Distribution, orientations, and ages of mafic dikes in central New England

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ABSTRACT

Geometric data from more than 1,100 localities and 13 radiometric ages have been compiled and measured for postmetamorphic dikes in eastern New York, Vermont, New Hampshire, western Maine, and southern Quebec. Alkalic lamprophyres (monchiquite and camptonite) in Vermont and Quebec form three westward-trending lobate swarms. The northernmost lobe envelops the Monteregian Hills of Quebec, the central lobe crosses the central Lake Champlain Valley into the eastern Adirondacks, and the southernmost lobe crosses the northern Taconic Mountains into New York. These lobes extend from central New England, where numerous alkalic lamprophyre, spessartite, and diabase dikes were intruded in several episodes and orientations during Mesozoic time.

Most of the monchiquite dikes are found in the Monteregian and Champlain areas, and with associated camptonite dikes intruded west-northwest– to east-trending regional fractures during Early Cretaceous time. Alkalic lamprophyres of this episode can also be found in New Hampshire and Maine. Most diabase dikes are found east of central Vermont, where they intruded northeast-trending fractures during Late Triassic to Early Jurassic time. Many camptonite and some spessartite dikes in eastern New England and the Taconics lobe have northeast trends and may also be of Early Jurassic age.

Extensional stress directions in the New England crust shifted from northwest to north or north-northeast between Early Jurassic and Early Cretaceous time, as inferred from dike trends. The dikes may delineate extensional fracture zones that also controlled the emplacement of Mesozoic plutons in Quebec and New England.

INTRODUCTION

Mafic dikes crop out in large numbers throughout New England, frequently in road cuts that postdate most of the geologic mapping of the area. Even when included in field reports, detailed descriptions are rare, and no comprehensive regional and petrographic survey has been carried out for these rocks. This paper is the first part of such a study, and contains both new and literature-derived information on the distribution, orientations, and some ages of roughly 1,100 postmetamorphic (essentially post-Paleozoic) dikes in eastern New York, Vermont, New Hampshire, southern Quebec, and western Maine (Fig. 1). Felsic and more intermediate dikes have a very restricted distribution and are not considered. Also, dikes in southern New England and along the Maine coast (except for a few for which previous data exist) have been excluded, mainly for lack of time to study such a large area. In addition to an outline of the physical aspects of these dike swarms, the most important results of this work may be the inferred fracture tectonics and stress regimes that controlled the dike patterns, and which in turn may be related to rifting events and plutonic magmatism in New England. Other tectonic studies have been made for eastern North American dikes by de Boer (1967) and May (1971), who hypothesized stress patterns to account for dike orientations consistent with pre-opening events of the Atlantic Ocean.

This study is mainly the result of graduate work (McHone, 1975, 1977) and includes field examination of 215 dikes as well as a literature compilation of roughly 900 other dike localities in New England. Most of the information for Monteregian (Quebec) dikes is from Hodgson (1968), while Corneille (1975) provided considerable data for dikes of the Lake Champlain area in Vermont. Although many quadrangle reports mention mafic dikes (see the compilation by McIntosh and Eister, 1974), few publications show them on maps and fewer provide detailed analyses of mineralogy or discuss petrogenesis. Notable exceptions are papers by Kemp and Marsters (1893), Jaffe (1953), Woodland (1962), and Billings and Fowler-Billings (1975). A future paper will discuss the chemistry and petrology of dikes in the study area in more detail. A complete list of the references consulted for this study may be obtained from me. Plutonic complexes referred to in the text are labeled A through G in Figure 1.

Thin-section studies to date indicate four basic dike types in the study area, based on the classification schemes of Williams and others (1954), Joplin (1966), and Rock (1977). These are monchiquite and camptonite (subsilicic alkalic lamprophyres), spessartite (herein used as a group name for the relatively felsic lamprophyres spessartite, kersantite, and minette), and diabase. The petrographic criteria used to group the dikes are presented in Table 1. The most important of these are the lack of feldspar phenocrysts and presence of hydrous minerals in alkalic lamprophyres, and the lack of hydrous minerals and ocelli in diabase. Spessartite apparently has some characteristics of both those groups and thus is the most difficult to classify. These criteria have been adopted specifically for this study area and may not be the most valid for other dike suites.

Diabase types referred to in the literature include "porphyritic diabase," "metadiabase," "olivine diabase," "trachydiabase," and "basalt," but such subdivisions on the general scale of this paper are unwarranted. The considerable variety of rock types as demonstrated by petrography (and, where available, by chemistry) clearly implies several different episodes of magma generation and intrusion. Because hand samples and field appearances of the dikes can be very similar, microscopic examination is necessary to distinguish the various types. This in itself throws some doubt on the ac-

