Developments in Geotectonics 22

TRIASSIC-JURASSIC RIFTING

Continental Breakup and the Origin of the Atlantic Ocean and Passive Margins

Part B

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W. MANSPEIZER

Department of Geological Sciences, Faculty of Arts and Sciences,
Rutgers University, Newark, NJ 07102, U.S.A.

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Tectonic and paleostress patterns of Mesozoic intrusions in eastern North America

J. GREGORY McHONE

ABSTRACT

Linear trends are evident within Mesozoic dike swarms and plutonic provinces of eastern North America. Regional dike trends can be used to model paleostress patterns for which minimum compression influences the direction of planar intrusion. Early Jurassic dikes and sills are found along the entire eastern side of the Appalachian orogen, with dike patterns that vary in orientation from NW – SE to N – S to NE – SW from south to north. Cretaceous and younger igneous provinces are more local in extent but cross the orogen, with dike trends that vary by region even within the same province. The Early Jurassic tholeiitic dikes indicate southwesterly to westerly extension in the southern Appalachians during or close to the same time as northwesterly extension in the northern Appalachians. North – south to north-northeast extension occurred in the western to central Appalachians of western New England and nearby Quebec during Early Cretaceous alkalic magmatism, but Cretaceous and younger intrusions in eastern New England and the eastern Appalachians show northwest extension.

Plate stresses and movement as driven by mantle convection are mechanisms for extension of the lithosphere perpendicular to dike trends of several directions. Early Jurassic dike trends align with segments of the final rifted continental borders, and both features may be related to activation of similar high-angle lithospheric structures. An Early Cretaceous shift in plate stresses extended the crust in new orientations, allowing alkalic magmas to upwell from deeper sources and different trends, while rift strains produced the Atlantic basins north of Newfoundland and south of Florida. Mesozoic faults and sedimentary basins of the new ocean margin show orientations that are closely controlled by shallow crustal anisotropies, perhaps activated by events separate from dike intrusions.

Introduction

Magmas moving from mantle or deep-crustal sources to the upper crust and surface are frozen and later exhumed as dikes and chains of plutons, recording fluid paths of least resistance. During these events large numbers of fracture planes, either new or old, actively expand in accord with minimum or extensional stresses as they are filled by dolerite (diabase) and lamprophyre dikes. Linear trends of igneous rocks, especially dike swarms, are thus a strain record that can be used in studies of tectonic controls and paleostresses active at the time of intrusion. Many new radiometric dates and maps of Mesozoic dikes in eastern North America are now available for this work.

This paper is concerned with Mesozoic stress/strain patterns indicated by the geometry of tabular intrusions in eastern North America. A brief discussion of the rationale for assigning stress directions from dike trends is given, followed by possible relationships with observed fractures. The next section describes the Mesozoic dike provinces of the Appalachian region. The paper ends with a model of extensional stress patterns as derived from the dike patterns, and points out major tectonic correlations with the model.

Many problems exist for such modeling. Because most of our observation of dikes, plutons, and high-angle fractures in eastern North America is superficial or near-surface, we only conjecture about their characteristics at deeper levels of the lithosphere. Different structural controls for the emplacement of magmas must exist between the continental and oceanic lithospheres but have received little consideration, even in studies of igneous provinces that appear to cross such crustal boundaries as in the western Atlantic basin. The mantle and plate events that are the ultimate cause of the magmatism and crustal strains are even more conjectural. There is a concern that stress patterns derived from surface features cannot be well correlated with patterns at deeper levels. It seems certain that new or alternate interpretations will come through continued work on the structures and petrology of regional igneous rocks.

Dikes and stress in the lithosphere

It is generally agreed that magmas collect from small portions of partially melted rocks in the upper mantle (for basalts) or lower crust (for many granitoids). Density differences of 0.1 to 0.3 g cm^{-3} or greater should exist between the melt and overlying rock column, allowing a magma conduit to rise (as in a volcano) up to 3 to 5 km above the surface before hydrostatic equilibrium is achieved (Holmes, 1945, p. 478). Within 2 or 3 km of the surface, magmas with a few weight percent water and carbon dioxide also expand by boiling, as shown by abundant amygdules in dikes, and vugs or volatile-rich openings in upper portions of plutons. This expansion may be violent, brecciating the wall rocks and causing explosive volcanism. Calculations and observation show that the liquid pressure of magmas is quite capable of causing cracks to propagate at least through brittle regimes of the crust.

