted because of deficient instrumental neutron activation data.

tions of felsic and mafic rocks are comparable to those in the Ammonoosuc Volcanics (Gill and Stork, 1979) (see fig. 42*B*). This analog is discussed further below. Rocks of the Tonga-Kermadec arc (Bryan and others, 1972; Ewart and Bryan, 1972; Ewart and others, 1973; Bryan, 1979) have been invoked as a comparison with the Ammonoosuc Volcanics (Schumacher, 1988), but the dacites of this bimodal assemblage show only limited compositional overlap with the felsic Ammonoosuc Volcanics (Leo, 1985) (fig. 42*B*) and are less siliceous (60–69 percent SiO_2) and higher in Fe and Ca than the Ammonoosuc. The Tonga-Kermadec suite as a whole corresponds to island-arc tholeiite. Another limited analog to the Ammonoosuc is the Marianas arc, particularly Saipan, where andesite is associated with highly siliceous dacite (Schmidt, 1957; Barker and others, 1976; Meijer, 1983) (see figs. 41–43), but these rocks also show typical island-arc tholeiite characteristics. The dacite, moreover, may not be related to the andesite in any simple way (Meijer, 1983).

The foregoing discussion shows that the Ammonoosuc Volcanics are not compatible with Ringwood's (1974) model for the early phase of island-arc development, which results in a dominantly basaltic island-arc tholeiitic suite having low abundances of incompatible elements and unfractionated REE patterns. The generally calc-alkaline character of the Ammonoosuc Volcanics is in better accord with more evolved arcs showing calc-alkaline chemistry (Ringwood, 1974), such as the Indonesian or Andean continental-margin arcs. The major difficulty with such analogies is that the continental-margin arcs are dominated by andesite, which is only a minor type in the Ammonoosuc assemblage; also, they are not K-poor. Quite clearly, neither of Ringwood's (1974) two stages of arc development can account for the mixed characteristics of the Ammonoosuc Volcanics, which seem to reflect conditions intermediate between tholeiitic and calc-alkaline arcs.

The REE patterns of silicic Ammonoosuc rocks suggest a pyroxene residue, and so it is fair to postulate that

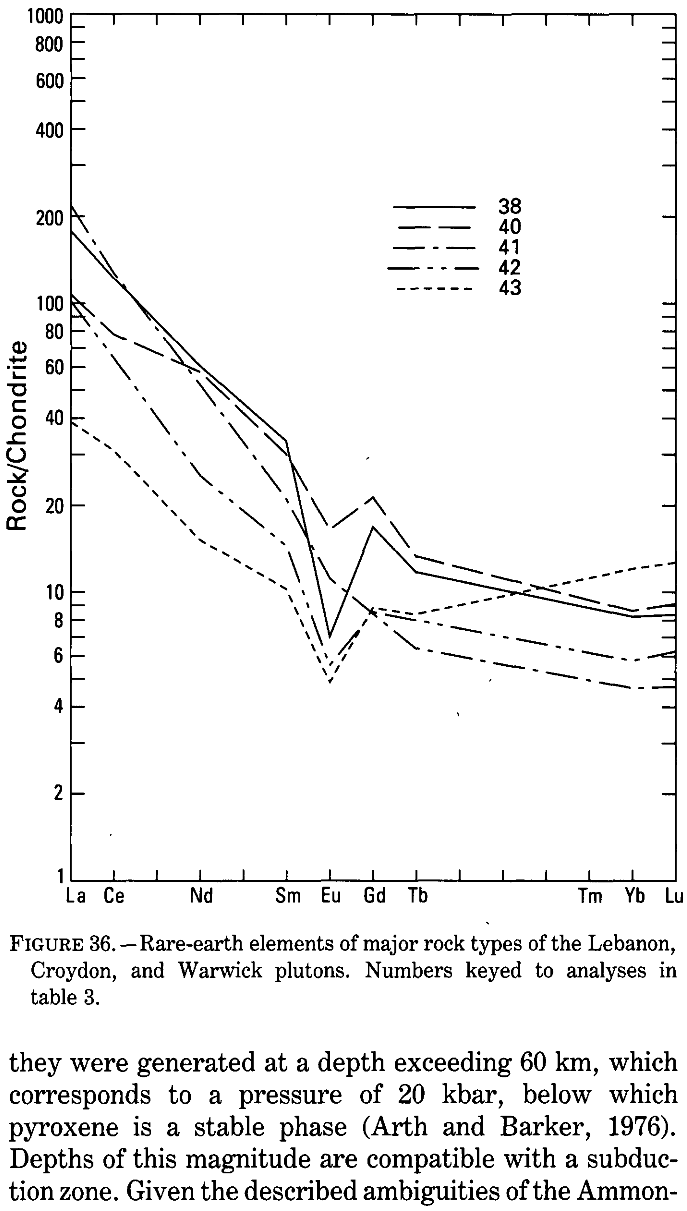


FIGURE 36.—Rare-earth elements of major rock types of the Lebanon, Croydon, and Warwick plutons. Numbers keyed to analyses in table 3.

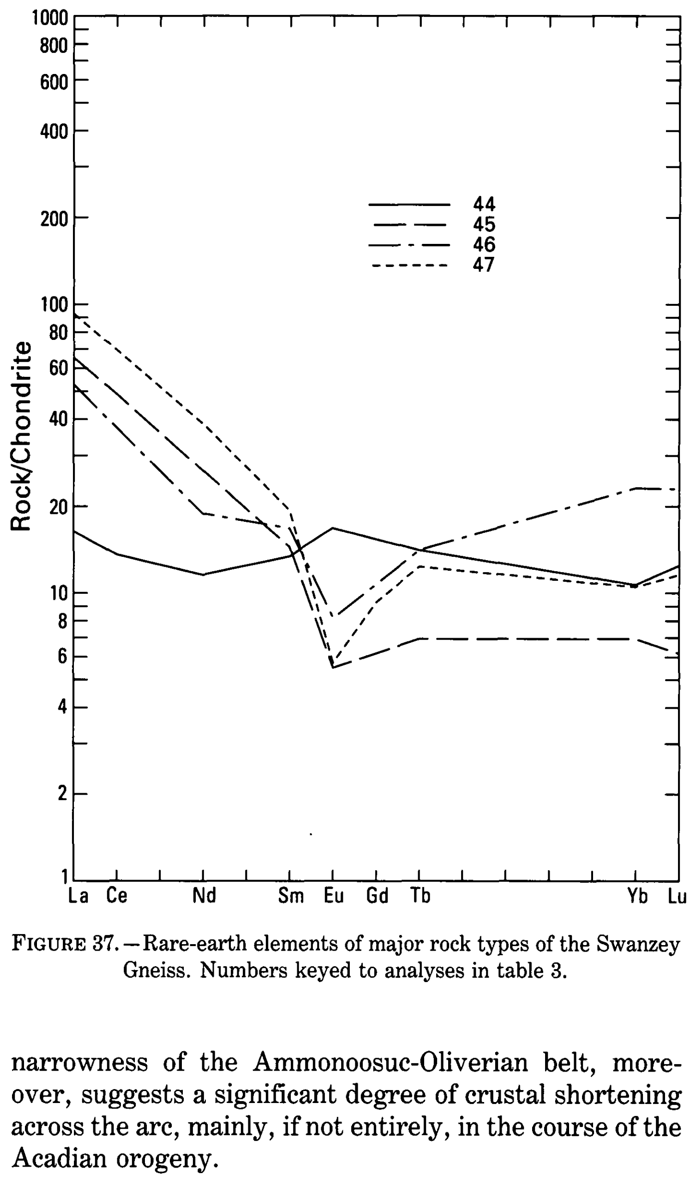


FIGURE 37.—Rare-earth elements of major rock types of the Swanzey Gneiss. Numbers keyed to analyses in table 3.

they were generated at a depth exceeding 60 km, which corresponds to a pressure of 20 kbar, below which pyroxene is a stable phase (Arth and Barker, 1976). Depths of this magnitude are compatible with a subduction zone. Given the described ambiguities of the Ammonoosuc assemblage and the known field relationships, a reasonable conjecture is that the Ammonoosuc reflects a relatively early stage of island-arc magmatism, which initially produced Fe-poor tholeiitic basalt and associated K-poor felsic rocks, as outlined above. The calc-alkaline trend may have been produced by limited contamination of basaltic magma by sialic crust east of the axis of the Bronson Hill anticlinorium, partial melting of which subsequently produced the Oliverian granite plutons. In effect, the early oceanic arc evolved into a continental-margin arc, acquiring some features of each. Such a model cannot be quantitatively tested with the available data because of a lack of reliable primary compositions of a basaltic parent. In any case, the close juxtaposition in time and space of the Oliverian gneisses and somewhat older mantling volcanics makes at least some chemical interaction between them appear plausible. The relative narrowness of the Ammonoosuc-Oliverian belt, moreover, suggests a significant degree of crustal shortening across the arc, mainly, if not entirely, in the course of the Acadian orogeny.

PARTIAL MELTING VERSUS FRACTIONAL CRYSTALLIZATION

AMMONOOSUC VOLCANICS

Leo (1985) concluded that the felsic Ammonoosuc Volcanics, including trondhjemite, were derived by partial melting of a basaltic source and that fractional crystallization played a minor to negligible role in the petrogenesis of the Ammonoosuc. Similar conclusions were reached by Schumacher (1988) and, regarding the Partridge Formation, by Hollocher (1985), although Hollocher (1985, p. 91) invoked fractional crystallization as a process involved especially in the genesis of dacitic layers in the Partridge Formation.

The main reasons for interpreting partial melting of basalt to be the major process for the genesis of the Ammonoosuc are (1) the lack of iron enrichment typical

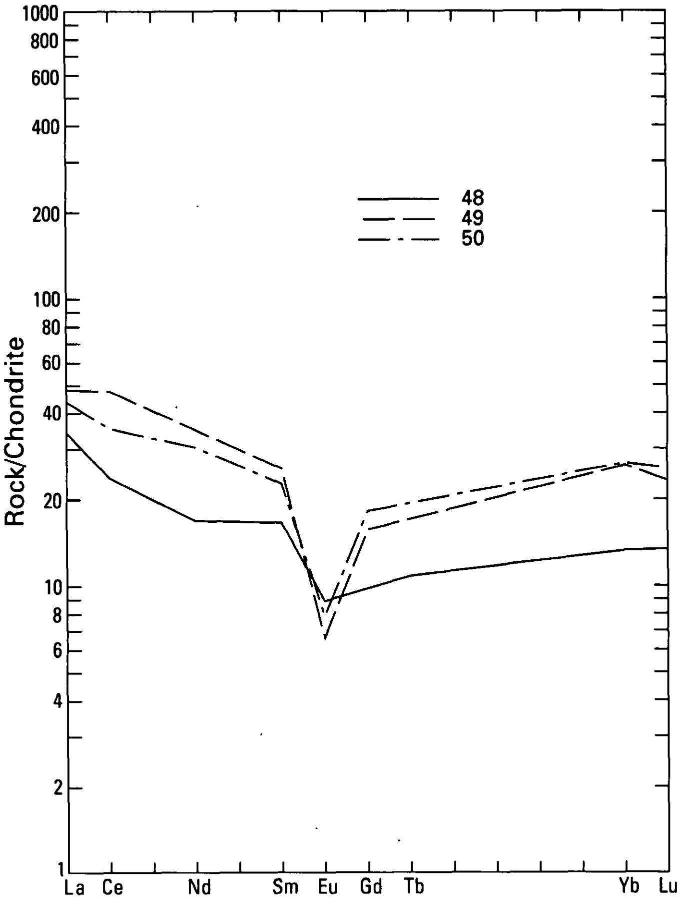


FIGURE 38.—Rare-earth elements of major rock types of the Monson Gneiss (see Leo and others, 1984, fig. 13*A*). Numbers keyed to analyses in table 3.

of granophyres produced by fractional crystallization, as well as the relatively lower amounts of CaO, TiO_2, and SiO_2 (Presnall, 1979); (2) the bimodal nature of the Ammonoosuc assemblage, which virtually lacks rocks of intermediate compositions; (3) experimental evidence that trondhjemitic compositions are produced by basalt melting in the 6- to 18-percent range (Holloway and Burnham, 1972; Helz, 1976; Spulber and Rutherford, 1983); and (4) REE modeling that suggests partial melting, not fractional crystallization, as the more likely mechanism (Leo, 1985). The major discrepancy in this regard is the high proportion of felsic rocks (estimated to range between 20 and 40 percent over the entire section). Most plagiogranites associated with ophiolites constitute on the order of 5 percent (Coleman and Donato, 1979) and seldom exceed 10 percent; rhyolitic rocks constitute about 10 percent of the Iceland volcanic pile (Walker, 1966, cited by Spulber and Rutherford, 1983). High proportions (30–40 percent) of felsic K-poor volcanic rocks and associated trondhjemite plutons appear to be known only on the islands of Fiji, where they are described as "20 to 40 percent partial melts of basalt at P_{H_2O}=5 kb" (Gill and Stork, 1979, p. 629). Further discussion of the petrogenesis of the Fijian silicic rocks centers on trace elements; the disproportionate volume of such rocks does not appear to be regarded as a major problem by Gill and Stork (1979). A somewhat mechanistic explanation for the high relative volume of felsic Ammonoosuc Volcanics is to regard them as an artifact of the present erosion level, which may be disproportionately enriched in quartz keratophyre accumulations and associated trondhjemite generated at greater depths. The true overall relative proportions of felsic and mafic Ammonoosuc thus could be different from the present outcrop pattern. Clearly, such an explanation is conjectural.

Despite certain differences in detail between the felsic Ammonoosuc Volcanics and Fijian rocks (lower SiO_2, higher FeO—also shown by the experimental melts of Spulber and Rutherford (1983, fig. 5)—and a generally more tholeiitic character, seen especially in REE patterns), the overall similarities are striking, so that Fiji appears to constitute the closest modern analog for the Ammonoosuc Volcanics.

A conjectural sequence of Ammonoosuc volcanism and subsequent history, taking the known data (including recent U-Pb age determinations) into account, is as follows:

1. Middle Ordovician (nonmagmatic episodes omitted): Local and explosive(?) eruptions of the Holts Ledge volcanic sequence derived either by fractional crystallization or by partial melting of an anhydrous basaltic source. Eruption of early Ammonoosuc phase at approximately 465 Ma.
2. Early Late Ordovician: Eruption of basalt, accompanied by emplacement of dikes and plugs of trondhjemite derived from the same mafic source. A gradual transition to felsic volcanism resulting in deposition of interlayered basaltic tuffs and flows, quartz keratophyre tuff, and associated coarser pyroclastic rocks (Ammonoosuc Volcanics). Approximately contemporaneous emplacement and (or) eruption of present-day Monson and Swanzey Gneisses, which resulted in intrusion into and nonconformable deposition onto Ammonoosuc Volcanics, respectively.
3. Late Ordovician to Early Devonian: Regional deformation and metamorphism related to the Acadian orogeny, which, among other effects, converted primary Ammonoosuc basalt to amphibolite. The hydrous character of the Acadian metamorphism throughout much of the Bronson Hill anticlinorium is apparent in the large and seemingly random variations in large-ion lithophile elements in all of the Ammonoosuc (tables 2, 3, fig. 44*A*, *B*).