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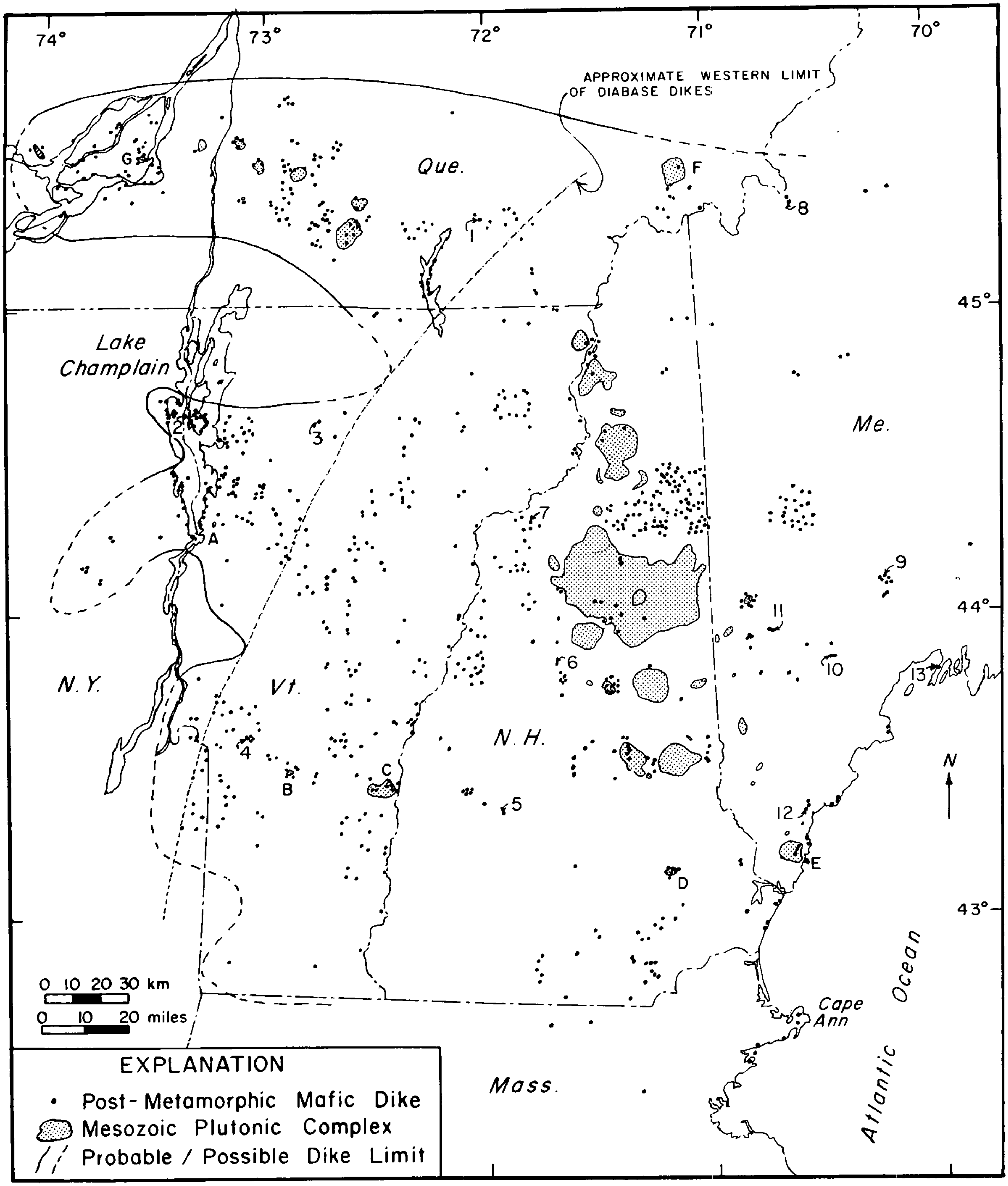

Figure 1. Map showing distribution of mafic dikes in central New England and adjoining areas of New York and Quebec. Dots may represent more than one dike. Numbers refer to dated dikes listed in Table 3. Plutonic complexes mentioned in text are labeled as follows: A = Barber Hill stock; B = Cuttingsville complex; C = Mt. Ascutney complex; D = Pawtuckaway Mountain complex; E = Cape Neddick stock; F = Megantic complex; G = Mt. Royal stock.

curacy of many dike identifications in the literature, which may also lack consistent criteria for petrographic classification.

Most New England dikes dip at angles greater than 70° and have widths between 20 and 100 cm. Only a few dikes are wider than 2 m, with the widest reported as 21.3 m (70 ft) in western Maine (Merrill and Perkins, 1930, p. 16). Many examples show small variations in strike, dip, and width within an outcrop, although horizontal exposures are less common than vertical ones, and therefore most strike measurements are limited to short segments.

In most cases, the dikes could not be traced more than a few metres because of sediment cover. However, the apparent lengths of individual dikes in Quebec (Hodgson, 1968, p. 6), New Hampshire (Fowler-Billings, 1944, p. 1260; Billings and Fowler-Billings, 1975, p. 115), Vermont (Christman, 1959, p. 42), and New York (Fisher, 1968, p. 33) are as much as 12.5 km and show width-to-length ratios exceeding 1:1,000. Similar ratios are suggested for lamprophyres at Callandar Bay, Ontario (Currie and Ferguson, 1970), and so may be common for dikes in the study area. Field relations indicate simple dilation of fractures during dike intrusions, mainly because irregularities in the dike walls fit together along lines perpendicular to the dike attitudes, indicating no shear motion. The general rarity of xenoliths shows little violent brecciation of the country rocks by the intrusions.

The dikes usually exhibit both cross (columnar) and parallel cooling fractures, and they align with one or more of the major regional fracture sets. Country-rock joints are sometimes more concentrated nearer the dikes, a feature discussed by Dale (1899) in the Taconic slates of western Vermont. Twelve dikes were found that appear to be faulted (Table 2). In these cases, other (noncooling) fractures could also be seen within the dikes. The fault surfaces range in dip from 24° to 74°; since examples with horizontal exposures are uncommon, most faults observed to intersect the dikes should show relatively low-angle dip-slip movement. All of the examples in Table 1 except for sample PM-6 intrude phyllitic or schistose country rocks. Although many of the faults do not parallel this prominent cleavage, such rocks may deform more readily than more massive types. Detailed fault-stress analyses were not attempted, but the predominance of normal over reverse faults may indicate extensional rather than compressional stresses. The fault activity was widespread, if only minor, and the north-northeast directions of the faults may show a reactivation of the pervasive north-northeast regional structures of New England. Possibly some of the activity may reflect a response to glacial depression and rebound.

TABLE 1. CHARACTERISTIC MINERALS AND TEXTURES OF THE FOUR DIKE GROUPS

	1	2	3	4
Phenocrysts				
Olivine	C	R	C	C
Augite	C	C	C	C
Hornblende	A	C	C	C
Biotite	A	R	A	R
Plagioclase	C	C	A	A
Matrix				
Olivine	R	R	R	R
Augite	U	U	U	U
Hornblende	R	C	U	U
Biotite	R	R	R	R
Plagioclase	U	U	U	R
K-feldspar	R	R	R	R
Analcime	A	R	C	U
Textures				
Porphyritic	C	C	C	C
Subophitic	C	R	R	A
Panidiomorphic	A	R	U	U
Granular	R	C	U	U
Trachytic	R	R	A	A
Amygdaloidal	C	C	C	C
Ocellar	A	R	C	C

Note: Column headings: 1, diabase; 2, spessartite; 3, camptonite; 4, monchiquite. U = ubiquitous, C = common, R = rare, A = absent.

DISTRIBUTION

Blank areas in Figure 1 in part reflect poor exposures or incomplete mapping, especially east of central Vermont. The dike density over much of this area is probably best represented by the Gorham, New Hampshire, quadrangle (Billings and Fowler-Billings, 1975) and the Bryant Pond, Maine, quadrangle (Guidotti, 1965), both near the central border between the two states, in which hundreds of dikes are mapped. The numerous dikes present along the New England coastline (see Kemp, 1890, and Chapman and Wingard, 1958) are probably southeastern representatives of these central swarms. In intermediate areas, quarries at Lewiston, Maine (Merrill, 1892), and road cuts along the Maine Turnpike also show high dike densities.