The relatively low viscosity of basaltic melts, especially because of higher pressures (Kushiro, 1980) and volatile contents (Scarfe, 1973) that may be expected before eruption, promotes their fluid behavior and characteristic form as dikes, commonly with length to width ratios exceeding 1000. A reasonable estimate of the time needed for mafic dike magmas to rise approximately 60 km is between 10^1 and 10^3 hours. In contrast, the diapiric rise of larger chambers of felsic magmas may exhibit velocities more in accordance with Stoke's Law, where the viscosity of the wall rocks themselves are taken into account as plastic solids that deform to admit the rising diapir. Much slower rates of perhaps 3 or 4 cm/year estimated for plutons result in time scales of $10^5 - 10^7$ years for a rise through 20 km of relatively homogeneous crust. A model in which linear chains of plutons intrude by diapiric rise along a zone of fractures may call upon rates of emplacement somewhat faster than 10^5 years, but still much slower than the 10^{-2}-year rate of mafic dikes (Marsh, 1982). Significant changes in stress patterns during magmatic events may produce different geometries for large plutons than are shown by contemporaneous dike swarms.

The response of an expanding liquid-filled crack under confining stress is to propagate in the plane of maximum and intermediate compression, as modified by anisotropies in the rock material (Anderson, 1951). This may result in horizontal sills and widening breccia cones near the surface, where minimum pressure is encountered vertically, but at depth the lithostatic pressure should normally produce more uniform compression. Major plate movements, extensional faults and rifts, and shifts in plate directions are here assumed to be caused by or even to mimic horizontal flow of the sublithospheric mantle as it drags on the base of the plate. Stresses related to translation of tectonic plates will produce some general direction of least compression (σ_3), promoting dilation and infilling of cracks by dike magmas along with propagation of the fracture perpendicular to σ_3 (Fig. 25-1). Only minimum (σ_3) rather than maximum (σ_1) or intermediate (σ_2) compression directions are well shown by dike trends in this model.

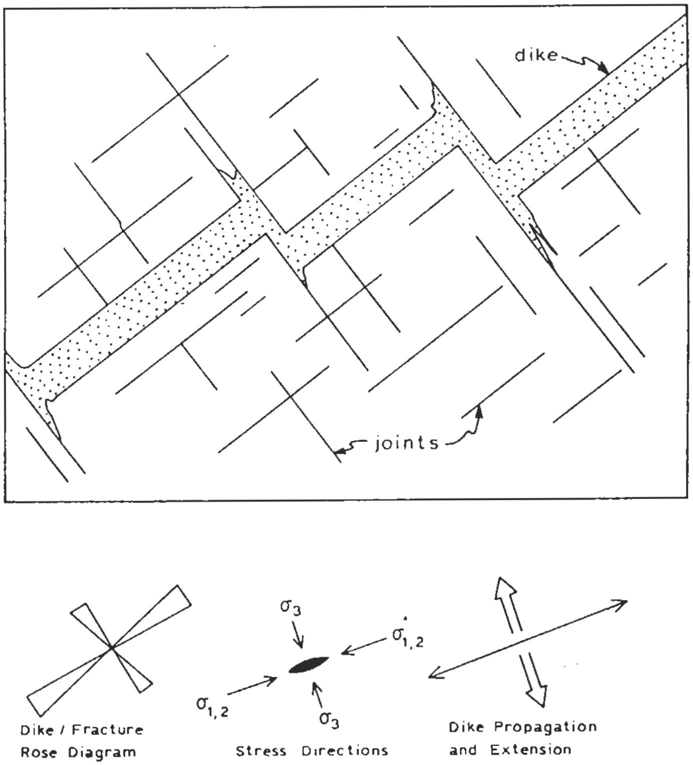

Fig. 25-1. Possible relation between a dike and joint pattern that follows an older anisotropy. Note that the rose diagram plotted for the intrusion segments is skewed from the true stress pattern, but that overall, the dike propagation is perpendicular to regional extension.