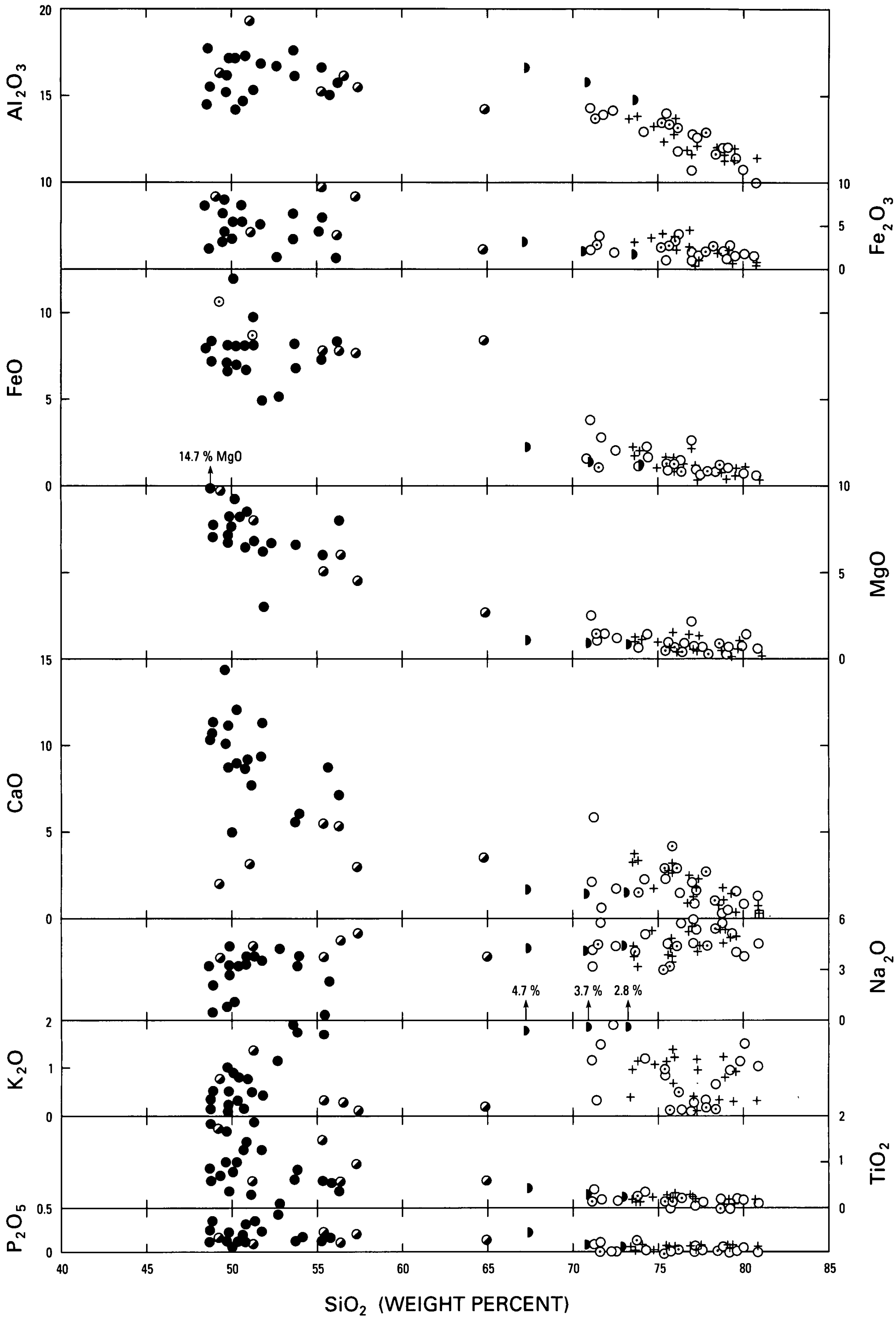


FIGURE 39.—Harker diagrams for the Ammonoosuc Volcanics, the Holts Ledge volcanic sequence, and related trondhjemite. Oxides in weight percent, calculated on a water-free basis. ●, mafic Ammonoosuc Volcanics; ◕, mafic to felsic Ammonoosuc containing Ca-poor amphiboles (cummingtonite, anthophyllite=gedrite); ○, felsic Ammonoosuc; ◗, metasomatized Ammonoosuc; ⊙, Holts Ledge volcanic sequence; +, trondhjemite.

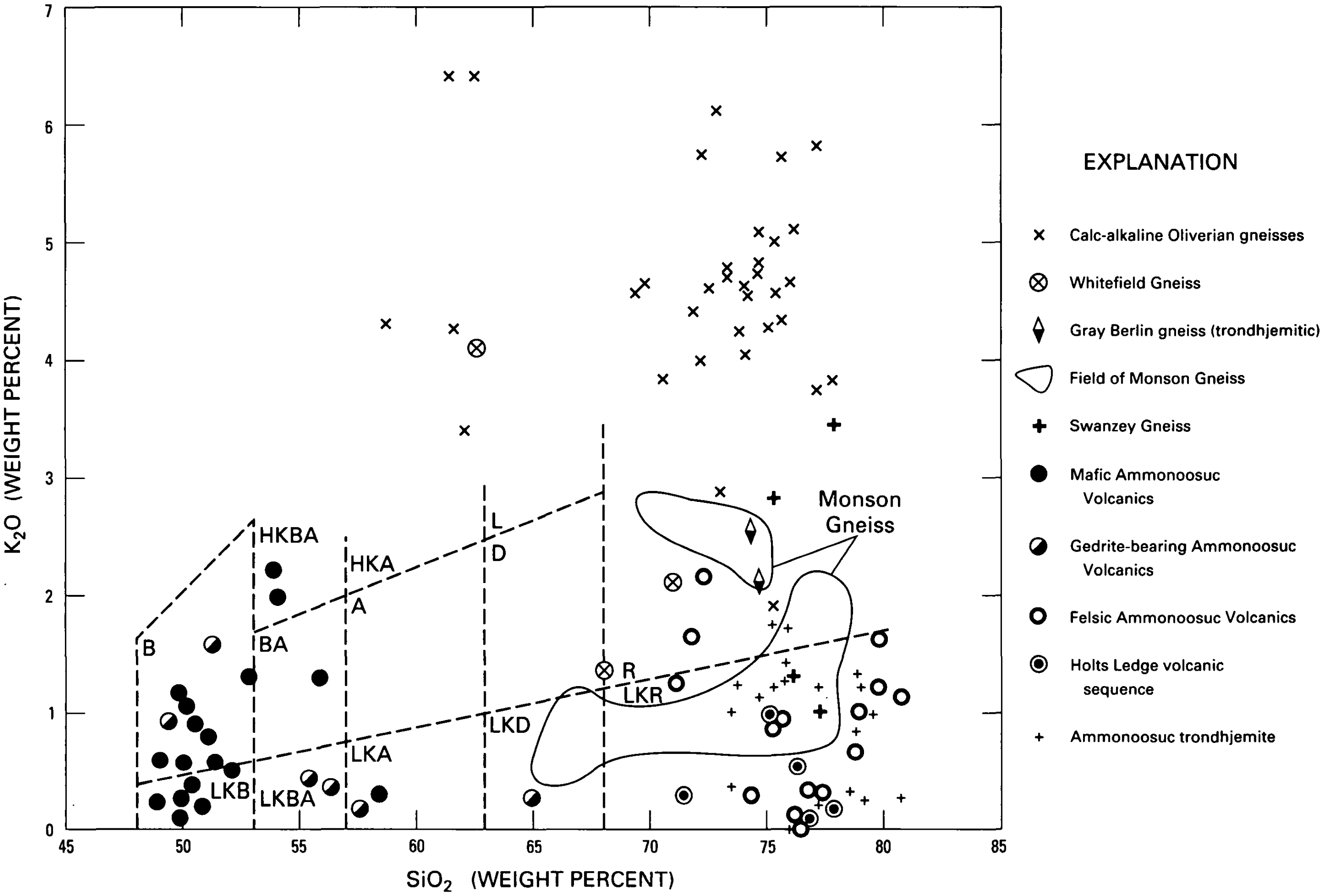


FIGURE 40.—K_2O versus SiO_2 for all analyzed samples. Symbols not explained on diagram are as follows: A, andesite; B, basalt; BA, basaltic andesite; D, dacite; HKA, high-K andesite; HKBA, high-K basaltic andesite; L, latite; LKA, low-K andesite; LKB, low-K basalt; LKBA, low-K basaltic andesite; LKD, low-K dacite; LKR, low-K rhyolite; R, rhyolite.

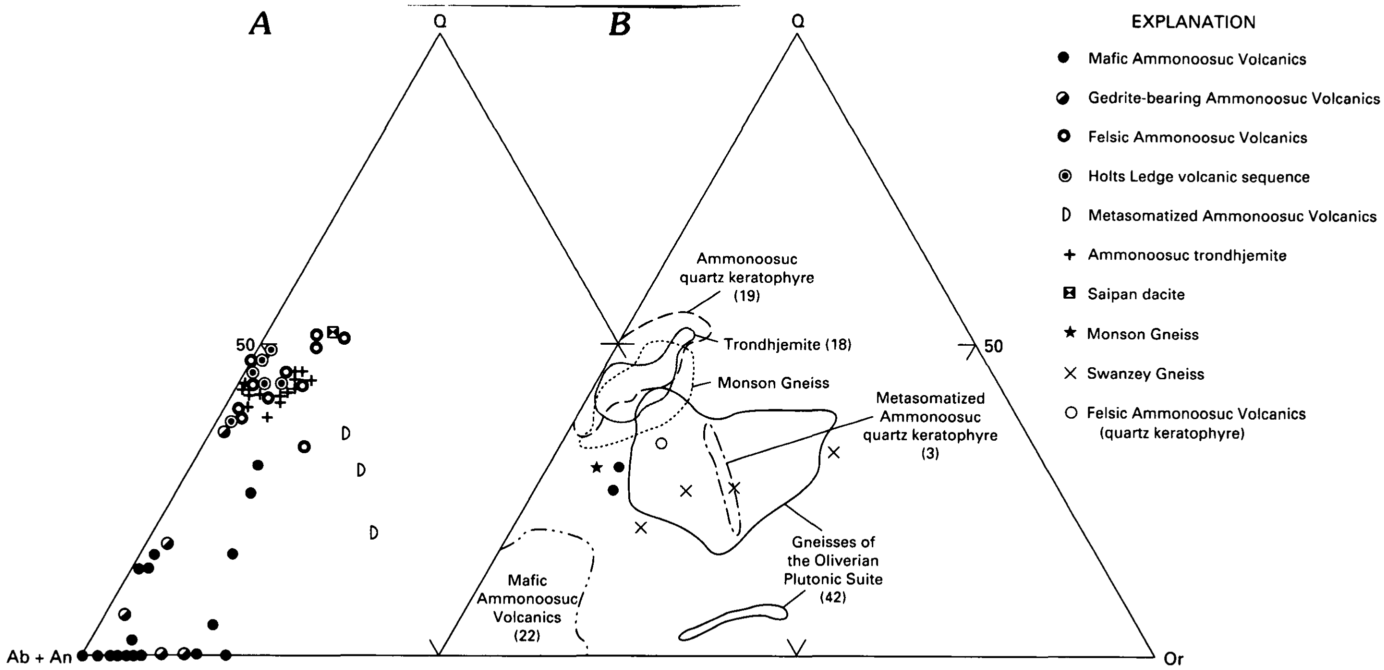


FIGURE 41.—Q-(Ab+An)-Or plots for all analyzed samples. *A*, Ammonoosuc Volcanics, Holts Ledge volcanic sequence, and trondhjemite. *B*, Samples in the various categories shown as fields, except for the Swanzey Gneiss, and samples of other rocks falling outside of compositional areas. Numbers in parentheses refer to the number of analyses in each category.

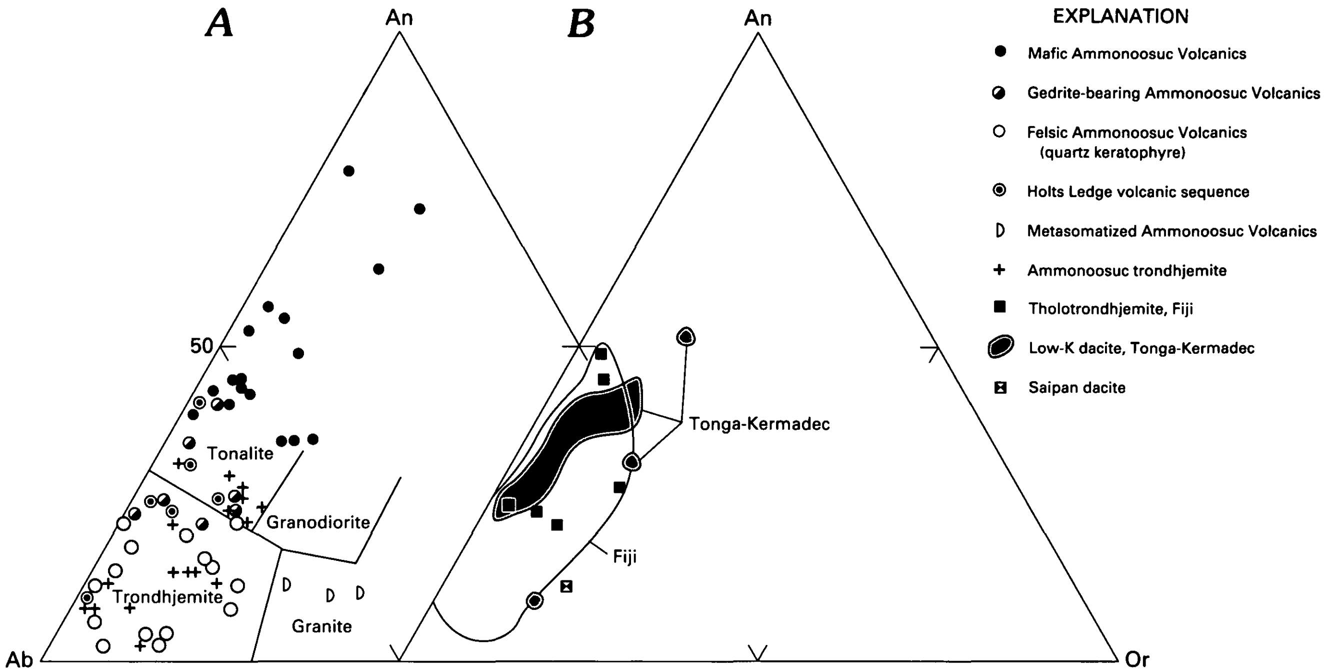


FIGURE 42.—An-Ab-Or plot for Ammonoosuc Volcanics, related rocks, and comparable volcanic suites. *A*, Ammonoosuc Volcanics, Holts Ledge volcanic sequence, and trondhjemite. *B*, Same plot showing fields for low-K dacite and trondhjemite from Fiji (Gill and Stork, 1979), Tonga-Kermadec (Bryan, 1979), and Saipan dacite (Meijer, 1983; Barker and others, 1976).