When the dikes are grouped into two series, the alkalic lamprophyres (monchiquite and camptonite) and more silicic dikes (spessartite and diabase), an important feature becomes apparent. Most dikes west of a line running north-northeast across Vermont (Fig. 1) are alkalic lamprophyres, whereas east of that line all types are found. Diabase dikes are particularly abundant in New Hampshire and Maine; Billings and Fowler-Billings (1975, p. 76) estimated that about 75% of more than 200 dikes mapped in the Gorham quadrangle are diabase.

The alkalic lamprophyres are contained along the west by a boundary forming three lobes that extend westward from central Vermont (Fig. 1). The Monteregian lobe envelops the Lower Cretaceous stocks and plutonic complexes of southern Quebec (Hodgson, 1968; Philpotts, 1974) and also contains some alnoite and carbonate-rich (ouachitite) lamprophyres in its westernmost area. The Champlain lobe crosses the central Lake Champlain Valley into the easternmost Adirondacks (Kemp and Marsters, 1893; Kemp and Alling, 1925; Buddington and Whitcomb, 1941; Jaffe, 1953), but west of the valley the similar appearance of the many upper Precambrian diabase dikes masks the true abundance and extent of the much younger lamprophyres. Virtually all of the dikes in the Champlain lobe are camptonite and monchiquite (Corneille, 1975). The Champlain lobe contains Barber Hill, a Lower Cretaceous syenitic complex (Laurent and Pierson, 1973), and the Plattsburg magnetic and gravity anomaly, inferred to result from a buried mafic stock of Monteregian affinity (Diment, 1968). Between the central and northern lobes, Lake Champlain lacks dikes despite the good shoreline exposures (Shimer, 1902). An apparent lack of dikes in the Potsdam sandstone along the Ausable River in New York (Fisher, 1968) indicates a split in the Champlain lobe on its western side (Fig. 1).

The southern Champlain Valley also has few if any dikes between the Champlain lobe and the Taconic lobe, which is a less well-defined swarm crossing the northernmost Taconic Mountains in southwestern Vermont and adjacent New York (Dale, 1899;

TABLE 2. DESCRIPTIONS OF DIKES KNOWN OR SUSPECTED TO BE FAULTED

Sample no.	Location lat (N)	long (W)	Dike orientation	Width (cm)	Dike type	Fault(?) orientation	Offset cm	type	Description
BU-8	44°19′15″	74°14′50″	N83°W, 78°N	148	Augite camptonite	N30°E, 69°SE	106	Normal	Possibly intrusional offset rather than fault
BA-3	44°05′40″	72°36′42″	N85°E, 76°N	41	Augite camptonite	N9°E, 40°W	36	Reverse	Fault and gouge well developed
BA-8	44°05′41″	72°36′42″	N70°E, 87°N	20	Augite camptonite	N11°E, 24°E	14	Normal	Clean fracture, follows country-rock cleavage
RD-3	43°57′12″	72°37′41″	N56°E, 75°S	63	Hornblende camptonite	N2°W, 74°W	17	Normal	Fault and gouge well defined
RD-4	43°57′10″	72°37′41″	N60°E, 63°S	16–47	Hornblende camptonite	Not measured	?	?	Fault similar to RD-3
WR-3	43°30′49″	73°03′20″	N15°E, 83°E	160	Hornblende spessartite	N19°E, 66°E	80	Normal	Thick fault zone; dike dated at 105 ± 4 m.y. (Zen, 1972)
HN-5	43°38′15″	72°20′32″	N5°W, 82°S	43	Spessartite	N12°W, 38°W	35	Normal	Internal slickensides
HN-9	43°40′09″	72°18′51″	N84°E, 89°S	43	Diabase	N24°E, 34°NW	15	Normal	Clean fracture
HN-10	43°40′09″	72°18′51″	N66°E, 68°SE	7	Diabase	N32°E, 55°NW	60	Normal	Clean fracture
WS-3	43°36′00″	72°42′23″	N75°E, 86°N	92	Augite camptonite	Same as dike(?)	?	?	Brecciated dike with abundant slickensides, no offset
SJ-3	44°24′47″	72°07′01″	N39°E, 69°NW	90	Camptonite	Same as dike(?)	?	?	Brecciated dike with slickensides, dike boundaries hidden
PM-6	43°47′12″	71°40′01″	N75°W, 90°	68	Hornblende camptonite	Same as dike(?)	?	?	Abundant internal slickensides, microscopic offsets; camptonite type locality

TABLE 3. K-Ar AGE DATA FOR MAFIC DIKES IN CENTRAL NEW ENGLAND AND ADJACENT QUEBEC

Sample no.	Location lat (N)	long (W)	Orientation	Width (cm)	Type	K (%)	Ar^{40*} (ppm)	Ar^{40*}/K^{40}	Age (m.y.)
1	49°19′15″	71°57′30″	N.A.	N.A.	Augite spessartite (?)	0.451	N.A.	N.A.	126 ± 1
2	44°38′43″	73°20′55″	N85°W	120	Biotite monchiquite	6.598	0.0662	0.00823	136 ± 7 (biotite)
3	44°38′28″	72°45′30″	N24°E, 86°NW	155	Hornblende monchiquite	1.353	0.01303	0.00789	130 ± 6 (hornblende)
4	43°30′59″	73°03′20″	N15°E, 83°SE	160	Hornblende spessartite	0.810	0.00514	0.00628	105 ± 4 (hornblende)
5	43°21′56″	71°55′05″	N76°W, 76°S	176	Augite monchiquite	1.615	0.01134	0.00575	96 ± 4
6	43°48′49″	71°40′19″	N50°E, 72°SE	124	Diabase	0.936	0.01262	0.01105	180 ± 8
7	48°18′11″	71°47′05″	N22°E, 90°	320	Biotite tonalite (?)	2.691	0.08831	0.02689	411 ± 15 (biotite)
8	45°19′42″	70°38′49″	N85°W, 80°S	39	Augite camptonite	1.110	0.00994	0.00733	121 ± 5
9	45°05′05″	70°12′30″	N77°E, 86°N	67	Olivine diabase	1.273	0.01754	0.01129	184 ± 8
10	43°51′07″	70°22′59″	N15°E, 87°SE	41	Olivine diabase	0.893	0.01346	0.01235	200 ± 9
11	43°54′07″	70°42′34″	N82°E, 81°N	22	Augite camptonite	1.725	0.02029	0.00964	158 ± 6
12	43°22′08″	70°33′25″	N78°W, 88°N	291	Augite camptonite	0.815	0.00744	0.00748	124 ± 6
13	43°48′45″	69°56′36″	NE	N.A.	Diabase	N.A.	N.A.	N.A.	191 ± 10