Extensional paleostress patterns from dike trends have been used in regional studies of magmatism and tectonics by many geologists, including Ode' (1957), Aucott (1970), May (1971), Jackson and Shaw (1975), Pollard and Muller (1976), Hill (1977), Nakamura (1977), McHone (1978), Isachsen (1985), and Pollard (1985). Simple dilation normal to the dike walls can be expected from the stress effect, and is the usual observation for dike-wall matchups (Currie and Ferguson, 1970; McHone, 1978). More-complex patterns arise where additional local stresses exist, especially near major anisotropies such as the Earth's surface, active faults, and other magma bodies.

Paleostresses and regional fractures

The present map geometry of sedimentary basins formed during rifting may not reflect the underlying or mantle stress directions, because crustal planar fabrics or fold boundaries have exerted a strong influence on the positions of border faults of the grabens. From detailed study of faults and fold structures, Goldstein (1975) concluded that the generally N – S Connecticut basin in southern New England formed by NW – SE extension along a N – S structural weakness. Wise (1982) has attributed local control of N – S border faulting in the Connecticut basin to the western flank of the Bronson Hill Anticlinorium, which superposes a 'core zone' of more NE – SW fracturing in southern New England. Similarly, Lindholm

(1978) found that border faults of many other Mesozoic basins also developed essentially along pre-Triassic bedrock foliations.

A common feature of Appalachian dikes is their alignment with one or more of the many joint sets that presumably formed in the upper, brittle crust during or before the Mesozoic activity. The joints are an obvious vertical anisotropy that can affect intrusions, and may locally cause dikes to vary from directions perfectly normal to extension. A possible configuration of joints that extend with dike infilling is shown in Figure 25-1, and also in a more detailed discussion by Roberts and Sanderson (1971). Individual segments of the dike show orientations in an échelon pattern, so that actual propagation perpendicular to least compression deviates from the segment trends. In some cases, the en échelon dike segments are detached, either by vertical flow into separate fractures or because the connecting segments have closed horizontally. Such deviation by anisotropy explains much of the 'scatter' in dike trends within small areas, as well as minor maxima in orientation plots. Only the main statistical trends within and between dike domains are likely to reflect general directions of the principle stresses.

Joints by themselves are problematic tools for stress interpretations. Fractures that are created under compressive stress and as satellites of brittle shear faults are important clues to local strain histories, but wide-ranging joints sets can have other causes. As discussed by Price (1966, pp. 127 – 130), most joint sets are shallow features that vary with rock type, rock unit size, rock anisotropies, topography, uplift rates, and probably other factors in addition to tectonic stresses. Finally, some linear zones of joints may form in response to deeper, more-ductile strains of limited duration.

The last class of surface fractures discussed above can be related to deep-level stress patterns. There are many topographic lineaments recognized as zones of intense fracturing (not necessarily faulting), along which erosion has created drainage linears and other valley patterns. Lineament domains of Italy have been studied by Wise et al. (1985) in relation to other structural features, and they conclude that most lineament 'swarms' are fracture zones developed above and parallel to linear ductile zones in the deeper lithosphere. Models for the origins of lineaments generally show development normal to directions of least compression (Anderson, 1951; Nur, 1982; Wise et al., 1985). Except for work by Wise (1982) in southern New England, little has been done to relate eastern North American lineament swarms to Mesozoic tectonic and igneous events.

Magmatic trends in regional igneous provinces

Mesozoic intrusions form distinct provinces along the Appalachian orogen of eastern North America, as shown generally by Figure 25-2. The outlines of the provinces are mainly determined by dike locations, although much detailed mapping is still needed for each area. As discussed by McHone (1978) and Ragland et al. (1983), dike densities vary within the provinces, and associated plutons appear to have independent intrusional histories. McHone and Butler (1984) suggested that camptonite dikes may represent magmas that were parental to associated alkalic plutons in New England and elsewhere. More-felsic dikes, such as the bostonite and trachyte dikes of the Lake Champlain Valley of Vermont (McHone and Corneille, 1980), do appear to form semiradial patterns around syenitic stocks, and may tap such plutons in the manner of dikes around the Spanish Peaks of Colorado (Ode', 1957). A radiating pattern for lamprophyre dikes has been suggested for some plutonic complexes of southern Quebec (Hodgson, 1968) and Newfoundland (Strong and Harris, 1974). Mafic dikes in all areas of the Appalachians also display regional trends that cross-cut local Mesozoic plutons.