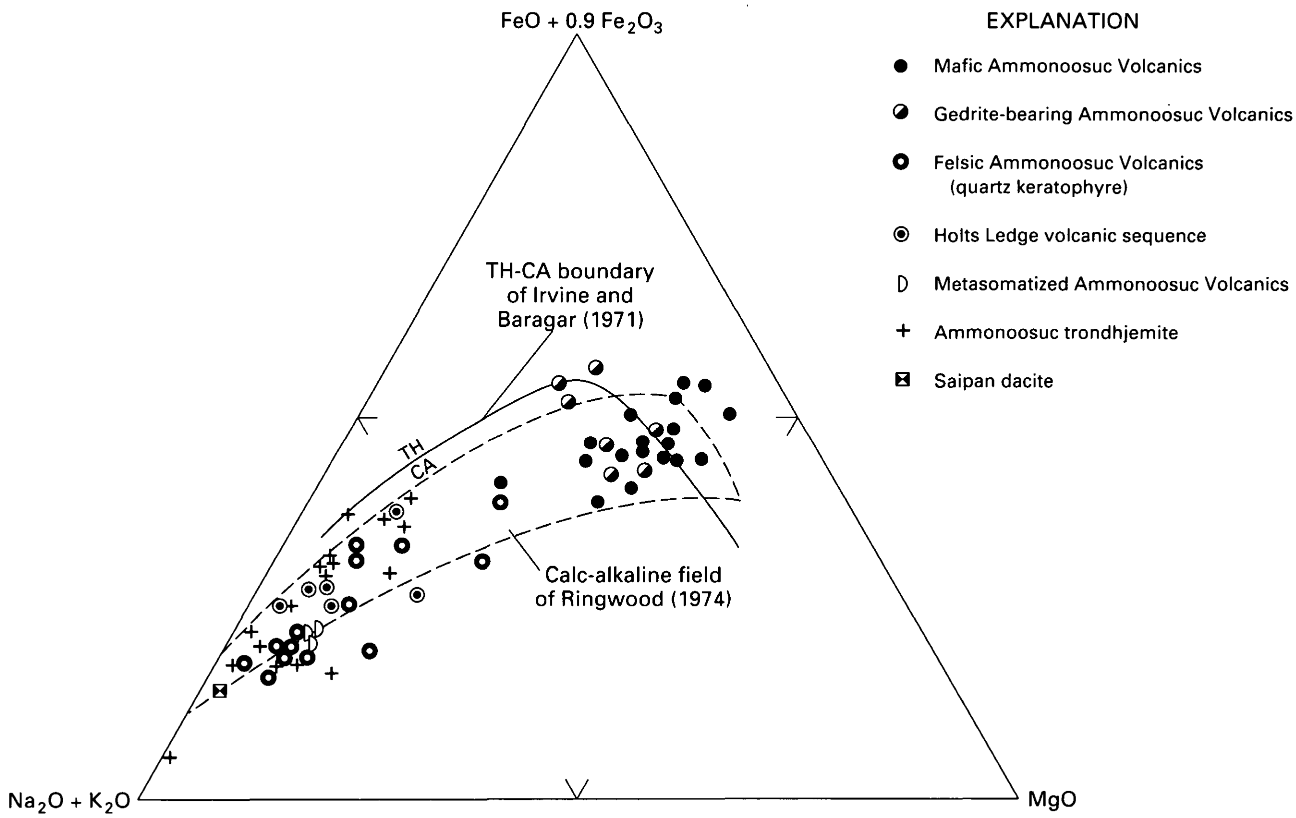


FIGURE 43.—AFM plot for Ammonoosuc Volcanics and related rocks. TH-CA is the tholeiitic–calc-alkaline boundary of Irvine and Baragar (1971). The calc-alkaline field of Ringwood (1974) is shown by a dashed line.

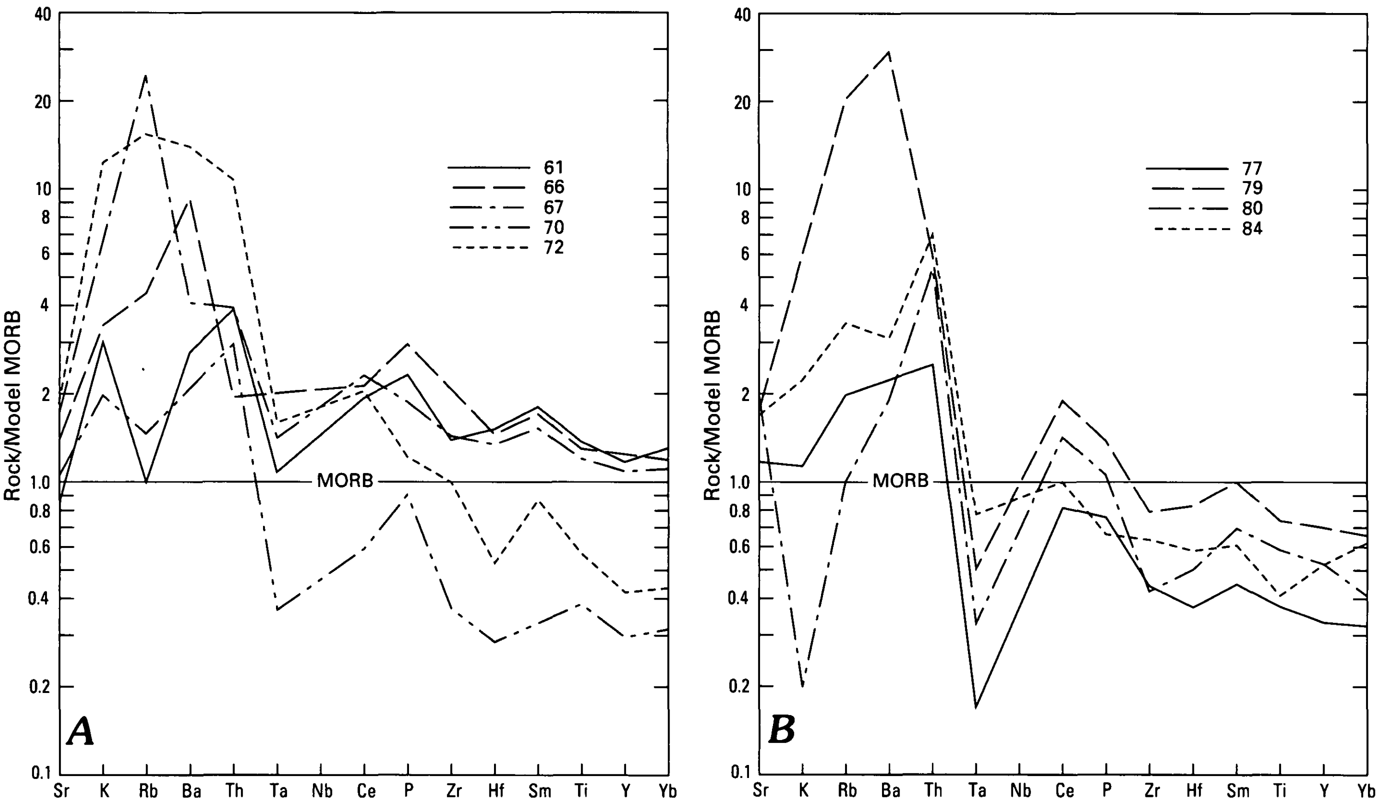


FIGURE 44.—Trace-element abundance for mafic Ammonoosuc Volcanics (table 3) normalized to a hypothetical tholeiitic mid-ocean ridge basalt (MORB) (Pearce, 1983). Generally more mobile elements are on the left, and less mobile elements are on the right. *A*, Hornblende-plagioclase amphibolites (anals. 61, 66, 67, 70, 72, table 3). *B*, More hornblende-plagioclase amphibolites (anals. 77, 79, 80, 84, table 3) and gedrite-bearing amphibolite (anal. 84, table 3).

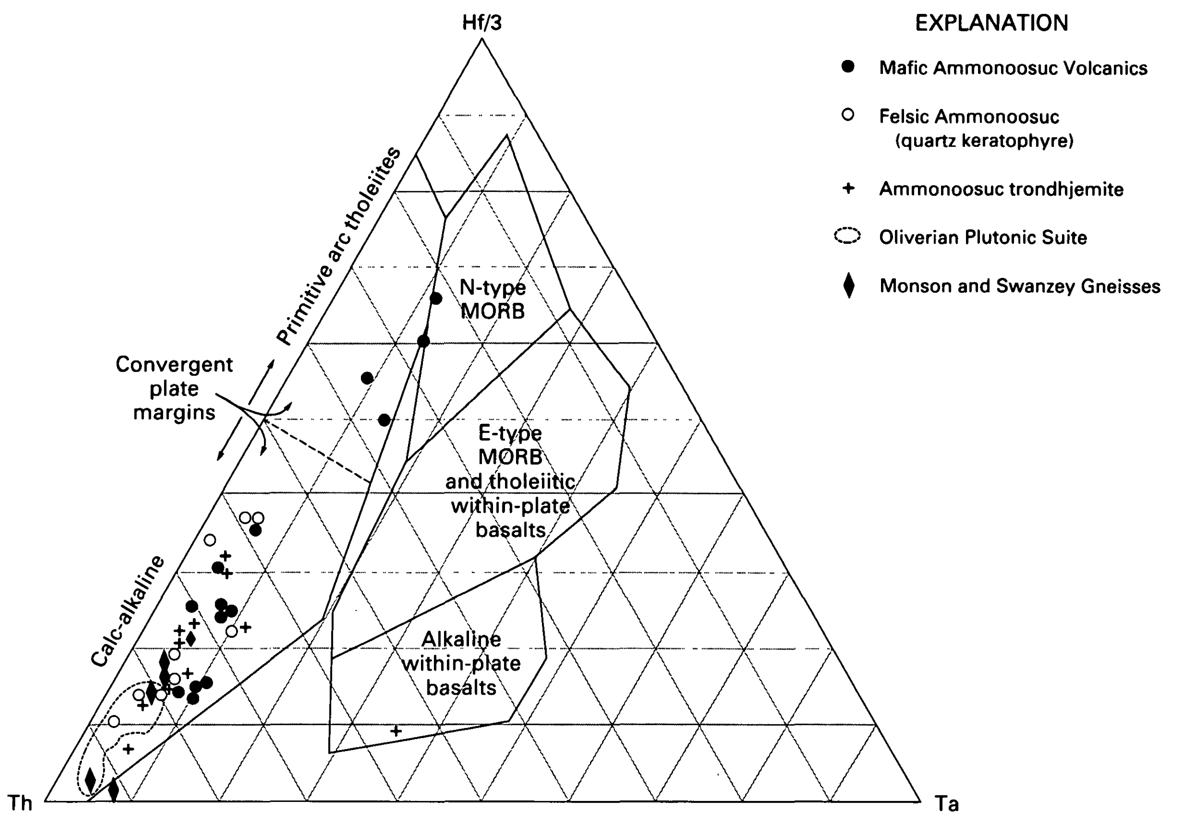
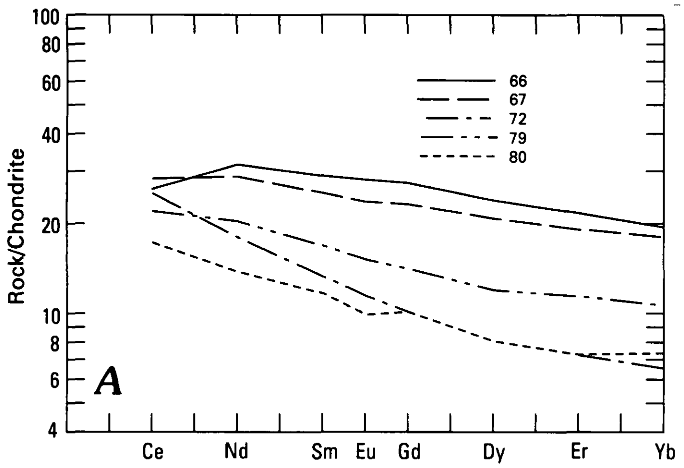


FIGURE 45.—Ta-Th-Hf/3 plot for all analyzed samples. After Wood (1980).



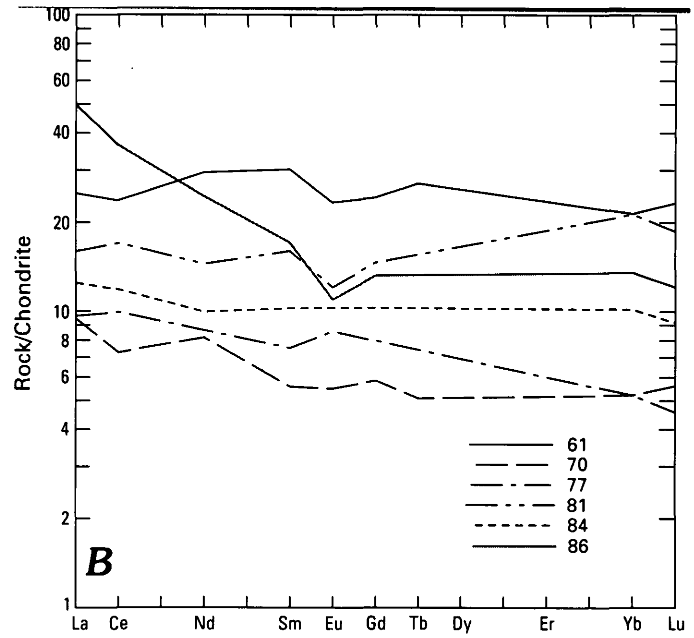


FIGURE 46.—Rare-earth elements of mafic Ammonoosuc Volcanics. *A*, Rare-earth elements determined by isotope dilution (from Leo, 1984). *B*, Rare-earth elements determined by instrumental neutron activation analysis. Numbers keyed to analyses in table 3.

OLIVERIAN PLUTONIC SUITE

The Oliverian plutons (excluding the Swanzey and Monson Gneisses of probable volcanic origin and the three small trondhjemite domes discussed earlier) have the appearance of calc-alkaline magmatic rocks—mostly granites but ranging locally to granodiorite, quartz diorite, and syenite. A plausible source for these rocks must now be considered.

An attempt to classify the rocks as S or I types (Chappell and White, 1974; B.W. Chappell, oral commun., 1974) yields mixed results. Characteristics of S types in Oliverian gneisses include the following: (1) the lack of associated gabbros and mafic xenolith and the presence of strong secondary foliation(s); (2) the presence of muscovite in some granites (for example, the Sugar Hill, Owls Head, Mascoma, and Lebanon), although it appears recrystallized rather than primary; (3) the abundance of biotite and the general absence of hornblende; (4) the generally siliceous composition (SiO_2>65 percent); and (5) the scatter of points on the Harker diagrams and on some other plots. By contrast, certain other characteristics are more indicative of the I type: (1) the molecular ratio of $(CaO+Na_2O+K_2O)/Al_2O_3$ (derivable from table 2, anals. 1–43, but not shown therein), which indicates a weakly metaluminous to weakly peraluminous character for most gneissic samples, as well as the low or nil values for normative corundum (table 2, anals. 1–43); (2) the abundance of hornblende±titanite in relatively mafic rocks (Jefferson batholith syenites, border facies of the Baker Pond and Lebanon plutons); and (3) lack of sediment-derived xenoliths containing aluminosilicates and cordierite±garnet. Moreover, given the scarcity of true S-type granites derived from pelitic sediments (Miller, 1985, 1986), it is safe to conjecture that such sediments did not constitute an important source for the Oliverian gneiss. Instead, the preceding observations suggest a compositionally mixed source having a significant volcanogenic component for the Oliverian gneisses. Such a protolith is also indicated by the K-poor volcanogenic Monson and Swanzey Gneisses. The Oliverian and related gneisses appear to be petrologically comparable to quartz monzonite (monzogranite) in the Archean crust of northeastern Minnesota, studied by Arth and Hanson (1975), who concluded that those rocks could have originated by partial melting of graywacke in the lower crust. One may speculate on a similar origin for the Oliverian plutons, although a graywacke protolith is not evident at the present erosional level.

Pogorzelski (1983) concluded, on the basis of *Q*-mode factor analysis, that fractional crystallization was a more likely mechanism than partial melting to produce the Oliverian plutons. However, partial melting is here considered a more probable origin than fractional crystallization, for reasons similar to those discussed for the felsic Ammonoosuc: (1) chemical differences, notably the lack of Fe enrichment, in comparison with granophyres that are the end products of fractional crystallization of basaltic magma (Presnall, 1979) and (2) the near-absence of rocks having bulk compositions more mafic than granodiorite (fig. 23)—that is, the absence of a compositional spectrum normally associated with a fractionally crystallized sequence. The kind of lithologic variation found in gneisses of the Jefferson batholith, notably the Bray syenites (Foland and Loiselle, 1981), is not compatible with a fractional crystallization series.