Note: Dates for samples 3 and 5 through 12 were determined by Geochron Laboratories, Cambridge, Massachusetts. Dates compiled from the literature are for sample 1, Wanless and others (1973); 2, Zartman and others (1967); 4, Zen (1972); 13, Weston Geophysical Research (1977). Ages are whole-rock except where otherwise noted. Sample numbers refer to Figure 1. Constants: $K^{40}/K = 0.0119$ atom %; $\lambda_\beta = 4.72 \times 10^{-10}$/yr; $\lambda_e = 0.585 \times 10^{-10}$/yr. N.A. = not available.

Fowler, 1950). A few diabase dikes in this area have been described by Bascom (in Dale, 1899), but most are camptonite or more rarely spessartite or monchiquite. The Taconic lobe contains the Cuttingsville alkalic complex (Eggleston, 1918; Laurent and Pierson, 1973) and possibly the Mt. Ascutney alkalic complex to the east (Daly, 1903), both Lower Cretaceous according to Foland and Faul (1977).

Literature reports of dikes in southern Vermont and western Massachusetts are rare, but the northeast-trending dikes of the Appalachian diabase swarms in southern New England (de Boer, 1967; Armstrong and Besançon, 1970) appear to be continuous into southern New Hampshire (Sririmadas, 1966; Greene, 1970). Mafic dikes in Maine are abundant in the west and south, as mentioned above, but Espenshade and Boudette (1964) and Boucot and others (1959) reported only a few lamprophyre dikes in north-central and northwestern Maine, respectively. Dikes are also rare in road cuts along the I-95 highway between Augusta and Bangor, Maine. The eastern boundary, if any, of the dikes of this study area cannot be fixed until more field data are available.

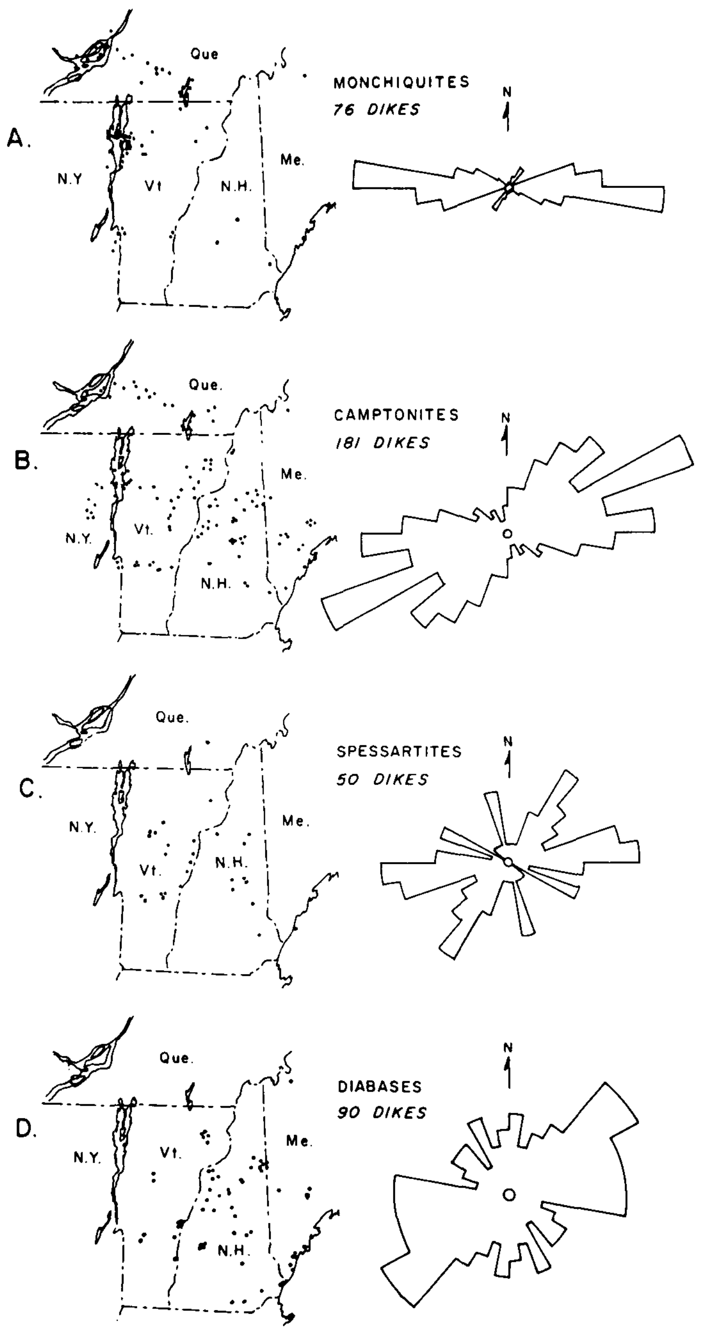

Figure 2. Location maps and rose diagrams for the four main dike types of central New England (excluding Monteregian dikes). Only localities for which detailed data exist are shown, and some dots may represent more than one dike.

Locations and orientation diagrams for each of the four main dike types are shown in Figure 2. Only those dikes sampled for this study or described in detail in the literature are shown (as dots); some dots represent more than one dike. Monchiquite dikes (Fig. 2, A) are mainly confined to the three western lobes, having their greatest proportion in the Champlain area (more than 60% of the mafic dikes present). Only a few monchiquite dikes are scattered across the rest of the study area, whereas camptonite dikes (Fig. 2, B) are abundant all through it. Similarly, Hodgson (1968) noted that monchiquite in the Monteregian area becomes less frequent relative to camptonite eastward from Mount Royal. Although camptonite is gradational in chemistry and petrography with monchiquite (Rock, 1977), this distribution suggests either independent modes of origin or else some obscure magmatic or tectonic restriction on an alkalic lamprophyre magma series. Diabase dikes (Fig. 2, D) are rare within the lobes, but the literature cites them as the most common dike type in New Hampshire and Maine. Spessartite dikes, inclding kersantite and "minette" are also uncommon in western Vermont (Fig. 2, C) but are more frequently mentioned in New Hampshire. Many such localities were too poorly documented to be included in Figure 2, C.