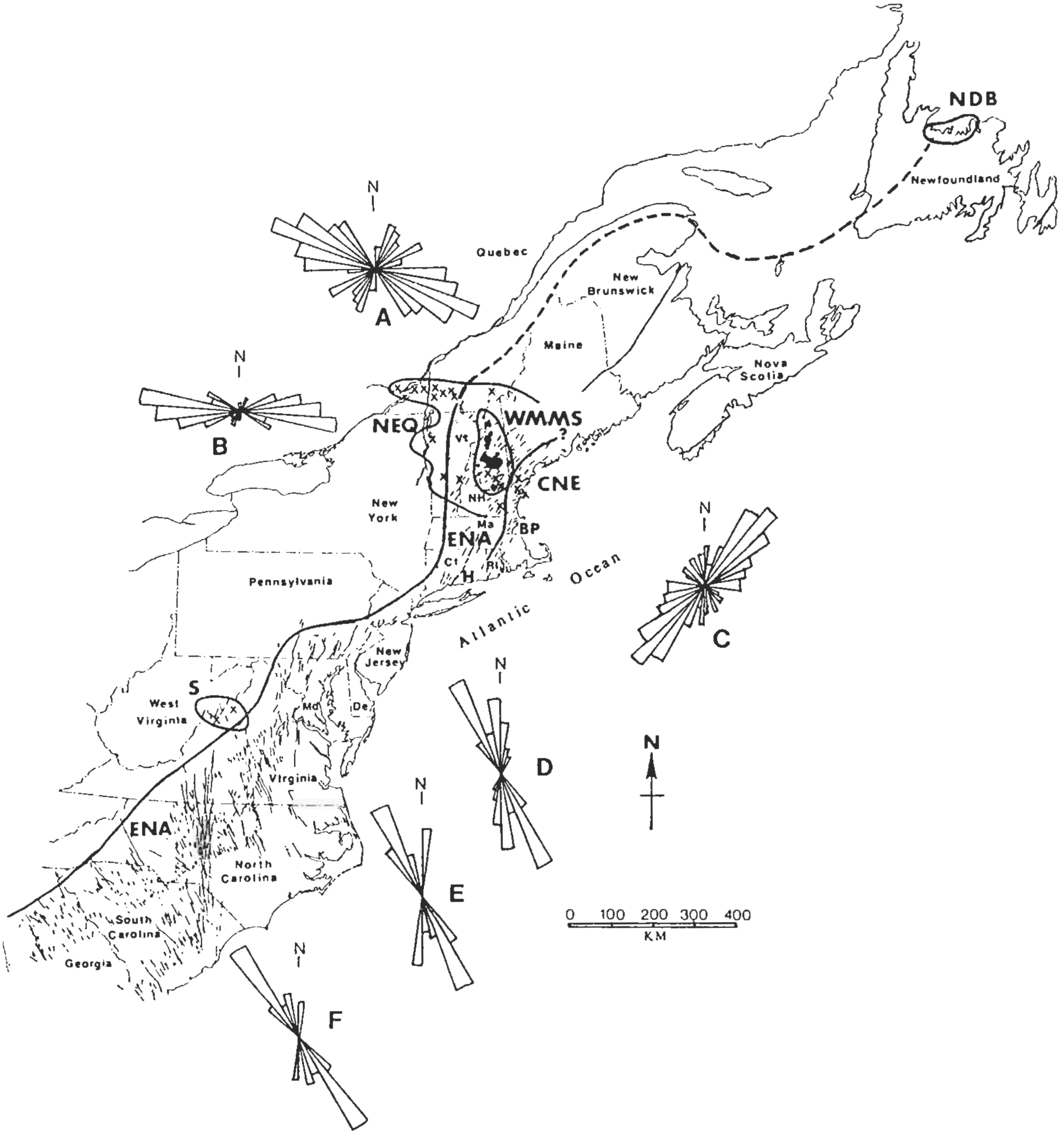

Fig. 25-2. Generalized map of Mesozoic igneous provinces of eastern North America. Provinces outlined with heavy lines: *NDB* = Notre Dame Bay; *NEQ* = New England-Quebec; *WMMS* = White Mountain Magma Series; *CNE* = Coastal New England; *ENA* = Eastern North America; *S* = Shenandoah. Lighter lines represent Early Jurassic dikes of the ENA province. Plutonic complexes are located as x's in the NEQ province and as solid areas in the WMMS province. Rose diagrams A – F are constructed from mafic dike trends as follows: A = 129 NEQ lamprophyre dikes of Quebec and northern Vermont; B = 155 NEQ lamprophyre dikes of western Vermont and adjacent New York; C = 239 ENA dolerite dikes of Atlantic Canada, New England, and New Jersey; D = 211 ENA dolerite dikes of Pennsylvania, Maryland, and Virginia; E = 184 ENA dolerite dikes of North Carolina; and F = 179 ENA dolerite dikes of South Carolina, Georgia, and Alabama.

Eastern North America dolerite province

King (1961, 1971) produced a compilation map for 'diabase' (dolerite) dikes found along the entire length of the eastern Appalachians, from Alabama to Newfoundland (Fig. 25-2). Weigand and Ragland (1970) provided the commonly used name of 'Eastern North America' or ENA dikes for members of this province. Most radiometric ages of dikes and associated basalts along the entire province fall between 185 and 195 Ma (Armstrong and Besancon, 1970; Burke et al., 1973; Deininger et al., 1975; Sutter and Smith, 1979; McHone, 1984), although scattered areas yield slightly younger ages near 175 Ma (Sutter and Smith, 1979). A common problem in these rocks is variable amounts of excess argon, producing spuriously – old dates (Dooley and Wampler, 1983).

Low-titanium olivine and quartz-normative tholeiite predominates among ENA dikes in the southern Appalachians, while high-titanium quartz-normative dolerite is found in the central and northern areas (Weigand and Ragland, 1970; Ragland and Whittington, 1983). Transitional to alkali-olivine dolerite types are common only in eastern New England, including