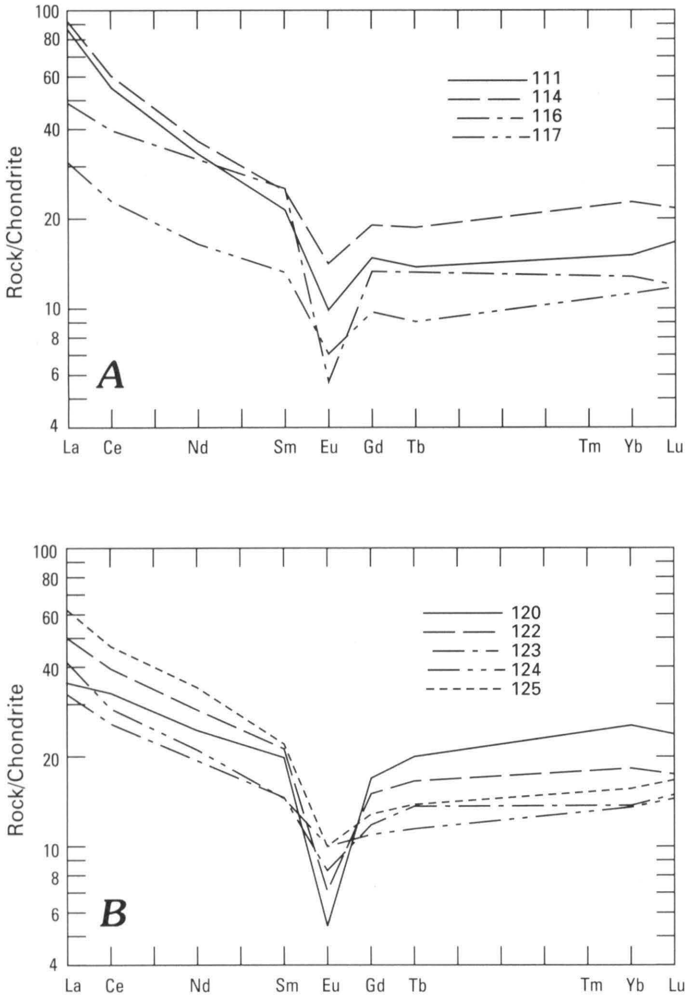


FIGURE 47.—Rare-earth elements of Ammonoosuc trondhjemite (from Leo, 1985). *A*, Samples from Berlin, N.H., White River Junction, Vt., and Plainfield, N.H. *B*, Samples from the Vernon, Unity, and Alstead domes. Numbers keyed to analyses in table 3.

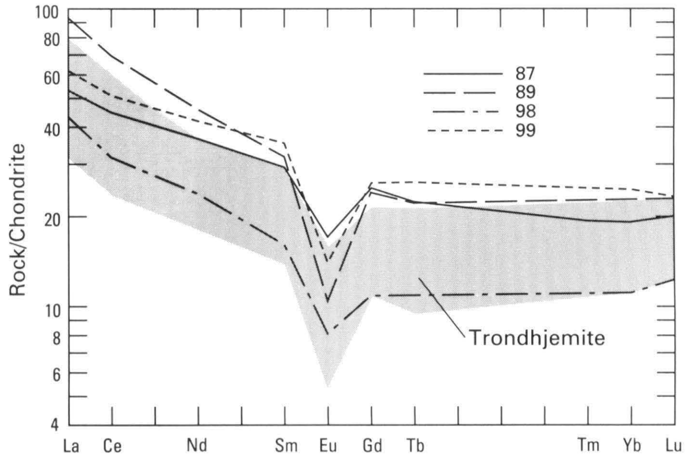


FIGURE 48.—Rare-earth elements of Ammonoosuc quartz keratophyre (from Leo, 1985). Trondhjemite field (fig. 47) shaded for comparison. Numbers keyed to analyses in table 3.

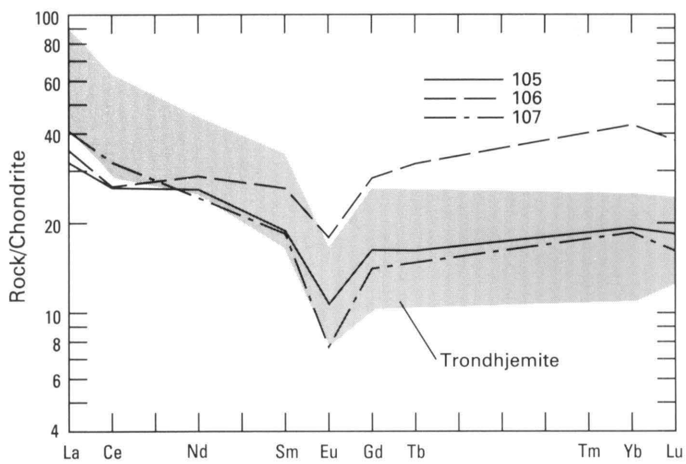


FIGURE 49.—Rare-earth elements of the Holts Ledge volcanic sequence (from Leo, 1985). Trondhjemite field (fig. 48) shaded for comparison. Numbers keyed to analyses in table 3.

Foland and Loiselle (1981) proposed that the syenites of the Jefferson batholith could have been derived from one of several sources: (1) eclogite representing altered MORB, (2) a mixture of MORB and sediments, or (3) eclogite from an island-arc setting. Their reasoning was based on the highly fractionated REE patterns (fig. 32), which suggest a residue of garnet and jadeitic pyroxene, and the high K, Sr, Rb, and other large-ion lithophile elements. Syenites included in the present study (see tables 2, 3, anals. 9, 11, 13) have generally similar chemistries. However, as Foland and Loiselle also pointed out, the syenite of the Jefferson batholith is an isolated type not found elsewhere along the Bronson Hill anticlinorium.

Lead isotope data from Devonian plutons in Maine (Ayuso, 1986; Ayuso and others, 1988) cluster in three groups corresponding to distinct tectonic blocks on $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{206}Pb$ plots. Data points in the Central Maine block (Ayuso, 1986, fig. 2), essentially on strike with the Bronson Hill anticlinorium, fall close to an "orogene" curve approximately comparable to the average earth curve of Stacey and Kramers (1975); they plot well above the Devonian mantle curve. The Central Maine points, moreover, largely overlap with lead isotopic data determined on Bronson Hill samples (J.N. Aleinikoff, unpub. data, 1987). Thus, lead isotope data yield indirect evidence (1) that a similar deep crust extends from central Maine into New Hampshire, including the Bronson Hill anticlinorium, and (2) that this crust is likely the major source of the Oliverian plutons. Generation of these plutons, presumably by partial melting, was essentially contemporaneous with the eruption of Ammonoosuc Volcanics and emplacement of related trondhjemite.

PLATE TECTONIC MODELS

Long before the advent of plate tectonics, rocks in the Bronson Hill anticlinorium were interpreted as an island arc or a volcanic arc (Kay, 1951). Bird and Dewey (1970) provided the first modern and comprehensive overview of the tectonic development of the northern Appalachians, which interpreted the Bronson Hill anticlinorium as the surface expression of a westward-dipping subduction zone accompanying the closing of Iapetus from Middle Ordovician to Late Devonian time. Osberg (1978) envisaged a fourfold basement for New England, in which the Oliverian domes and the Pelham dome constituted the western part of a broad central terrain (basement C). Osberg hypothesized an east-dipping subduction zone on the assumption that the western edge of the arc is the leading edge. Numerous ultramafic lenses in a south-trending belt in central Vermont (Chidester, 1968) have been tentatively interpreted as obducted, dismembered ophiolite related to an east-dipping subduction zone (Robinson and Hall, 1980, especially fig. 2).

Robinson and Hall's (1980) treatment of early Paleozoic plate tectonic development of New England divided southern New England into three tectonic plates—North American, Bronson Hill, and Avalon—and presented detailed cross sections depicting tectonic evolution from the Early Ordovician through the Middle Devonian. According to their interpretation, the Ammonoosuc Volcanics, together with the Ordovician(?) Hawley Formation to the west, were extruded over an east-dipping subduction zone on the North American margin. A modified version of Robinson and Hall's (1980) figures 2–3 and 2–4 is shown here as figure 50. The principal modification is to allow for deep-seated oceanic crust as a source for the Ammonoosuc Volcanics in a region shown by Robinson and Hall (1980, fig. 2–4) as continental crust.

Chapple's (1973) proposed model of abortive subduction of the North American plate implies an east-dipping subduction zone. Further support for eastward polarity is found in east-dipping reflections in seismic sections produced by the Consortium for Continental Reflection Profiling (Ando and others, 1983) and the USGS (interpreted by Phinney, 1986) (see fig. 50). Such features suggest a former locus of a subduction zone, developed during westward movement of the (possibly allochthonous) Avalon plate, culminating in accretion of the Bronson Hill plate to the North American plate (Robinson and Hall, 1980; Ando and others, 1983; Zen, 1983). Alternatively, the eastward-dipping planes could indicate a zone of deep imbrication or of detachment, which suggests that the Bronson Hill anticlinorium may be allochthonous (Ando and others, 1983). This concept was amplified by Stanley and Ratcliffe (1985), who presented a complex scenario involving imbricate stacking of Taconic thrust plates by westward tectonic transport. Williams and Hatcher (1983) interpreted the Bronson Hill anticlinorium as part of the Gander terrane.

The current study confirms the plausible arc setting of the Ammonoosuc Volcanics and thereby fits the arc model, in particular its oceanic character. Perhaps the strongest single argument for the eastward polarity of the Bronson Hill subduction zone is the absence of volcanics west of the putative suture (Stanley and Ratcliffe, 1985). It remains to be seen whether the Ammonoosuc and the Hawley Formation are geochemically related, as would be required for the Hawley to represent a forearc of the Bronson Hill (Ammonoosuc) volcanic arc. Preliminary chemical and lithologic data on the Hawley (G.W. Leo, unpub. data, 1989) indicate some similarity to the Ammonoosuc Volcanics, including bimodal lithology and strikingly low K contents.

The chemical character of the Ammonoosuc Volcanics and associated trondhjemite presented in this paper strongly suggests volcanic-arc affinities. Abundances and ratios of major and trace elements—in particular those regarded as relatively immobile—are generally similar to those of lower Paleozoic (Payne and Strong, 1979; Coish and Rogers, 1987) and Tertiary (Gill and Stork, 1979; Bryan, 1979; Meijer, 1983; Barker and others, 1976; see also Leo, 1985, fig. 9) volcanic assemblages thought to have formed above subduction zones. The relative narrowness of the Ammonoosuc-Oliverian belt, moreover, reflects a significant degree of shortening across the arc in the course of Taconic plate collision and subsequently in the Acadian.

The scenario outlined above implies a compressional tectonic regime. In this context, it is worth noting the well-established association of a bimodal (and, typically, alkalic) plutonic-volcanic suite with anorogenic (extensional) environments; orogenic (compressional) environments, on the other hand, are associated with calc-alkaline suites showing a spectrum of compositions (Martin and Piwinskii, 1972). This bimodality, for example, constitutes the major basis for interpreting the Silurian-Devonian Maine coastal volcanic belt as having formed under conditions of crustal extension (Gates and Moench, 1981). Owing to the above-described ambiguities of the Ammonoosuc assemblage (bimodal suite, calc-alkaline chemistry), the Ammonoosuc cannot be clearly designated as extensional or compressional on the basis of chemistry and lithology, except to note that alkalic rocks are completely lacking from the Ammonoosuc and that even normal rhyolites are negligible, at

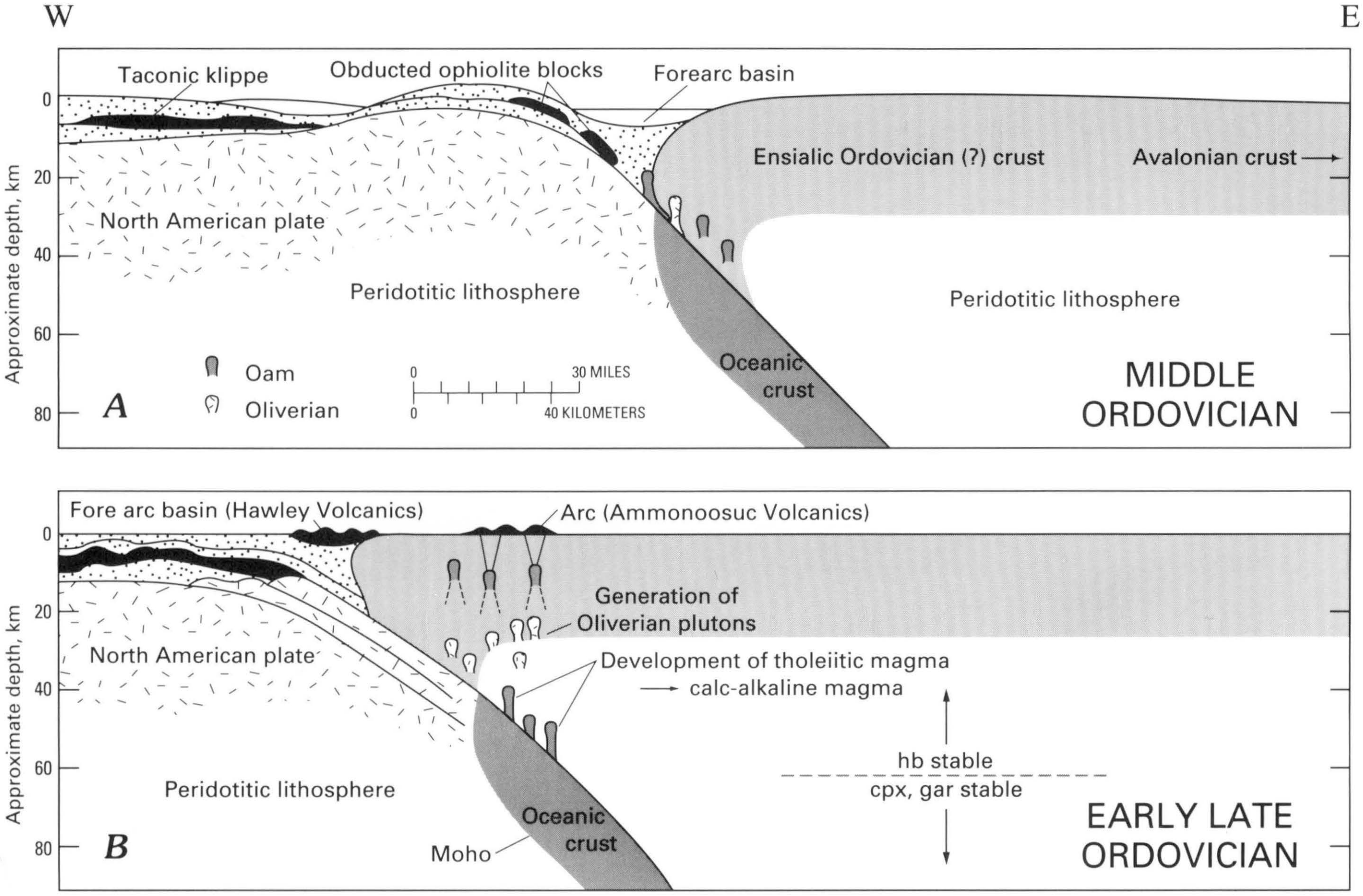


FIGURE 50.—Plate-tectonic development of the Bronson Hill magmatic arc (*A*) in the Middle Ordovician and (*B*) in the early Late Ordovician. Modified from Robinson and Hall (1980, figs. 2–3, 2–4) and Stanley and Ratcliffe (1985, pl. 2). The major modification of Robinson and Hall's (1980) work is the schematic plumbing system for producing the Ammonoosuc Volcanics and the Oliverian Plutonic Suite (based in part on Ringwood, 1974, figs. 9, 10). Timing for the arc-building episode (fig. 50*B*) is based on recent isotopic ages determinations, as related to the DNAG–Geological of Society America (1983) time scale. Eruption of Ammonoosuc Volcanics is tentatively regarded as about 454 Ma (Tucker and Robinson, 1990) in northern Massachusetts and no younger than about 465 Ma in northern New Hampshire (Aleinikoff and Moench, 1987). The time of Oliverian plutonism is taken as 444±8 Ma in central New Hampshire (Zartman and Leo, 1985), but it may have continued into the Early Silurian. *A*, Plate collision far advanced, Taconic allochthons slide westward, covering ophiolite fragments obducted earlier. Volcanics of the Hawley Formation may be erupted at this time in a forearc basin. The west-moving Avalon plate may have a western component of Ordovician age (here postulated, not identified) to provide a protolith for the Oliverian plutons. The east-pointing arrow at "Avalonian crust" indicates the postulated eastward continuation of such crust; it does not imply eastward crustal movement. *B*, Tholeiitic magma is generated from the downgoing slab and overlying mantle wedge by partial melting of basalt or amphibolite and differentiates to calc-alkaline magma to produce the Ammonoosuc Volcanics. Oliverian plutons are generated somewhat later by partial melting of the continental(?) crust of the Avalon plate.

least in western New Hampshire. There is, moreover, little field evidence for extensional tectonics, except sporadic northeast-trending amphibolite dikes of pre-Acadian age, which are not obviously related to the Ammonoosuc Volcanics and may well be somewhat younger.