The Monteregian and to a lesser extent the Champlain and Taconic lobes demonstrate a spatial overlap of alkalic plutonic complexes and lamprophyre dikes (Fig. 1). This general relationship is also true for the White Mountain magma series in New Hampshire and Maine, suggesting that abundant lamprophyres in parts of the study area distant from exposed plutons may indicate the presence of such bodies below the surface. In reference to this relationship, Rock (1977) suggested that lamprophyres of regional dike swarms are richer in hydrous mafic minerals (amphibole and biotite) near alkalic plutonic complexes. Such minerals are rather variable in abundance throughout this study area. More detailed geophysical surveys could test the presence of any buried mafic plutons. In general, however, mafic dikes are not most abundant in the *immediate* vicinities of most of the exposed plutonic complexes. Conclusions from local studies implying such a relationship are usually the result of the extra care spent in mapping the complex compared with surrounding areas. In addition, most (if not all) of the complexes are crosscut by the mafic dikes, in contrast to the usual mafic-to-felsic sequence of plutonic magmatism for the area. Furthermore, the mafic dikes are oriented perhaps more randomly but not radially in the vicinities of the complexes. The dikes are therefore not direct offshoots of the plutons, as has been suggested by Daly (1903), Wolff (1929), and others. The genetic tie inferred from the regional distribution must lie at a much greater depth than the present surface.

ORIENTATIONS

Rose diagrams of the dike types presented in Figure 2 exclude Monteregian examples because of lack of specific data. The trends were plotted by hand in 10° intervals, with measurements falling on boundaries included within the more east-west interval as a matter of convention. The monchiquite dikes (Fig. 2, A) are mainly represented by Champlain dikes and show nearly east-west trends. Most Champlain camptonite dikes also have east-west trends, but elsewhere in New England are both east-west and more northeast in direction (Fig. 2, B). There is a suggestion of three slightly different east to northeast trends in Figure 2, B, but these could not be related to specific regions of occurrence. The spessartite diagram (Fig. 2, C) is based upon a statistically poor population, but its northeast and east-northeast maxima are somewhat similar to both camptonite and diabase. The diabase dikes (Fig. 2, D) show mainly northeast trends, which are broadly variable to east-west. If most of the New England dikes that are loosely described as "basalt" were included in this diagram, a much stronger northeast maxima would result. This trend is essentially the same as that of the Upper Triassic–Lower Jurassic diabase dikes of southern New England as plotted by de Boer (1967).

Rose diagrams constructed for regional subdivisions (Fig. 3) contain a much larger number (1,023) of dikes than does Figure 2 because many unclassified samples have been included. The Monteregian diagram (Fig. 3, A) is after Hodgson (1968, p. 8), who plotted only regional dikes not intimately associated with the plutonic complexes. The broad west-northwest maximum roughly parallels the trend of the Monteregian Hills and is nearly perpendicular to the Green Mountain–Sutton Mountain anticlinorium in northern Vermont and Quebec. This trend has its easternmost extent in northeastern Vermont (Woodland, 1962) and is rare among post-Paleozoic dikes in the rest of New England. It is significant that dikes near Mt. Megantic (F, Fig. 1) have more northeast than west-northwest trends, although this area is considered part of the Monteregian Hills petrographic province (Gold, 1967).

Dikes of the Champlain lobe (Fig. 3, B) consist mainly of alkalic lamprophyres that maintain a strong east-west trend, only a minor shift from the Monteregian maximum. Dikes of the Taconic lobe (Fig. 3, C) display a major northeast set and only small east-west and northwest tendencies. Dikes in the rest of Vermont (Fig. 3, D)