Rhode Island (Hermes et al., 1984), and may be closer to 220 to 240 Ma in age (McHone, 1984). McHone and Butler (1984) group such dikes into a Triassic igneous province called 'Coastal New England' or CNE (Fig. 25-2). Petrological relationships that may exist between the CNE and ENA magmas have not been explored.

Also shown in Figure 25-2, many southern ENA dikes trend around N35°W from Alabama through South Carolina, and N25°W through North Carolina and Virginia. From eastern South Carolina to Virginia, a group of nearly N – S dikes appears to overlap the NW group, especially as shown by geophysical maps in areas covered by post-Jurassic sediments of the Coastal Plain (Ragland et al., 1983). Burt et al. (1978) provided the original details about the N – S pattern in central North Carolina, observing that the dikes appear to have intruded tensile fractures under the influence of deep-seated stresses.

From New Jersey northward to Newfoundland, ENA dikes trend generally between N30°E and N60°E. Relative abundances change as well, with fewer dikes in sections of the Carolinas, southern Virginia, the 'New York Promontory' between northern New Jersey and southwestern New England, northern Maine, and the Maritime provinces of Canada (Fig. 25-2). Trends and abundances of the dikes in the adjacent marine continental shelf are not well known. Where mapped, ENA dikes crosscut all regional structures and maintain the same trends for their entire lengths.

Shenandoah igneous province

More than 90 dikes and other small intrusions occur over an area approximately 50 km by 80 km in western Virginia and adjacent West Virginia (Fig. 25-2). The swarm crosses Shenandoah Mountain between the Blue Ridge and Valley and Ridge provinces of the Appalachians. Watson and Cline (1913) and Johnson et al. (1971) describe alkalic dikes of kaersutite camptonite, 'teschenite' (monchiquite?), nepheline syenite, and 'granitic felsite', as well as numerous intrusions of olivine dolerite and a few bodies of quartz gabbro. Several ultramafic dikes are also recognized within and nearby the province.