CONCLUSIONS

The major conclusions of this study are based on field and laboratory studies of gneissic Oliverian plutons and mantling Ammonoosuc Volcanics, both of mainly Middle to Late Ordovician age, which trend along the axis of the Bronson Hill anticlinorium. The results may be summarized as follows:

1. These rocks exhibit petrologic and geochemical characteristics of a plausible, although chemically anomalous, magmatic arc. The new data are compatible with earlier interpretations of a magmatic arc (Hitchcock, 1883; Kay, 1951; Berry, 1968) over an east-dipping subduction zone (for example, Osberg, 1978; Robinson and Hall, 1980).
2. The Bronson Hill magmatic arc is peculiar in that bulk compositions of the Ammonoosuc Volcanics range from tholeiitic to calc-alkaline, despite pervasively

low K contents and anomalous felsic-mafic ratios near 1:1. The closest modern analog appears to be Fiji (Gill and Stork, 1979).

3. Gneissic rocks in cores of domes comprise three general types: calc-alkaline granite and associated syenite and quartz syenite of the Oliverian Plutonic Suite; Ammonoosuc-related trondhjemite, which constitutes three small domes as well as abundant smaller dikes and plugs; and volcanogenic gneiss (Monson type). The first type is properly designated Oliverian; the other two are not. The considerable range in the composition of granitic plutons (notably in the Jefferson batholith) suggests a variety of source materials. Indirect Pb (Ayuso, 1986) and Sr (Foland and Loiselle, 1981) isotope evidence suggests a continental crustal source having a subordinate eclogitic component. Ammonoosuc trondhjemite appears to be comagmatic with the Ammonoosuc Volcanics, probably derived by partial melting of a basaltic source (Leo, 1985).
4. Oliverian plutons may be approximately coeval but are not comagmatic with the Ammonoosuc Volcanics. Oliverian rocks intrude the Ammonoosuc Volcanics in several of the domes; in others, the relationship is uncertain. The Ammonoosuc-Monson contact, despite its unconformable appearance, is now ambiguous in view of newly determined, closely confined U-Pb zircon ages of 453 ± 2 Ma on the Ammonoosuc and $449+3/-2$ Ma on the overlying Partridge Formation (Robinson and Tucker, 1990). The new age determinations still leave unresolved the question of correlation between the Ammonoosuc of northern Massachusetts and the apparently older (465 ± 4 Ma) Ammonoosuc section of central and northern Massachusetts (Aleinikoff and Moench, 1987). Further precise U-Pb zircon age determinations on carefully selected Ammonoosuc samples and associated rocks will be required to resolve this problem.
5. The Oliverian domes are not typified by the Mascoma dome (Naylor, 1969). In particular, the Holts Ledge volcanic sequence, generally similar to overlying felsic Ammonoosuc Volcanics, was identified in only three domes and nowhere else is as well developed as it is in the Mascoma dome.

REFERENCES CITED

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

Aleinikoff, J.N., and Moench, R.H., 1985, Metavolcanic stratigraphy in northern New England—U-Pb zircon geochronology [abs.]: Geological Society of America Abstracts with Programs, v. 17, no. 1, p. 1.

———1987, U-Pb geochronology and Pb isotopic systematics of plutonic rocks in northern New Hampshire: Ensimatic vs. ensialic sources [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 1, p. 1.

Anders, E., and Ebihara, M., 1982, Solar-system abundances of the elements: Geochimica et Cosmochimica Acta, v. 46, p. 2363–2380.

Ando, C.J., Cook, F.A., Oliver, J.E., Brown, L.D., and Kaufman, S., 1983, Crustal geometry of the Appalachian orogen from seismic reflection studies, *in* Hatcher, R.O., Jr., Williams, H., and Zietz, I., eds., Contributions to the tectonics and geophysics of mountain chains: Geological Society of America Memoir 158, p. 83–102.

Annis, M.P., 1982, Banded magnetite-quartz iron formation in the Ammonoosuc Volcanics, Sugar Hill, New Hampshire [abs.]: Geological Society of America Abstracts with Programs, v. 14, nos. 1&2, p. 2.

Arndt, R.H., 1949, Oliverian Plutonic Series: Cambridge, Mass., Harvard University, unpublished Ph.D. dissertation, p. 86–164.

Arth, J.G., 1981, Rare-earth element geochemistry of the island-arc volcanic rocks of Rabaul and Talasea, New Britain: Geological Society of America Bulletin, v. 92, p. 858–863.

Arth, J.G., and Barker, F., 1976, Rare-earth partitioning between hornblende and dacitic liquid and implications for the genesis of trondhjemite-tonalite magmas: Geology, v. 4, p. 534–536.

Arth, J.G., and Hanson, G.N., 1975, Geochemistry and origin of the early Precambrian crust of northeastern Minnesota: Geochimica et Cosmochimica Acta, v. 39, p. 325–362.

Ashenden, D.D., 1973, Stratigraphy and structure, northern portion of the Pelham dome, north-central Massachusetts, *in* Contribution 16: Amherst, University of Massachusetts, Department of Geology, 132 p.

Ayuso, R.A., 1986, Lead-isotopic evidence for distinct source of granite and for distinct basements in the northern Appalachians, Maine: Geology, v. 14, p. 322–325.

Ayuso, R.A., Horan, M.F., and Criss, R.E., 1988, Pb and O isotopic geochemistry of granitic plutons in northern Maine: American Journal of Science, v. 288A, p. 421–460.

Baedecker, P.A., Rowe, J.J., and Steinnes, E., 1977, Application of epithermal neutron activation in multi-element analysis of silicate rocks employing both coaxial Ge(Li) and low-energy photon detector systems: Journal of Radioanalytical Chemistry, v. 40, p. 115–146.

Balk, R., 1956, Bedrock geologic map of the Millers Falls quadrangle, Massachusetts: U.S. Geological Survey Geologic Quadrangle Map GQ–93, scale 1:31,680.

Barker, F., 1979a, Trondhjemite: Definition, environment and hypotheses of origin, *in* Barker, F., ed., Trondhjemites, dacites, and related rocks: Developments in petrology 6: New York, Elsevier, p. 1–12.

———1979b, ed., Trondhjemites, dacites, and related rocks: Developments in petrology 6: New York, Elsevier, 659 p.

Barker, F., Arth, J.G., Peterman, Z.E., and Friedman, I., 1976, The 1.7 to 1.8 b.y.-old trondhjemites of southwestern Colorado and northern New Mexico: Geochemistry and depths of genesis: Geological Society of America Bulletin, v. 87, p. 189–198.

Basaltic Volcanism Study Project, 1982, Basaltic volcanism on the terrestrial planets: Houston, Tex., Lunar and Planetary Institute, p. 193–213.

Berry, W.B.N., 1968, Ordovician paleogeography of New England and adjacent areas based on graptolites, *in* Zen, E., White, W.S., Hadley, J.B., and Thompson, J.B., Jr., eds., Studies of Appalachian geology, northern and maritime: New York, Interscience, p. 23–34.

Billings, M.P., 1937, Regional metamorphism of the Littleton-Moosilauke area, New Hampshire: Geological Society of America Bulletin, v. 46, p. 463–566.

———1955, compiler, Geologic map of New Hampshire: New Hampshire Planning and Development Commission, Harvard University, and the U.S. Geological Survey, scale 1:250,000.

———1956, The geology of New Hampshire, pt. II, Bedrock geology: Concord, New Hampshire State Planning and Development Commission, 200 p.

Billings, M.P., and Fowler-Billings, K., 1975, Geology of the Gorham quadrangle, New Hampshire-Maine: State of New Hampshire Department of Resources and Economic Development Bulletin 6, 120 p.

Billings, M.P., and Keevil, N.B., 1946, Petrography and radioactivity of four Paleozoic magma series in New Hampshire: Geological Society of America Bulletin, v. 57, p. 797–828.

Billings, M.P., and Rabbitt, J.C., 1947, Chemical analyses and calculated modes of the Oliverian magma series, Mt. Washington quadrangle, New Hampshire: Geological Society of America Bulletin, v. 58, p. 573–596.

Billings, M.P., Chapman, C.A., Fowler-Billings, K., and Loomis, F.B., 1946, Geology of the Mt. Washington quadrangle, New Hampshire: Geological Society of America Bulletin, v. 57, p. 261–274.

Bird, J.M., and Dewey, J.F., 1970, Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen: Geological Society of America Bulletin, v. 81, p. 1031–1060.

Bowen, R.W., 1971, Graphic normative analysis program: U.S. Geological Survey Computer Contribution 13, U.S. Geological Survey Open-File Report USGS-CCD-71-004, 80 p.

Bryan, W.B., 1979, Low-K dacite from the Tonga-Kermadec island arc: Petrography, chemistry, and petrogenesis, *in* Barker, F., ed., Trondhjemites, dacites and related rocks: Developments in petrology 6: New York, Elsevier, p. 581–600.

Bryan, W.B., Stice, G.D., and Ewart, A., 1972, Geology, petrology, and geochemistry of the volcanic islands of Tonga: Journal of Geophysical Research, v. 77, no. B8, p. 1566–1585.

Chapman, C.A., 1939, Geology of the Mascoma quadrangle, New Hampshire: Geological Society of America Bulletin, v. 50, p. 127–180.

———1942, Intrusive domes of the Claremont-Newport area, New Hampshire: Geological Society of America Bulletin, v. 53, p. 889–916.

———1952, Structure and petrology of the Sunapee quadrangle, New Hampshire: Geological Society of America Bulletin, v. 63, p. 889–916.

Chapman, C.A., Billings, M.P., and Chapman, R.W., 1944, Petrology and structure of the Oliverian magma series in the Mt. Washington quadrangle, New Hampshire: Geological Society of America Bulletin, v. 55, p. 497–516.

Chapman, R.W., 1948, Petrology and structure of the Percy quadrangle, New Hampshire: Geological Society of America Bulletin, v. 59, p. 1059–1100.

———1949, The geology of the Percy quadrangle, New Hampshire: Concord, New Hampshire Planning and Development Commission, 38 p.

Chappell, B.W., and White, A.J.R., 1974, Two contrasting granite types: Pacific Geology, v. 8, p. 173–174.

Chapple, W.M., 1973, Taconic orogeny: Abortive subduction of the North American continental plate? [abs.]: Geological Society of America Abstracts with Programs, v. 5, p. 573.

Chidester, A.H., 1968, Evolution of the ultramafic complexes of northwestern New England, *in* Zen, E., White, W.S., Hadley, J.B., and Thompson, J.B., Jr. eds., Studies of Appalachian geology: Northern and maritime: New York, Interscience, p. 343–354.

Coish, R.A., and Rogers, N.W., 1987, Geochemistry of the Boil Mountain ophiolitic complex, northwest Maine, and tectonic implications: Contributions to Mineralogy and Petrology, v 57. p. 51–65.

Coleman, R.G., and Donato, M.M., 1979, Oceanic plagiogranite revisited, *in* Barker, F., ed., Trondhjemites, dacites, and related rocks: Developments in petrology 6: New York, Elsevier, p. 149–168.

Costa, V.R., Barnett, R.L., and Kerrich, R., 1983, The Mattagami Lake Mine Archean Zn-Cu sulfide deposit, Quebec: Hydrothermal coprecipitation of talc and sulfides in a sea-floor brine pool—Evidence from geochemistry, $^{18}O/^{16}O$, and mineral chemistry: Economic Geology, v. 78, p. 1144–1203.

Cullers, R.L., and Graf, J.L., 1984, Rare earth elements in igneous rocks of the continental crust: Intermediate and silicic rocks— Ore petrogenesis, *in* Henderson, P., ed., Rare earth element geochemistry: Developments in geochemistry 2: New York, Elsevier, ch. 8, p. 275–307.

DNAG-Geological Society of America, 1983, 1983 geologic time scale: Geology, v. 11, p. 504.

Doll, C.G., Cody, W.M., Thompson, J.B., Jr., and Billings, M.R., compilers and eds., 1961, Centennial geologic map of Vermont: Montpelier, Vermont Geological Survey, scale 1:250,000.

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

Ewart, A., Bryan, W.B., and Gill, J.B., 1973, Mineralogy and geochemistry of the younger volcanic islands of Tonga, S.W. Pacific: Journal of Petrology, v. 14, p. 429–465.

Foland, K.A., and Loiselle, M.C., 1981, Oliverian syenites of the Pliny region, northern New Hampshire: Geological Society of America Bulletin, v. 92, pt. 1, p. 179–188.

Fowler-Billings, K., 1942, Geologic map of the Cardigan quadrangle, New Hampshire: Geological Society of America Bulletin, v. 53, p. 177–178.

Gates, O., and Moench, R.A., 1981, Bimodal Silurian and Lower Devonian volcanic rock assemblages in the Machias-Eastport area, Maine: U.S. Geological Survey Professional Paper 1134, 32 p.

Gill, J.B., 1981, Orogenic andesites and plate tectonics: New York, Springer-Verlag, 390 p.

Gill, J.B., and Stork, A.L., 1979, Miocene low-K dacites and trondhjemites of Fiji, *in* Barker, F., ed., Trondhjemites, dacites, and related rocks: Developments in petrology 6: New York, Elsevier, p. 629–649.

Hadley, J.B., 1942, Stratigraphy, structure, and petrology of the Mt. Cube area, New Hampshire: Geological Society of America Bulletin, v. 53, p. 113–176.

———1949, Bedrock geology, Mt. Grace quadrangle, Massachusetts: U.S. Geological Survey Geologic Quadrangle Map GQ-3, scale 1:31,680.

Hall, L.M., and Robinson, P., 1982, Stratigraphic-tectonic subdivisions of southern New England, *in* St. Julien, P., and Beland, J., eds., Major structural zones and faults of the northern Appalachians: Geological Association of Canada Special Paper 24, p. 15–41.

Harris, A.G., Hatch, N.L., Jr., and Dutro, J.T., Jr., 1983, Late Silurian conodonts update the metamorphosed Fitch Formation, Littleton area, New Hampshire: American Journal of Science, v. 283, p. 722–738.

Harwood, D.S., and Berry, W.B.N., 1967, Fossiliferous Lower Paleozoic rocks in the Cupsuptic quadrangle, west-central Maine, *in* Geological Survey research 1967: U.S. Geological Survey Professional Paper 575-D, p. D16–D23.

Hatch, N.L., Jr., 1988, Some revisions to the stratigraphy and structure of the Connecticut Valley through eastern Vermont: American Journal of Science, v. 288, p. 1041–1059.

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

Hepburn, J.C., Trask, N.J., Rosenfeld, J.L., and Thompson, J.B., Jr., 1984, Bedrock geology of the Brattleboro quadrangle, Vermont–New Hampshire: Vermont Geological Survey Bulletin 32, 162 p.