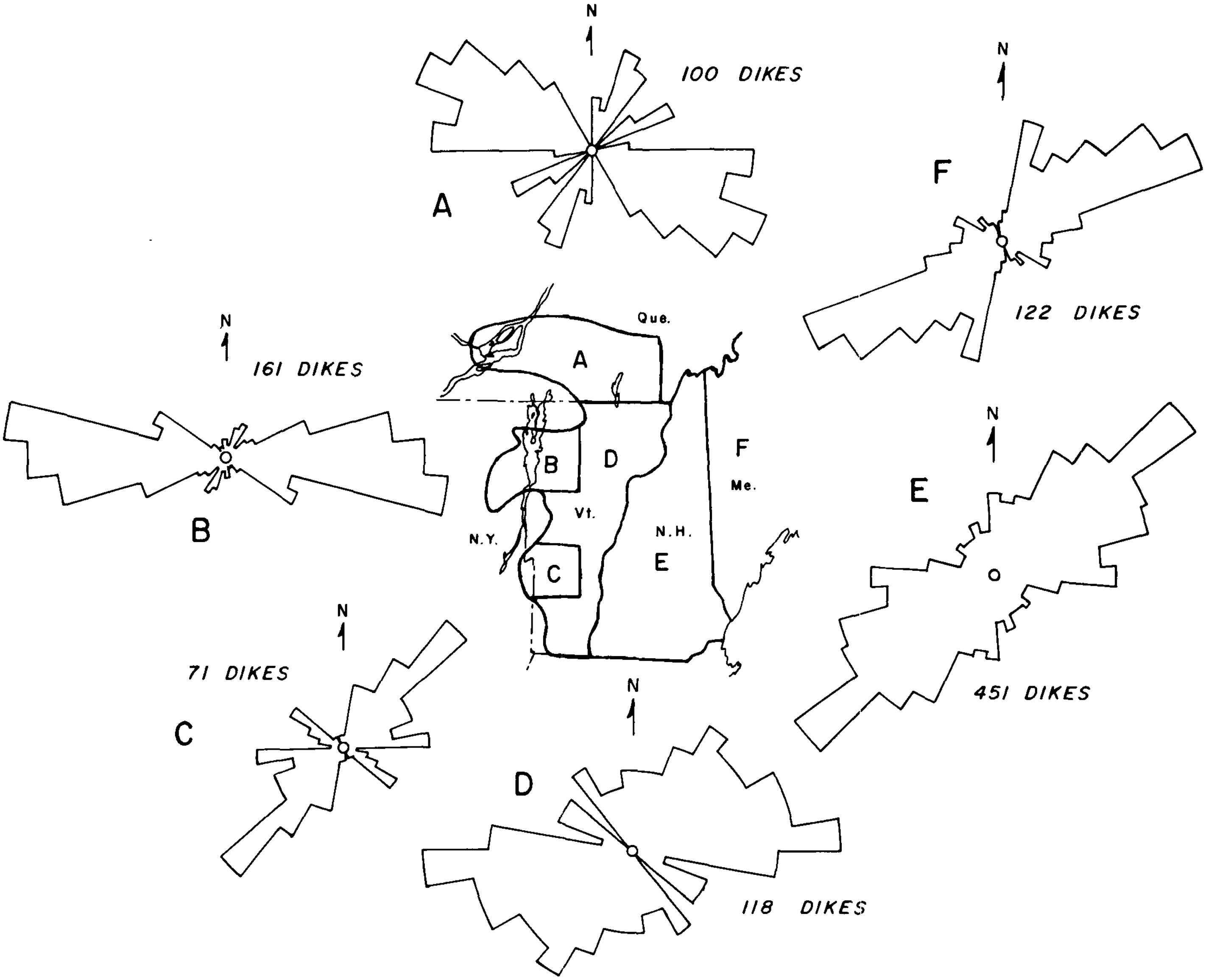

Figure 3. Rose diagrams showing dike orientations by region: A, Monteregian lobe; B, Champlain lobe; C, Taconics lobe; D, Vermont outside of B and C; E, New Hampshire; and F, western Maine. Diagram A is from Hodgson (1968); about half of data in diagram B are from Corneille (1975).

show a combination of northeast and east-west trends, with no regional dividing line. The western limit for diabase dikes (Fig. 1) thus forms a western boundary for most northeast-trending dikes, but it is not also an eastern boundary for the east-trending dikes. The northeast trend becomes much more pronounced in New Hampshire (Fig. 3, E), although nearly half of the measurements are for dikes in the Mt. Washington (Fowler-Billings, 1944) and Gorham (Billings and Fowler-Billings, 1975) quadrangles. Likewise, about half of the measurements for western Maine dikes (Fig. 3, F) are for the Bryant Pond quadrangle (Guidotti, 1965), but the northeast trend clearly predominates, while east-trending dikes are rare.

AGES

Thirteen K-Ar whole-rock and mineral ages are available for mafic dikes within the study area (Table 3), 10 of which were recently determined by Geochron Laboratories, Inc. Their locations are shown in Figure 1. Samples 3 and 5 through 12 were collected by me and were examined in thin section for any weathering and deuteric effects. Olivine in samples 8, 9, 10, 11, and 12 is partly converted to talc and serpentine, but coexisting clinopyroxene and/or amphibole in each of these rocks remains fresh. Samples 6 and 11 contain small zones of very fine-grained, dark matrix material which may represent devitrified glass. The plagioclase in sample 12 is somewhat cloudy, which may indicate incipient sericitization or some deuteric alteration. Dike samples 8, 11, and possibly 12 were observed to crosscut diabase dikes in the same outcrops. Samples 3 and 5 contain analcime and minor calcite in the groundmass, but these are considered to be magmatic in origin, and the rock is fresh.

The fact that most of the samples were rapidly cooled less than 200 m.y. ago and are fine-grained, nearly holocrystalline rocks with considerable K contents should enhance the reliability of their age determination (Mankinen and Dalrymple, 1972). Nevertheless, argon loss or even gain (Dalrymple and others, 1975) is not uncommon in basalts, and the ages should initially be considered as only approximate, not absolute. Although the values agree with crosscutting relations between dikes and plutons and between dikes themselves, consistent ages shown by several dikes are certainly more valid than individual age determinations.

Most of the plutonic complexes have been dated (Foland and Faul, 1977). Although K-Ar dates for plutonic rocks represent minimum or cooling ages, they approximate maximum ages for dikes crossing them. Lamprophyre and some diabase (?) dikes cut Lower Cretaceous rocks of the Cape Neddick (Haff, 1939), Pawtuckaway (Roy and Freedman, 1944), Ascutney (Daly, 1903), and Cuttingsville (Eggleston, 1918) complexes in Maine, New Hampshire, and Vermont, as well as older plutons in New Hampshire and Maine. The Lower Cretaceous Monteregian Hills in Quebec are likewise crosscut (Hodgson, 1968).

Sample 7 of Table 3 was originally classified as an abnormally silicic, coarse-grained biotite spessartite, but the Silurian age obtained indicates consanguinuity with a Paleozoic magma series. The most likely source is the Remick tonalite exposed about 1 km north of the dike, which is mineralogically similar, although Billings (1935) assigned this pluton to the Devonian or Carboniferous periods. If accurate, this determination also places an upper age limit on the Ammonoosuc volcanics, which the dike intrudes.

Assuming reasonable accuracy for the isotopic ages, dikes of the study area (excluding sample 7 of Table 3) span Late Triassic through Early Cretaceous time (using the time table compiled by Van Eysinga, 1975) and overlap the two main magmatic peaks of Mesozoic plutons as plotted by Foland and Faul (1977), shown in Figure 4. By analogy with these age groups, however, the dikes can be divided into 96 to 136 m.y. (Early Cretaceous) and 180 to 200 m.y. (Early Jurassic) time intervals, except for sample 11 of Table 3. Except for that sample, the striking result of the age data is the