Higgins, M.W., 1972, Age, origin, regional relationships, and nomenclature of the Glenarm Series, Central Appalachian Piedmont: A reinterpretation: Geological Society of America Bulletin, v. 83, p. 989–1026.

Hitchcock, C.H., 1883, The early history of the North American continent: Science, v. 2, p. 293–297.

Hollocher, K.T., 1985, Geochemistry of metamorphosed volcanic rocks in the Middle Ordovician Partridge Formation, and amphibole dehydration reactions in the high-grade metamorphic zones of central Massachusetts, *in* Contribution 56: Amherst, University of Massachusetts, Department of Geology and Geography, 275 p.

———1988, Geochemical comparisons of the Monson Gneiss and associated tonalitic Acadian plutons and overlying Ordovician volcanics, Mass. [abs.] : Geological Society of America Abstracts with Programs, v. 20, p. 28.

Hollocher, K.T., and Lent, A.D., 1987, Comparative petrology of amphibolites in the Monson Gneiss and the Ammonoosuc and Partridge Volcanics [sic], Massachusetts: Northeastern Geology, v. 9, no. 3, p. 145–152.

Holloway, J.R., and Burnham, C.W., 1972, Melting relations of basalt with equilibrium water pressure less than total pressure: Journal of Petrology, v. 13, p. 1–29.

Irvine, T.N., and Baragar, W.R., 1971, A guide to the chemical classification of the common igneous rocks: Canadian Journal of Earth Science, v. 8, p. 523–548.

Johansson, W.I., 1963, Geology of the Lunenburg-Brunswick-Guildhall area, Vermont: Vermont Geological Survey Bulletin 22, 86 p.

Kaiser, E.P., 1938, Geology of the Lebanon granite, Hanover, N.H.: American Journal of Science, v. 36, ser. 5, p. 107–136.

Kay, M., 1951, North American geosynclines: Geological Society of America Memoir 48, 143 p.

Kruger, F.C., 1946, Structure and metamorphism of the Bellows Falls quadrangle of New Hampshire and Vermont: Geological Society of America Bulletin, v. 57, p. 161–206.

Kunk, M.J., and Sutter J.F., 1984, $^{40}Ar/^{39}Ar$ age spectrum dating of biotite from Middle Ordovician bentonite, eastern North America, *in* Bruton, D.L., ed., Aspects of the Ordovician system: Paleontological Contributions from the University of Oslo 295, p. 11–22.

Kunk, M.J., Sutter, J.F., Obradovich, J.D., and Lanphere, M.A., 1985, Age of biostratigraphic horizons within the Ordovician and Silurian systems, *in* The chronology of the geological record: Geological Society of America Memoir 10, p. 89–92.

Leo, G.W., 1985, Trondhjemite and metamorphosed quartz keratophyre tuff of the Ammonoosuc Volcanics (Ordovician), western New Hampshire and adjacent Vermont and Massachusetts: Geological Society of America Bulletin, 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 radiometric age: U.S. Geological Survey Professional Paper 1295, 45 p.

Lyons, J.B., 1955, Geology of the Hanover quadrangle, New Hampshire-Vermont: Geological Society of America Bulletin, v. 66, p. 105–146.

Lyons, J.B., Boudette, E.L., and Aleinikoff, J.N., 1982, The Avalonian and Gander zones in central eastern New England, *in* St. Julien, P., and Biland, J., eds., Major structural zones and faults of the northern Appalachians: Geological Association of Canada Special Paper 24, p. 43–66.

Lyons, J.B., Aleinikoff, J.N., and Zartman, R.E., 1986a, Uranium-thorium-lead ages of the Highlandcroft Plutonic Suite, northern New England: American Journal of Science, v. 286, p. 489–509.

Lyons, J.B., Bothner, W.A., Moench, R.H., and Thompson, J.B., Jr., eds., 1986b, Interim geologic map of New Hampshire, Durham, N.H.: Concord, New Hampshire Department of Resources and Economic Development, scale 1:250,000.

Malpas, J., 1979, Two contrasting trondhjemite associations from transported ophiolites in western Newfoundland: Initial report, *in* Barker, F., ed., Trondhjemites, dacites, and related rocks: Developments in petrology 6: New York, Elsevier, p. 465–487.

Martin, R.F., and Piwinskii, A.J., 1972, Magmatism and tectonic settings: Journal of Geophysical Research, v. 77, no. B26, p. 4966–4975.

Masuda, Y., Nishimura, S., Ikeda, T., and Katsui, Y., 1975, Rare-earth and trace elements in the Quaternary volcanic rocks of Hokkaido, Japan: Chemical Geology, v. 15, p. 251–271.

Meijer, A., 1983, The origin of low-K rhyolites from the Mariana frontal arc: Contributions to Mineralogy and Petrology, v. 83, p. 45–51.

Miller, C.F., 1985, Are strongly peraluminous magmas derived from pelitic sedimentary sources?: Journal of Geology, v. 93, p. 673–689.

———1986, Comment on S-type granites and their probable absence in southwestern North America: Geology, v. 14, p. 804–805.

Milton, D.J., 1961, Geology of the Old Speck Mountain quadrangle, Maine: Cambridge, Mass., Harvard University, unpublished Ph.D. dissertation, 190 p.

Moench, R.H., ed., 1984, Geologic map of the Sherbrooke-Lewiston area, Maine, New Hampshire, and Vermont: U.S. Geological Survey Open-File Report 84–650, scale 1:250,000.

———1989, Day 4—Metamorphic stratigraphy and structure of the Connecticut Valley area, Littleton to Piermont, New Hampshire, Trip T-162, *in* Lyons, J.B., and Bothner, W.A., leaders, Transect across the New England Appalachians, p. 45–53.

———1991, The Piermont allochthon, northern Connecticut Valley area, New England: Preliminary description and resource implications, *in* Slack, J.F., ed., Summary of results of the Glens Falls CUSMAP project, New York, Vermont and New Hampshire: U.S. Geological Survey Bulletin 1887, p. J1–J23.

Moench, R.H., and Aleinikoff, J.N., 1985, Metavolcanic stratigraphy in northern New England: Stratigraphic revisions [abs.]: Geological Society of America Abstracts with Programs, v. 17, no. 1, p. 54.

———1987, The Piermont allochthon of northwestern New Hampshire: Stratigraphic and isotopic evidence [abs.]: Geological Society of America Abstracts with Programs, v. 19, no. 1, p. 30.

Moench, R.H., Pankiwskyj, K.A., Boone, G.M., Boudette, E.L., Ludman, A., Newell, W.R., and Vehrs, T.I., 1982, Geologic map of western interior Maine: U.S. Geological Survey Open-File Report OF–82–656, 34 p., scale 1:250,000.

Moench, R.H., Hafner-Douglas, K., Jahrling, C.E., II, and Pyke, A.R., 1987, Metamorphic stratigraphy of the classic Littleton area, New Hampshire: Geological Society of America Centennial Field Guide—Northeastern Section, 1987, p 247–256.

Moore, G.E., Jr., 1949a, Geology of the Keene-Brattleboro quadrangle [sic], New Hampshire and Vermont: Concord, New Hampshire Planning and Development Commission, 31 p.

———1949b, Structure and metamorphism of the Keene-Brattleboro area, New Hampshire-Vermont: Geological Society of America Bulletin, v. 60, p. 1630–1670.

Naylor, R.S., 1968, Origin and regional relationships of the core-rocks of the Oliverian domes, *in* Zen, E., White, W.S., Hadley, J.B., and Thompson, J.B., Jr., eds., Studies of Appalachian geology, northern and maritime: New York, Interscience, p. 231–240.

———1969, Age and origin of the Oliverian domes, central-western New Hampshire: Geological Society of America Bulletin, v. 80, p. 405–428.

———1987, Mascoma dome, New Hampshire: An Oliverian gneiss dome, *in* Roy, D.C., ed., Geological Society of America Centennial Field Guide, Northeastern Section, p. 243-246.

O'Connor, J.T., 1965, A classification for quartz-rich igneous rocks based on feldspar ratios, *in* Geological Survey research 1965: U.S. Geological Survey Professional Paper 525–B, p. 79–84.

Osberg, P.H. 1978, Synthesis of the geology of the northeastern Appalachians, U.S.A., *in* IGCP Project 27, Caledonian Appalachian orogen of the north Atlantic region: Geological Survey of Canada Paper 78–13, p. 137–147.

Page, L.R., 1940, Geologic map and structure sections of the Rumney quadrangle, New Hampshire: Concord, New Hampshire Highway Department, scale 1:62,500.

Pavlides, L., 1981, The central Virginia volcanic-plutonic belt: An island arc of Cambrian(?) age: U.S. Geological Survey Professional Paper 1231–A, 34 p.

Payne, J.G., and Strong, D.F., 1979, Origin of the Twillingate trondhjemite, north-central Newfoundland: Partial melting in the roots of an island arc, *in* Barker, F., ed., Trondhjemites, dacites, and related rocks: Developments in petrology 6: New York, Elsevier, p. 489–516.

Pearce, J.A., 1983, Role of the subcontinental lithosphere in magma genesis at active continental margins, *in* Hawkesworth, C.J., and Norry, M.J., eds., Continental basalts and mantle xenoliths: Nantwich, Conn., Shiva Publications, p. 230–249.

Pearce, J.A., Harris, N.B.W., and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 25, p. 256–283.

Peper, J.D., Jr., 1966, Stratigraphy and structure of the Monson area, Massachusetts-Connecticut: Rochester, N.Y., University of Rochester, unpublished Ph.D. dissertation, 126 p.

———1976, Preliminary geologic maps of the Palmer quadrangle, south-central Massachusetts: U.S. Geological Survey Open-File Report 76–489, 22 p., 3 pls., scale 1:24,000.

Phinney, R.A., 1986, A seismic cross section of the New England Appalachians: The orogen exposed, *in* Reflection seismology: The continental crust: American Geophysical Union Geodynamics Series, v. 14, p. 157–172.

Pogorzelski, B.K., 1983, Petrochemistry and petrogenesis of the Highlandcroft Plutonic Series, N.H., Vt., and Me.: Hanover, N.H., Dartmouth College, unpublished M.Sci. thesis, 97 p.

Presnall, D.C., 1979, Fractional crystallization, *in* Yoder, H.S., Jr., ed., The evolution of the igneous rocks: Fiftieth anniversary prospectives: Princeton, N.J., Princeton University Press, p. 59–75.

Ringwood, A.E., 1974, The petrological evolution of island-arc systems: Journal of the Geological Society of London, v. 130, p. 183–204.

Robinson, P., 1963, Gneiss domes of the Orange area, Massachusetts and New Hampshire: Cambridge, Mass., Harvard University, unpublished Ph.D. thesis, 253 p.

———1967, Gneiss domes and recumbent folds of the Orange area, west-central Massachusetts, *in* Robinson, P., ed., Field trips in the Connecticut Valley of Massachusetts: New England Intercollegiate Geological Conference annual meeting, 59th, Amherst, Mass., 1967, Guidebook, p. 17–47.

———1977, Bedrock geology of the Orange area, Massachusetts and New Hampshire: U.S. Geological Survey Open-File Report OF–77–788, 5 p., 1 pl., scale 1:24,000.

———1979, Bronson Hill anticlinorium and Merrimack synclinorium in central Massachusetts, *in* Skehan, J.W., SJ, and Osberg, P.H., eds., The Caledonides in the U.S.A.—Geological excursions in the northeast Appalachians: IGCP Project 27—Caledonide orogen: Weston, Mass., Weston Observatory, p. 126–150.

Robinson, P., and Hall, L.M., 1980, Tectonic synthesis of southern New England, *in* Wones, D.R., ed., The Caledonides in the U.S.A., Symposium on IGCP Project 27—Caledonide orogen, Blacksburg, Va., 1979, Proceedings, p. 73–82.

Robinson, P., and Jaffe, H.W., 1969, Chemographic exploration of amphibole assemblages from central Massachusetts and southwestern New Hampshire: Mineralogical Society of America Special Paper 2, p. 251–274.

Robinson, P., Tracy, R.J., Hollocher, K.T., Schumacher, J.C., and Berry, H.N., IV, 1986, The central Massachusetts metamorphic high, *in* Regional metamorphism and phase relations in northwestern and central New England, Trip B–5, July 22–27, 1986: International Mineralogical Association general meeting, 14th, Amherst, Mass., 1986, Guidebook, p. 195–265.

Saunders, A.D., 1984, The rare earth element characteristics of igneous rocks from ocean basins, *in* Henderson, P., ed., Rare earth element geochemistry: Developments in geochemistry 2: New York, Elsevier, ch. 6, p. 205–230.

Schmidt, R.G., 1957, Geology of Saipan, Mariana Islands: Petrology of the volcanic rocks: U.S. Geological Survey Professional Paper 280–B, p. B127–B175.

Schumacher, J.C., 1988, Stratigraphy and geochemistry, of the Ammonoosuc Volcanics, central Massachusetts and southwestern new Hampshire: American Journal of Science, v. 288, p. 619–663.

Seiders, V.M., 1978, A chemically bimodal, calc-alkaline suite of volcanic rocks, Carolina volcanic slate belt, central North Carolina: Southeastern Geology, v. 19, p. 241–265.

Shapiro, L., 1975, Rapid analysis of silicate, carbonate, and phosphate rocks (revised ed.): U.S. Geological Survey Bulletin 1401, 76 p.

Southwick, D.L., 1979, The Port Deposit Gneiss revisited: Southeastern Geology, v. 20, p. 101–118.

Spear, F.S., and Rumble, D., III, 1986, Mineralogy, petrology, and P-T evolution of the Orfordville area, west-central New Hampshire and east-central Vermont, *in* Robinson, P., ed., Field trip guidebook—Regional metamorphism and metamorphic phase relations in northwestern and central New England: Contribution 59: Amherst, University of Massachusetts, Department of Geology and Geography, ch. D, p. 57–93.

Spulber, S.D., and Rutherford, M.J., 1983, The origin of rhyolite and plagiogranite in oceanic crust: An experimental study: Journal of Petrology, v. 24, p. 1–25.

Stacey, J.S., and Kramers, J.D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: Earth and Planetary Science Letters, v. 26, p. 207–221.

Stanley, R.S., and Ratcliffe, N.M., 1985, Tectonic synthesis of the Taconian orogen in western New England: Geological Society of America Bulletin, v. 96, p. 1227–1250.

Stuckless, J.S., and Van Trump, George, Jr., 1979, A revised version Graphic Normative Analysis Program (GNAP) with examples of problems solving: U.S. Geological Survey Open-File Report 79–1237, 115 p.

Thompson, J.B., Jr., 1950, A gneiss dome in southeastern Vermont: Cambridge, Massachusetts Institute of Technology, unpublished Ph.D. thesis, 160 p.

Thompson, J.B., Robinson, P., Clifford, T.N., and Trask, N.J., Jr., 1968, Nappes and gneiss domes in west-central New England, *in* Zen, E., White, W.S., and Hadley, J.B., eds.: Studies in Appalachian geology, northern and maritime: New York, Interscience, p. 203–218.

Tucker, R.D., and Robinson, P., 1990, Age and setting of the Bronson Hill magmatic arc: A reevaluation based on U-Pb zircon ages in southern New England: Geological Survey of America Bulletin, v. 102, p. 1404–1419.

Walker, G.P.L., 1966, Acid volcanic rocks in Iceland: Bulletin Volcanologique, v. 29, p. 375–402.

Webster, J.R., and Wintsch, R.P., 1987, Petrochemistry and origin of the Killingworth dome rocks, Bronson Hill anticlinorium, south-central Connecticut: Geological Society of America Bulletin, v. 98, p. 464–474.

Whitney, J.A., Paris, T.A., Carpenter, R.H., and Hartley, M.E., III, 1978, Volcanic evolution of the southern Slate Belt of Georgia and South Carolina: A primitive oceanic island arc: Journal of Geology, v. 86, p. 173–192.

Williams, C.R., and Billings, M.P., 1938, Petrology and structure of the Franconia quadrangle, New Hampshire: Geological Society of America Bulletin, v. 49, p. 1011–1044.

Williams, H., and Hatcher, R.D., Jr., 1983, Appalachian suspect terranes, *in* Hatcher, R.D., Jr., Williams, H., and Zietz, I., eds., Contributions to the tectonics and geophysics of mountain chains: Geological Society of America Memoir 158, p. 33–54.

Wood, D.A., 1980, The application of a Th-Hf-Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province: Earth and Planetary Science Letters, v. 50, p. 11–30.

Zartman, R.E., and Leo, G.W., 1985, New radiometric ages on Oliverian core gneisses, New Hampshire and Massachusetts: American Journal of Science, 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: Geological Society of America Bulletin, v. 95, p. 522–529.

Zen, E., 1983, Exotic terranes in the New England Appalachians—Limits, candidates and ages, *in* Hatcher, R.D., Jr., Williams, H., and Zietz, I., eds., Contributions to the tectonics and geophysics of mountain chains: Geological Society of America Memoir 158, p. 55–82.

DESCRIPTIONS AND LOCATIONS OF ANALYZED SAMPLES

DESCRIPTIONS AND LOCATIONS OF ANALYZED SAMPLES

Sample numbers match the analysis numbers used in tables 2 and 3. Unless otherwise noted, all samples show predominantly metamorphic fabrics; therefore, the prefix "meta" is generally omitted, but it is assumed throughout. Likewise, quartz and (or) plagioclase are ubiquitous and are not included in rock designations unless their presence is especially significant. For greater petrographic detail, see table 1.

Oliverian Plutonic Suite and associated gneisses

1. Medium-grained granitic gneiss near Berlin, N.H. Roadcut on western side of New Hampshire Route 16, 3.6 km south of center of Berlin; Berlin 7½-min quadrangle of New Hampshire (44° N., 71° W.).
2. Pink, pegmatitic segregation in Berlin gneiss. Same location as sample 1.
3. Medium-grained, light-gray granitic gneiss. Roadcut on western side of New Hampshire Route 16, 1 km north of sample 1 location (44°26.72′ N., 71°11.43′ W.).
4. Fine-grained, light-gray gneiss intruding amphibolite of the Ammonoosuc. Western side of New Hampshire Route 16 at Catello and Son sign, 1.7 km south of center of Berlin (44°27.19′ N., 71°11.34′ W.).
5. Medium-grained, strongly foliated, light-gray gneiss (Jefferson batholith trondhjemite of Aleinikoff and Moench (1987)) showing splotchy biotite aggregates. Low knob on New Hampshire Route 110, 7.6 km northwest of its intersection with New Hampshire Route 116 in Berlin. Southeastern corner of Percy 15-min quadrangle of New Hampshire (44°31.17′ N., 71°15.05′ W.).
6. Medium-grained tonalitic gneiss, generally similar to sample 5, intruding(?) amphibolite of the Ammonoosuc Volcanics. New Hampshire Route 110, 1.1 km northwest of sample 5 location (44°31.56′ N., 71°15.42′ W.).
7. Fine-grained, even-textured, weakly foliated gneiss. Southern slope of Mt. Randolph, approximately 2,400 ft (730 m) below Lookout Ledge; Mt. Washington 15-min quadrangle of New Hampshire (44°22.89′ N., 71°18.42′ W.).
8. Coarse, pink, slightly foliated granite on U.S. Route 2, 3 km west of Bowman and approximately 100 m east of Jefferson town line; Mt. Washington 15-min quadrangle of New Hampshire (44°21.30′ N., 71°22.83′ W.).
9. Foliated, medium- to coarse-grained hornblende syenite at Godfrey Dam on upper Ammonoosuc River; Mt. Washington 15-min quadrangle of New Hampshire (44°29.08′ N., 71°19.27′ W.).
10. Medium-grained clinopyroxene-hornblende-biotite monzogranite. One kilometer northeast of Jefferson Highland on Ingerson Road; Mt. Washington 15-min quadrangle of New Hampshire (44°23.33′ N., 71°24.55′ W.).
11. Porphyritic biotite quartz syenite. Summit of Bray Hill, 7 km northeast of the center of Whitefield; Whitefield 15-min quadrangle of New Hampshire and Vermont (44°24.41′ N., 71°32.30′ W.).
12. Pink, coarse-grained granite (coarse granite of Chapman and others (1944)). Lennon Road between New Hampshire Route 3 and a railroad track, about 5 km north of Twin Mountain; Whitefield 15-min quadrangle of New Hampshire and Vermont (44°19.00′ N., 71°32.82′ W.).
13. Pink, coarse-grained granite (Scrag Granite of Billings (1937)) very similar to sample 12. Summit of Mt. Agassiz, 2 km south-southeast of Bethlehem, N.H.; Whitefield 15-min quadrangle of New Hampshire and Vermont (44°15.97′ N., 71°40.02′ W.).
14. Strongly foliated and laminated hornblende-biotite gneiss (Whitefield Gneiss) at Mountain View House west of New Hampshire Route 3, 3.2 km northeast of Whitefield; Whitefield 15-min quadrangle of New Hampshire and Vermont (44°23.87′ N., 71°35.55′ W.).
15. Biotite-epidote-K-feldspar gneiss (Whitefield Gneiss) along East Whitefield Road 2.3 km south of Prospect Mountain; Whitefield 15-min quadrangle of New Hampshire and Vermont (44°25.87′ N., 71°34.00′ W.).
16. Well-foliated biotite-epidote gneiss (Whitefield Gneiss). Median of Interstate 93, 1.7 km southeast of Littleton, N.H.; Littleton 7½-min quadrangle of New Hampshire and Vermont (44°17.62′ N., 71°45.91′ W.).
17. Felsic volcanic porphyry (hypabyssal) related to the Sugar Hill pluton. Carpenter Road between Lafayette and The Birches Roads, 1.9 km west-southwest of Sugar Hill Village (fig. 7); Sugar Hill 7½-min quadrangle of New Hampshire (44°12.50′ N., 71°46.54′ W.).
18. Pink, fine-grained, hypidiomorphic-textured granite of the Sugar Hill pluton (Sugar Hill quartz monzonite of Billings (1937)). Eastern slope of Ore Hill at 1,700-ft (510 m) elevation, 0.8 km south of intersection of Carpenter and Lafayette Roads (fig. 7); Sugar Hill 7½-min quadrangle of New Hampshire (44°11.83′ N., 71°46.75′ W.).
19. Similar pink granite, 0.1 km northeast of sample 18 location (fig. 7) (44°11.85′ N., 71°46.71′ W.).
20. Pink, fine-grained granite of the Landaff pluton. At 1,640-ft (500 m) elevation on unnamed hill, 0.3 km south of intersection of Hadley and Dyke Roads (fig. 7); Sugar Hill 7½-min quadrangle of New Hampshire (44°11.03′ N., 71°48.67′ W.).

21. Gray, fine-grained hastingsite-bearing granodiorite of the Landaff pluton. One kilometer southwest of sample 20 location at 2,200-ft (670-m) elevation (44°10.74′ N., 79°49.27′ W.).
22. Pink, fine-grained granite of the northern Moody Ledge pluton. Cobble Hill Trail 2.0 km north of New Hampshire Route 112; northwestern corner of Mt. Moosilauke 7½-min quadrangle of New Hampshire (44°07.37′ N., 71°52.27′ W.).
23. Pink, fine-grained granite similar to sample 22. Outcrop on road to Cobble Hill Trail 1.0 km north of New Hampshire Route 112; northwestern corner of Mt. Moosilauke 7½-min quadrangle of New Hampshire (44°06.85′ N., 71°72.50′ W.).
24. Pink, medium-grained granite of the southern Moody Ledge pluton. Eastern side of North South Road 1.5 km south of Boutin Corner, East Haverhill 7½-min quadrangle of New Hampshire (44°05.08′ N., 71°52.90′ W.).
25. Pink, medium-grained gneissic granite of the Owls Head pluton (Owls Head Granite of Billings (1937)). Cut on New Hampshire Route 25, 1.7 km southeast of East Haverhill Village (fig. 8); East Haverhill 7½-min quadrangle of New Hampshire (44°01.26′ N., 71°57.47′ W.).
26. Pink, medium-grained gneissic granite of the Owls Head pluton, similar to sample 25. From cut on New Hampshire Route 25, 5.3 km southeast of East Haverhill Village (fig. 8), Warren 7½-min quadrangle of New Hampshire (43°59.61′ N., 71°54.40′ W.).
27. Fine-grained granite border phase of the Owls Head pluton. Northern side of New Hampshire Route 25, 0.2 km west of East Haverhill village (fig. 8); East Haverhill 7½-min quadrangle of New Hampshire (44°01.64′ N., 71°58.49′ W.).
28. Fine- to medium-grained, pinkish-gray border phase granite of the Owls Head pluton. In small northeast-trending stream 2 km north of East Haverhill Village (fig. 8) (44°02.53′ N., 71°57.51′ W.).
29. Fine-grained, strongly foliated border phase granite of the Owls Head pluton. At 1,860-ft (560-m) elevation along powerline trending southeast from East Haverhill; Warren 7½-min quadrangle of New Hampshire (43°54.03′ N., 71°59.73′ W.).
30. Sparsely porphyritic, biotite-muscovite granite of the Baker Pond pluton (porphyritic facies of Page (1940)). Half a kilometer west of Gilman's Corner; Warren 7½-min quadrangle of New Hampshire (43°54.03′ N., 71°59.73′ W.).
31. Gray, gneissic biotite-muscovite granite of the Baker Pond pluton (nonporphyritic facies of Page (1940)). Unnamed road east of Lake Armington, 2.5 km south of New Hampshire Route 25C; Warren 7½-min quadrangle of New Hampshire (43°54.03′ N., 71°59.73′ W.).
32. Hornblende-biotite-epidote granodiorite of the Baker Pond pluton (border facies of Page (1940)). 1.1 km south along road from sample 31 location (43°56.46′ N., 71°58.06′ W.).
33. Gray granitoid rock from the Smarts Mountain pluton. Seven-tenths of a kilometer west of summit, 2,800-ft (856-m) elevation; Mt. Cube 15-min quadrangle of New Hampshire and Vermont (43°49.55′ N., 72°02.60′ W.).
34. Similar gray granitoid rock. One kilometer west of summit, 2,600-ft (260-m) elevation, Mt. Cube 15-min quadrangle of New Hampshire and Vermont (43°49.52′ N., 72°02.77′ W.).
35. Pink, medium-grained granite of the Mascoma dome (unstratified core gneiss of Naylor (1969)). Quarry on small peak west of Moose Mountain; Mascoma 15-min quadrangle of New Hampshire and Vermont (43°41.16′ N., 72°08.84′ W.).
36. Tabular aplite dike at sample 35 location.
37. Coarse-grained Mascoma Granite (unstratified core gneiss of Naylor (1969)). Quarry 2.2 km north of Enfield, N.H., near end of May Street; Mascoma 15-min quadrangle of New Hampshire and Vermont (43°40.05′ N., 72°08.42′ W.).
38. Pink, medium-grained granite (interior phase) of the Lebanon pluton. Cut in New Hampshire Route 120 on Mt. Support, 3.7 km north of Lebanon; Hanover 7½-min quadrangle of New Hampshire and Vermont (43°40.42′ N., 72°15.71′ W.).
39. Similar granite of Lebanon pluton (interior phase). Cut in New Hampshire Route 120, 2 km southeast of the center of Hanover, N.H.; Hanover 7½-min quadrangle of New Hampshire and Vermont (43°41.48′ N., 72°16.25′ W.).
40. Dark-gray, biotite-epidote granodiorite border phase of the Lebanon pluton. One hundred and fifty meter cut in Interstate 89 immediately northeast of Poverty Lane overpass; Hanover 7½-min quadrangle of New Hampshire and Vermont (43°38.13′ N., 72°17.00′ W.).
41. Pink, medium-grained gneissic granite. Croydon dome, approximately 2 km northwest of North Newport along Kimball Brook Road; Sunapee 15-min quadrangle of New Hampshire (43°23.84′ N., 72°13.75′ W.).
42. Light-gray, medium-grained gneissic granite (Pauchaug Gneiss of Robinson (1963)). South of Quarry Road, 800-ft (245-m) elevation, southeastern corner of Mt. Grace 7½-min quadrangle of Massachusetts and New Hampshire (42°37.63′ N., 72°21.96′ W.).

43. Gray, fine-grained gneissic granite (border phase of Pauchaug Gneiss of Robinson (1963)). Northfield Road, 0.9 km northwest of Wendell Road intersection; Mt. Grace 7½-min quadrangle of Massachusetts and New Hampshire (42°40.86′ N., 72°21.15′ W.).
44. Medium-grained, strongly lineated gray gneiss (Swanzey Gneiss). Rabbit Hollow Road approximately 5 km northeast of Winchester, N.H.; Keene-Brattleboro 15-min quadrangle of New Hampshire (42°48.2′ N., 72°19.9′ W.).
45. Medium-grained K-feldspar-bearing gneiss (Swanzey Gneiss). New Hampshire Route 12A, 2.7 km north of quadrangle boundary; Bellows Falls 15-min quadrangle of New Hampshire (43°1.43′ N., 72°19.60′ W.).
46. Gray, medium-grained banded gneiss (Swanzey Gneiss). New Hampshire Route 119, 6.4 km east of Winchester, N.H.; Keene-Brattleboro 15-min quadrangle of New Hampshire and Vermont (42°45.64′ N., 72°18.74′ W.).
47. Gray, medium-grained gneiss (Swanzey Gneiss). Roadcut on New Hampshire Route 12, approximately 8 km southeast of Keene, N.H.; Monadnock 15-min quadrangle of New Hampshire (42°52.40′ N., 72°13.81′ W.).
48. Gray, banded biotitic gneiss (Monson Gneiss). Cut on southern side of Connecticut Route 2 at Exit 12; Marlborough 7½-min quadrangle of Connecticut (41°38.96′ N., 72°29.28′ W.).
49. Felsic, striped Kspar-biotite-muscovite-epidote gneiss (Monson Gneiss). Cut on northern side of Interstate 90 (Massachusetts Turnpike) directly east of Breckenridge Street overpass; Palmer 7½-min quadrangle of Massachusetts (42°10.64′ N., 72°18.88′ W.).
50. Monson Gneiss, similar to sample 49. About 10 m east along cut from sample 49 location.
51. Fine-grained biotite-epidote gneiss (Monson Gneiss). Upper Palmer Road at 590-ft (215-m) elevation, 0.85 km west of Chicopee Mountain; Palmer 7½-min quadrangle of Massachusetts (42°08.33′ N., 72°19.96′ W.).
52. Pink, medium- to coarse-grained gneiss (Monson Gneiss). Outcrop at about 700-ft (215-m) elevation on unnamed hill west of South Monson, Mass.; Monson 7½-min quadrangle of Massachusetts and Connecticut (42°05.54′ N., 72°18.28′ W.).
53. Striped hornblende-biotite gneiss (Monson Gneiss). Cut in southern side of Massachusetts Route 2, 1.1 km northwest of New Hampshire Route 122 (Orange) interchange, Orange 7½-min quadrangle of Massachusetts (42°33.87′ N., 72°18.78′ W.).
54. Relatively homogeneous, faintly foliated hornblende-biotite-epidote gneiss (Monson Gneiss). Cut on Massachusetts Route 2A at intersection with East Main Street, about 2.3 km east of center of Orange; Orange 7½-min quadrangle of Massachusetts (42°35.20′ N., 72°17.01′ W.).
55. Granodiorite of the Highlandcroft Plutonic Suite. U.S. Route 3 directly west of Prospect Mountain, about 4 km south of center of Lancaster, N.H.; Whitefield 15-min quadrangle of New Hampshire and Vermont (44°27.19′ N., 71°34.75′ W.).
56. Porphyritic monzogranite (Highlandcroft Plutonic Suite). U.S. Route 3, 1.8 km southwest of Guildhall, Vt.; Guildhall 15-min quadrangle of New Hampshire and Vermont (44°33.43′ N., 71°34.79′ W.).
57. Sample omitted
58. Sample omitted
59. Hornblende-epidote-sphene-biotite metadiorite (Highlandcroft Plutonic Suite). Page Hill Road 1.5 km east of Coos Junction, N.H. (U.S. Route 3), Guildhall 15-min quadrangle of Vermont and New Hampshire (44°30.78′ N., 71°32.88′ W.).
60. Coarse-grained chlorite-sausserite-epidote metagabbro (Highlandcroft Plutonic Suite). Page Hill Road 0.8 m southwest of sample 59 location (44°30.69′ N., 71°33.38′ W.).