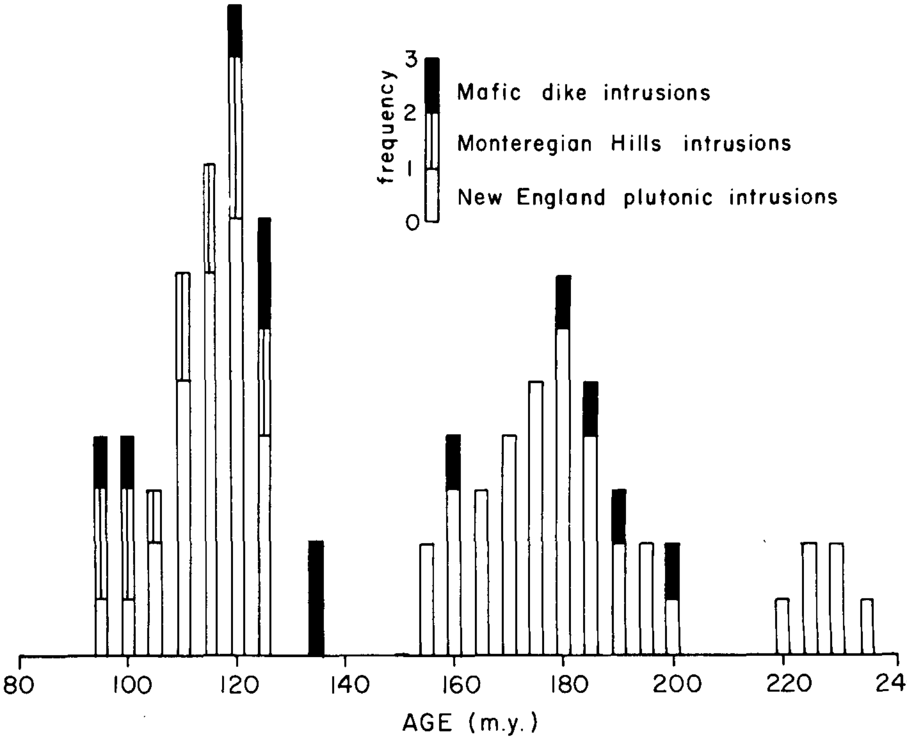

Figure 4. Foland and Faul's (1977) histogram of ages determined for Mesozoic plutons of study area, modified by addition of dike ages. Dates have been rounded off to 5-m.y. time intervals.

separation of the diabase and lamprophyres into the older and younger groups, respectively. The 158-m.y.-old camptonite (sample 11) is, however, observed to crosscut an olivine diabase dike within the same outcrop. Because of the small number of determinations and the uncertainties inherent in the K-Ar age interpretations, further subdivision of dike generations must be inferred from other considerations as well.

DISCUSSION

Dike orientations should be controlled both by the stresses existing within the lithosphere (or at least the upper crust) at the time of intrusion and by the orientations of pre-existing fracture sets in the region. Fracture sets (joints) are generally abundant throughout New England, so dike magmas should select these earlier or nearly coeval regional fractures rather than form new ones.

Since true tension is probably nonexistent below a few kilometres depth (Brace, 1964), the magma's pressure must overcome some minimum compressive stress (σ_3) and so intrude what effectively become extensional fractures. This magmatic pressure need not be much higher than the lithostatic pressure, according to Murrell (1970, p. 240). During nonorogenic times, such as the Mesozoic in New England, the maximum compressive stress (σ_1) may be vertical very deep within the crust but is close to horizontal at least within the upper crust, as shown today by in situ stress measurements (Sbar and Sykes, 1973) and hydrofracturing at depths of as much as 5 km in Michigan (Haimson, 1976). Since dikes will follow that fracture set most nearly perpendicular to σ_3 (Anderson, 1951, p. 25), under ideal conditions a vertical dike swarm trending in one direction will define the state of stress with σ_1 and σ_3 both horizontal and, respectively, parallel and perpendicular to the trend maximum, and σ_2 (the intermediate stress) vertical. If no fractures exist perpendicular to σ_3, the magma may follow one or more sets at high angles to σ_3, perhaps alternating in steps or en echelon (Roberts and Sanderson, 1971). Such fractures should show some shear motion rather than simple dilation upon opening, which is not apparent in the study area. A limited availability of suitable fractures for dike intrusion could explain some of the scatter in the diagrams of Figures 2 and 3.

On the basis of these arguments, a tentative stress model during the sequence of dike intrusions in New England can be constructed. The related extensional directions (representing the orientations of σ_3) are summarized in Figure 5. Diabase dikes of Late Triassic to Early Jurassic age show trends varying from northwest to north to northeast from Georgia to Nova Scotia (King, 1961; Fig. 5, D). In central New England, diabase dikes show essentially similar ages and orientations (Table 3; Fig. 2, D); therefore many or most probably belong to this tholeiitic series. Of related interest, lower Paleozoic(?) diabase dikes at Cape Ann, Massachusetts (Fig. 1; Shaler, 1889; Zartman and others, 1970; Dennen, 1976), show a strong north-northwest trend maximum that is not found elsewhere in the study area. These older, uniquely oriented dikes may suggest some lack of physical continuity with the rest of New England at the time of their intrusion.

Many of the trend data for camptonite dikes in the eastern study area are similar to those for the diabase dikes. Two dated lamprophyre dikes have northeast trends (samples 3 and 4, Table 2) but occur within the western lobes and appear petrographically similar to more east-trending lamprophyres at or near the same localities. In contrast, many of the northeast-trending camptonite dikes of the eastern study area are more olivine-rich, like samples 9 and 10 (Table 2), although none of them are dated. This is especially evident at the sample 9 locality (Lewiston, Maine, city quarry) where northeast-trending camptonite and olivine diabase dikes occur together in a single, gradational series. Geochemical data (Merrill, 1892; my unpub. data) support their classification as alkali olivine basalts, distinctly different from the tholeiitic basalts of the southern New England diabase dikes (Weigand and Ragland, 1970). By petrology, then, the northeast-trending camptonite dikes are part of a Lower Jurassic olivine diabase group. This is within the same age span (160 to 220 m.y.) as the older White Mountain plutons (Fig. 4) as well as the tholeiitic diabase dikes in central New England. The age data are not precise enough to determine whether these magma series were contemporaneous within the eastern study area, or if they were in temporally discrete magmatic episodes. A similar northwest-southeast extensional stress existed for all these Lower Jurassic dikes.

Most lamprophyre dikes of the Taconic lobe also have a northeast trend (Fig. 3, C) and, despite the single young date (105 m.y., Table 3) for a dike in this area, may for the most part be within the older age group. If most of these dikes were Lower Cretaceous, then their radical trend difference with dikes of similar age in the Champlain and Monteregian areas connotes a boundary between stress regimes that is not seen in central Vermont. Spessartite dikes of New England (Fig. 2, C) have variable trends and so may be partly of this age and also younger.

The east to west-northwest trends of the younger lamprophyre dikes in the Champlain and Monteregian areas (Fig. 2, A and B), as well as some dikes in the rest of New England (samples 5, 8, and 10, Table 3), indicate a clockwise rotation or change-over of extension to a more north-south direction by the end of Jurassic time. If the younger dikes of the study area are subdivided into 136 to 125 and 124 to 96 m.y. age groups, extensional directions may have rotated from north-south in the earlier subdivision, as shown in the Champlain region (Fig. 5, B) to north-northeast–south-southwest in the Monteregian area and possibly elsewhere (Fig. 5, A) in the later subdivision.