Mafic and intermediate Ammonoosuc Volcanics

Unless otherwise indicated, "amphibolite" refers to rocks consisting predominantly of plagioclase and hornblende.

61. Amphibolite. 1.6 km northwest of Norwich, Vt.; Hanover 7½-min quadrangle of Vermont and New Hampshire (43°43.93′ N., 72°18.58′ W.). Collected by J.N. Aleinikoff.
62. Garnet-bearing amphibolite. Beaver Brook on New Hampshire Route 12, 1.6 km north of Plainfield, N.H. (Aleinikoff, 1977); North Hartland 7½-min quadrangle of New Hampshire and Vermont (43°36.13′ N., 72°19.32′ W.). Collected by J.N. Aleinikoff.
63. Amphibolite. Hewes Brook, 3.2 km southwest of Lyme, N.H.; Mt. Cube 15-min quadrangle of New Hampshire and Vermont (43°46.97′ N., 72°10.92′ W.). Collected by J.N. Aleinikoff.
64. Amphibolite. Same location as sample 63. Collected by J.N. Aleinikoff.
65. Amphibolite. Same location as sample 62. Collected by J.N. Aleinikoff.
66. Amphibolite. Ompompanoosuc River near its confluence with the Connecticut River; near southwestern corner of Mt. Cube 15-min quadrangle of New Hampshire and Vermont (43°45′ N., 72°15′ W.). Collected by J.N. Aleinikoff.
67. Amphibolite dike (late- or post-Ammonoosuc) cutting Oliverian gneiss. Western side of Cascade, N.H.

(fig. 2); Berlin 7½-min quadrangle of New Hampshire (44°26.95′ N., 71°11.44′ W.).

68. Sample omitted
69. Amphibolite from banded Ammonoosuc Volcanics. Northern side of Cascade-Alpine Brook near its terminus in Androscoggin River, directly east across river from Cascade, N.H. (fig. 2); Berlin 7½-min quadrangle of New Hampshire (44°26.94′ N., 71°10.95′ W.).
70. Hornblende-augite amphibolite. Cascade-Alpine Brook, 1,120-ft (345-m) elevation; Berlin 7½-min quadrangle of New Hampshire (44°26.94′ N., 71°10.88′ W.). Collected by M.P. Billings.
71. Biotitic amphibolite. Western edge of Berlin near end of 4th Street; Berlin 7½-min quadrangle of New Hampshire (44°28.01′ N., 71°11.96′ W.).
72. Massive hornblende-biotite amphibolite. Cut in southern side of Interstate 93, 1.3 km east of intersection with New Hampshire Route 10; Littleton 7½-min quadrangle of New Hampshire and Vermont (44°18.20′ N., 71°47.23′ W.).
73. Hornblende-biotite amphibolite. Same location as sample 72.
74. Hornblende-biotite amphibolite. New Hampshire Route 112, 1.7 km southeast of junction with New Hampshire Route 10; Lisbon 7½-min quadrangle of New Hampshire (44°08.33′ N., 71°58.13′ W.).
75. Carbonate-bearing amphibolite. Same location as sample 74.
76. Hornblende-epidote amphibolite. New Hampshire Route 112 near confluence of Davis Brook and Wild Ammonoosuc River; Mt. Moosilauke 7½-min quadrangle of New Hampshire (44°06.10′ N., 71°51.55′ W.).
77. Amphibolite. Jeffers Brook, approximately 1,900-ft (582-m) elevation, 1.2 km east of Blueberry Mountain; southeastern corner of East Haverhill 7½-min quadrangle of New Hampshire (location approximate).
78. Hornblende-biotite amphibolite. New Hampshire Route 25 at Glencliff, N.H.; Warren 7½-min quadrangle of New Hampshire (44°59.01′ N., 71°53.61′ W.).
79. Hornblende-biotite amphibolite. Holts Ledge at approximately 2,000-ft (610-m) elevation, about 3.5 km. southeast of Lyme Center, N.H.; Mt. Cube 15-min quadrangle of New Hampshire and Vermont (43°46.70′ N., 72°06.21′ W.).
80. Amphibolite. New Hampshire Route 123A about 5 km northeast of Alstead, N.H.; Bellows Falls 15-min quadrangle of New Hampshire and Vermont (43°10.43′ N., 72°18.96′ W.).
81. Gedrite-biotite amphibolite. Railroad cut about 1 km north of Cascade, N.H.; Berlin 7½-min quadrangle of New Hampshire (44°27.44′ N., 71°11.33′W.). Collected by M.P. Billings.
82. Gedrite-biotite amphibolite. Northern corner of Berlin High School; Berlin 7½-min quadrangle of New Hampshire (44°28.92′ N., 71°11.28′ W.).
83. Hornblende-cummingtonite amphibolite. 1,330-ft (410-m) elevation on Bean Brook; Berlin 7½-min quadrangle of New Hampshire (44°28.82′ N., 71°08.43′ W.). Collected by M.P. Billings.
84. Cummingtonite-hornblende amphibolite. Same location as sample 69.
85. Anthophyllite-cummingtonite amphibolite. 1,310-ft (400-m) elevation on Bean Brook; Berlin 7½-min quadrangle of New Hampshire (44°28.87′ N., 71°08.24′ W.). Collected by M.P. Billings.
86. Garnet-gedrite-biotite granofels. Western edge of Berlin, N.H. ("Sixth Avenue, Berlin" (Billings and Fowler-Billings, 1975, p. 99)); coordinates not available. Collected by M.P. Billings.

Felsic Ammonoosuc Volcanics

Unless otherwise indicated, samples contain more than 90 percent quartz+plagioclase and less than 3 percent K-feldspar.

87. Biotite-anthophyllite granofels. Same location as sample 69.
88. Chloritic granofels. Cascade-Alpine-Brook, approximately 1,040-ft (340-m) elevation; Berlin 7½-min quadrangle of New Hampshire (44°26.91′ N., 71°10.88′ W.).
89. Biotite-muscovite granofels. Southwestern corner of 6th and Madigan Streets, Berlin, N.H.; Berlin 7½-min quadrangle of New Hampshire (44°28.33′ N., 71°11.52′ W.).
90. Low-grade crystal tuff displaying well-preserved volcanic texture. Cut on New Hampshire Route 18–135, 150 m east of viaduct over Moore Reservoir; Littleton 7½-min quadrangle of New Hampshire and Vermont (44°18.57′ N., 71°51.91′ W.).
91. Biotite-K-feldspar tuff. Blocks along The Birches Road, 0.4 km east of junction with New Hampshire Route 117; Sugar Hill 7½-min quadrangle of New Hampshire (44°12.88′ N., 71°46.83′ W.).
92. Tuff similar to sample 90. Northeastern slope of Ore Hill (fig. 7), approximately 1,640-ft (500-m) elevation; Sugar Hill 7½-min quadrangle of New Hampshire (44°11.98′ N., 71°46.66′ W.).
93. Biotite granofels. 1.4 km northwest of Glencliff, N.H., north of Oliverian Brook along trail to Owls Head; Warren 7½-min quadrangle of New Hampshire (43°49.65′ N., 71°54.15′ W.).
94. Quartz-plagioclase granofels from different part of outcrop at sample 92 location.
95. Biotite-muscovite tuff displaying well-preserved porphyritic texture. 0.3 km east of Limekiln Road,

approximately 3.6 km northeast of East Haverhill, N.H.; East Haverhill 7½-min quadrangle of New Hampshire (44°03.10′ N., 71°56.95′W.).

96. Biotite-garnet granofels. 0.6 km northeast of Wyatt Hill, approximately 1,380-ft (422-m) elevation; Warren 7½-min quadrangle of New Hampshire (43°59.67′ N., 71°54.17′ W.).
97. Biotite-muscovite granofels. New Hampshire Route 25C, 6.3 km northeast of junction with New Hampshire Route 25 at Warren; Warren 7½-min quadrangle of New Hampshire (43°57.32′ N., 71°57.11′ W.).
98. Laminated chloritic granofels. Holts Ledge at approximately 1,800-ft (550-m) elevation, same location as sample 79.
99. Chlorite-epidote granofels. Approximately 1 km southwest of South Acworth, N.H., and 0.4 km south of Beryl Mountain; Bellows Falls 15-min quadrangle of New Hampshire and Vermont (43°10.57′ N., 72°17.72′ W.).
100. Biotite-chlorite-garnet-cummingtonite granofels. Northfield Road approximately 4.6 km east of Northfield, Mass., 400-ft (123-m) elevation; Northfield 7½-min quadrangle of Massachusetts, New Hampshire, and Vermont (42°42.30′ N., 72°24.12′ W.).

Metasomatized Ammonoosuc Volcanics

101. Biotite-K-feldspar granofels (metasomatized Ammonoosuc Volcanics). Three kilometers south of East Haverhill, N.H.; East Haverhill 7½-min quadrangle of New Hampshire (44°00.08′ N., 71°58.92′ W.).
102. Biotite-K-feldspar granofels. Approximately 100 m north of sample 101 location.
103. Biotite-K-feldspar granofels. Two hundred meters northwest of sample 28 location (44°02.65′ N., 71°57.68′ W.).

Holts Ledge volcanic sequence

Unless otherwise indicated, samples contain more than 90 percent quartz+plagioclase and less than 3 percent K-feldspar.

104. Massively bedded hornblende-epidote granofels. New Hampshire Route 25A, 1.6 km east of Gilman's Corner, N.H.; Warren 7½-min quadrangle of New Hampshire (43°53.77′ N., 71°58.33′ W.).
105. Biotite granofels. Unnamed north-south road, 0.3 km east of Aswell Hill, N.H.; Warren 7½-min quadrangle of New Hampshire (43°54.40′ N., 71°57.79′ W.).
106. Hornblende-biotite-fibrolite granofels. Same location as sample 79, approximately 1,500-ft (458-m) elevation.
107. Hornblende-biotite granofels. Same location as sample 79, approximately 1,470-ft (450-m) elevation.
108. Hornblende-epidote granofels. Same location as sample 79, approximately 1,400-ft (430-m) elevation.
109. Biotite-K-feldspar-epidote granofels. Same location as sample 79, approximately 1,150-ft (353-m) elevation.

Trondhjemite associated with the Ammonoosuc Volcanics

Unless otherwise noted, all samples contain more than 90 percent quartz and plagioclase and less than 1 percent K-feldspar.

110. Strongly lineated, light-gray, equigranular biotite trondhjemite. New Hampshire Route 110, approximately 5 km northwest of Berlin, N.H., and about 180 m northwest of the road to Jericho Road Park; southwestern corner of the Milan 15-min quadrangle of New Hampshire (44°30.32′ N., 71°41.35′ W.).
111. Biotite trondhjemite. Intersection of Sullivan and Champlain Streets, Berlin, N.H. (eastern side of Androscoggin River); Berlin 7½-min quadrangle of New Hampshire (44°30.36′ N., 71°14.20′ W.).
112. Biotite trondhjemite. Railroad cut 100 m directly west of Berlin, N.H., post office; Berlin 7½-min quadrangle of New Hampshire (44°28.03′ N., 71°11.18′ W.).
113. Hornblende-epidote K-feldspar trondhjemite dike(?), northwestern slope of Cole Hill, approximately 1,920-ft (587-m) elevation; Sugar Hill 7½-min quadrangle of New Hampshire (44°10.65′ N., 71°49.54′ W.).
114. Muscovite-epidote-biotite trondhjemite. Intersection of Interstate 89 and New Hampshire Route 12A, 1.3 km west of Lebanon Municipal Airport; Hanover 7½-min quadrangle of New Hampshire and Vermont (43°37.89′ N., 72°19.32′ W.).
115. Altered chlorite-epidote trondhjemite ("gneiss at White River Junction, Vt." of Lyons (1955)). Cut on Interstate 91 approximately 1 km west of White River Junction, Vt.; Hanover 7½-min quadrangle of New Hampshire and Vermont (43°39.16′ N., 72°20.02′ W.).
116. Greenish, altered trondhjemite. Same location as sample 114.
117. Epidote-chlorite trondhjemite ("gneiss east of Plainfield, N.H." of Lyons (1955)). Porter Road about 6 km northeast of Plainfield, N.H.: North Hartland 7½-min quadrangle of New Hampshire and Vermont (43°34.27′ N., 72°18.41′ W.).
118. Biotite K-feldspar trondhjemite. Cut on western side of Interstate 89, about 2 km north of North Grantham exit; North Hartland 15-min quadrangle of New Hampshire and Vermont (43°31.60′ N., 72°08.29′ W.).

119. Biotite-hornblende-epidote trondhjemite. Cut in Interstate 89, 1.3 km south of sample 118 location (43°30.88′ N., 72°08.15′ W.).
120. Biotite-muscovite trondhjemite. Old New Hampshire Route 103, 6 km west of center of Claremont, N.H.; Claremont 15-min quadrangle of New Hampshire and Vermont (43°22.13′ N., 72°16.57′ W.).
121. Biotite-epidote-K-feldspar trondhjemite. 1.4 km west of "Quaker City" in stream; Claremont 15-min quadrangle of New Hampshire and Vermont (43°16.39′ N., 72°18.78′ W.).
122. Hornblende-epidote trondhjemite. 0.8 km east of sample 80 location in barnyard north of road; Bellows Falls 15-min quadrangle of New Hampshire and Vermont (43°10.60′N., 72°18.41′ W.).
123. Hornblende-garnet tonalite. New Hampshire Route 12A, 6 km south of Alstead, N.H.; Bellows Falls 15-min quadrangle of New Hampshire and Vermont (43°06.79′ N., 72°19.42′ W.).
124. Biotite-epidote-garnet trondhjemite. Bald Hill, approximately 1,100-ft (340-m) elevation north of Ashuelot River; Bellows Falls 15-min quadrangle of New Hampshire and Vermont (43°03.35′ N., 72°18.59′ W.).
125. Biotite-K-feldspar-garnet-epidote trondhjemite gneiss. Roadcut in New Hampshire Route 119 at western edge of Hinsdale, N.H.; Keene 15-min quadrangle of New Hampshire and Vermont (42°47.10′ N., 72°29.72′ W.).
126. Biotite-epidote-garnet trondhjemite gneiss. Oxbow Road approximately 1 km northwest of North Hinsdale, N.H.; Brattleboro 15-min quadrangle of New Hampshire and Vermont (42°49.83′ N., 72°31.34′ W.).
127. Biotite trondhjemite. New Hampshire Route 10, 1.6 km northeast of intersection with Burnt Hill Road; Northfield 7½-min quadrangle of Massachusetts, New Hampshire, and Vermont (42°43.87′ N., 72°24.61′ W.).

☆ U.S. G.P.O. 1991- 296-222