The extension inferred from Monteregian dikes may also be a factor aiding intrusion of the Monteregian plutonic complexes along a west-northwest–trending fracture zone (Gold, 1967; Hodgson, 1968; Philpotts, 1970). The same cannot be shown in New England, particularly since plutons of the White Mountain magma series are aligned roughly north-northwest, a direction not common for dikes, and were intruded in two time periods with apparently different paleostress regimes. Perhaps these plutons were controlled by the intersections of younger extensional fractures and an older fracture zone, mechanisms proposed by Chapman (1968) for New Hampshire plutons and by Philpotts (1970) for Monteregian stocks.

If this mechanism is realistic, the north-northwest trend of the New Hampshire plutons may represent a major linear weakness, perhaps an active "hot line" or linear mantle upwelling such as proposed by Bonatti and Harrison (1976), or a continental expression of the Kelvin fracture zone in the North Atlantic (Le Pichon and Fox, 1971). A continental-oceanic fracture zone association has been used by Marsh (1973) as a mechanism for plutonic intrusions in South America and Africa. Activation of the Kelvin–New England fracture zone in Early Jurassic time could have produced the huge volumes of mildly alkalic felsic rocks of the older White Mountain plutons. Perhaps these earlier intrusions were localized by northeast-trending fractures, which also filled with diabasic and camptonitic magmas in Early Jurassic time. Although extension for

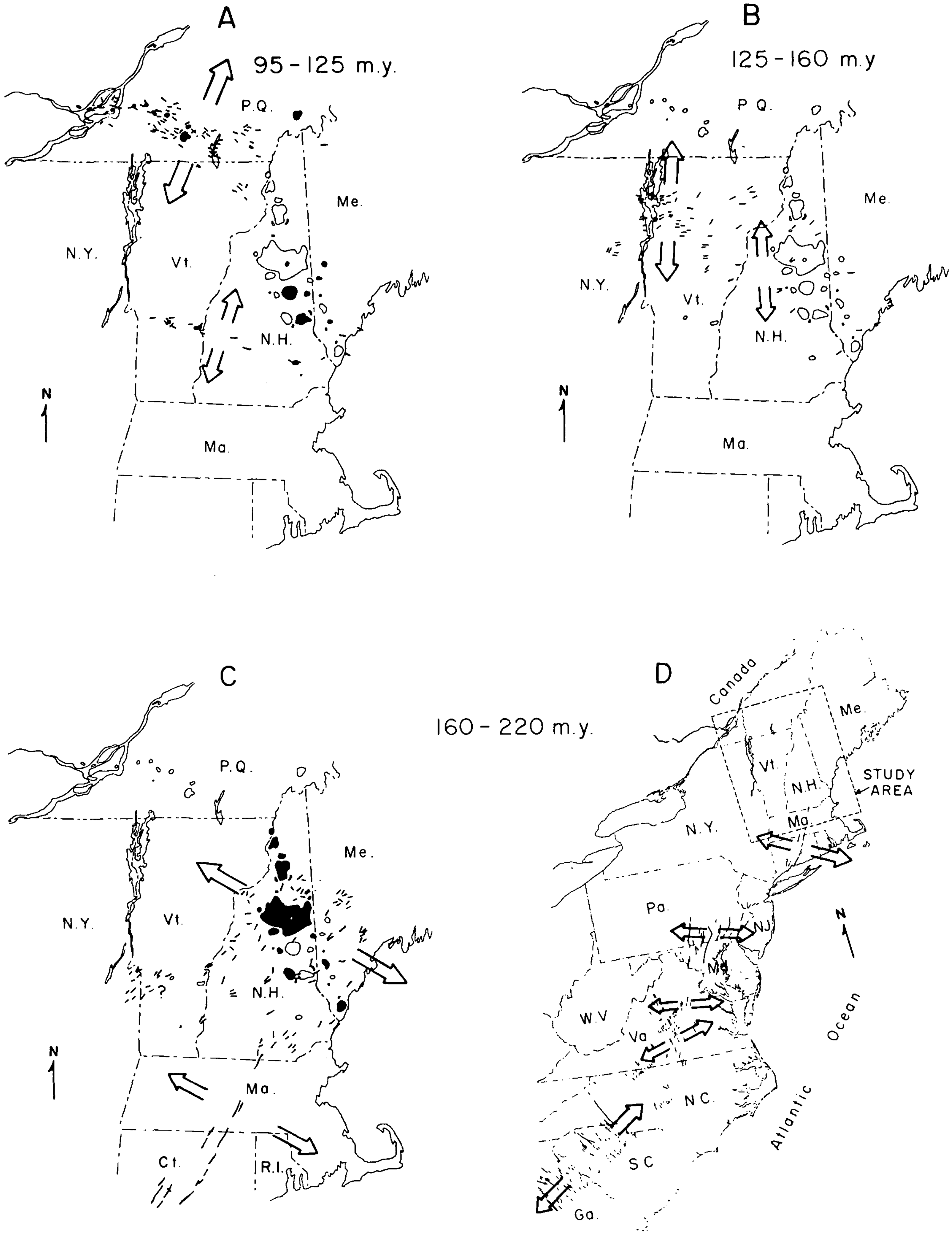

Figure 5. Proposed directions of extensional stresses as inferred from Mesozoic dike trends in central New England (A, B, and C) and by Applachian diabase dikes (D). Solid areas represent plutonic intrusions within the stress-age divisions.

the northeast dikes fits well with tensile patterns associated with the opening of the Atlantic Ocean (de Boer, 1967; May, 1971), it does not relate closely to possible stresses responsible for faulting along the Triassic grabens (King, 1961).

The intersecting east-west lattice lines of Chapman's (1968) model could represent fracture zones active throughout central New England and nearby Quebec in Early Cretaceous time. These zones localized plutonic intrusions along the older north-northwest–trending White Mountain zone as well as orienting other plutons and dikes to form the Monteregian and Champlain lobes. The Taconic lobe has elements of both the earlier and later tectonic-magmatic activity. As with the Triassic grabens, possible activation of the St. Lawrence–Champlain graben system during Mesozoic time (Kumarapeli and Saull, 1966) may not express stresses associated with the dike emplacement.

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