Most of the dated dikes in the western part of the Shenandoah province yield Rb-Sr and K-Ar ages around 46 Ma, or Late to Middle Eocene (Fullagar and Bottino, 1969; Ressetar and Martin, 1980), but a few of the mafic dikes in the area show Jurassic to Early Cretaceous ages (Zartman et al., 1967). Given the strong support of Eocene paleomagnetic poles

(Ressetar and Martin, 1980), the younger age is likely for many of the intrusions. It appears that some ENA dolerite dikes (Jurassic) penetrate the Blue Ridge just east of the province (Fig. 25-2).

On published maps of the Shenandoah province, dikes appear to trend mainly northwest, but Kettren (1970) reports that most dikes around Monterey in Highland County, Virginia trend N70°E to N80°E, parallel to a major joint set. Thus, NE – SW extension on the eastern side of the province in Jurassic time was replaced by NNW extension by Early Eocene, at least near the present Blue Ridge – Valley and Ridge border.

White Mountain magma series

Large Early Jurassic intrusions of central and northern New Hampshire, the White Mountain magma series (WMMS) of Billings (1956), form a roughly NNW-trending belt of large syenite-monzonite-alkali granite plutons when grouped according to McHone and Butler (1984), as shown in Figure 25-2. Chapman (1968) noted that a grid pattern of fractures could have controlled the pattern of intrusions, and several workers (e.g., Foland and Faul, 1977; Morgan, 1983) note that the province falls roughly along a great circle with younger intrusions of the western North Atlantic. McHone (1978, 1984) mapped NE-trending ENA dolerite dikes across the same region, although it appears that fewer dikes cross-cut the plutons than cut the surrounding rocks because the dikes are generally slightly older.

Few structures have been mapped that correlate with the pluton trend of the WMMS. As discussed by McHone and Butler (1984), some large crustal anomaly may be involved in the formation and emplacement of the WMMS, perhaps a basement suture or an especially thick crust. Massive plutons do not clearly respond to extensional stresses except in a more general way than dikes, often showing less alignment along rift zones. The northeast trend of Jurassic dikes among the WMMS plutons indicates this lack of correlation.

New England – Quebec igneous province

Early Cretaceous magmas of southern Quebec and northern New England produced the classic Monteregian Hills intrusions (Philpotts, 1974; Eby, 1984) in Canada as well as several complexes in Vermont, New Hampshire, and southern Maine (McHone and Butler, 1984; Bedard, 1985). Early Cretaceous lamprophyre dikes in the region form a continuous dike province among and crosscutting all of the coeval plutons, overlapping the older WMMS province as well as part of the ENA swarm (Fig. 25-2). McHone and Butler (1984) group all of the Early Cretaceous dikes and plutons under the new name New England – Quebec (NEQ) igneous province. Hodgson (1968), McHone (1978, 1984), McHone and Corneille (1980), and McHone and Trygstad (1982) mapped and described more than 1300 of the estimated 10,000 – 20,000 dikes of the overlapping provinces.

Dike trends vary across the NEQ province. As shown in Figures 25-2 and 25-3, the major trends are near N65°W in southern Quebec, almost E – W in west-central Vermont, and between N45°E and N60°E throughout southern Vermont and the rest of New England. Some overlap is seen in eastern Vermont (Fig. 25-3). Part of this pattern may be caused by age differences: Early Jurassic lamprophyres in New Hampshire and Maine are very similar to the NEQ dikes and many may be mismapped. However, new dates (McHone, 1984) show that northeastern trends apparently predominate among Cretaceous as well as Jurassic dikes in eastern New England.

Dike trends of the NEQ province correlate with some major topographic and geophysical lineaments (Fig. 25-3). The longest examples of the topographic lineaments are probably controlled by regional fracture zones caused by movement of deep, high-angle crustal breaks (Wise, 1982), perhaps related to unloading by uplift with erosion (Nur, 1982). Many other lineaments follow mapped faults, fold limbs, and rock unit boundaries (Shake and McHone,

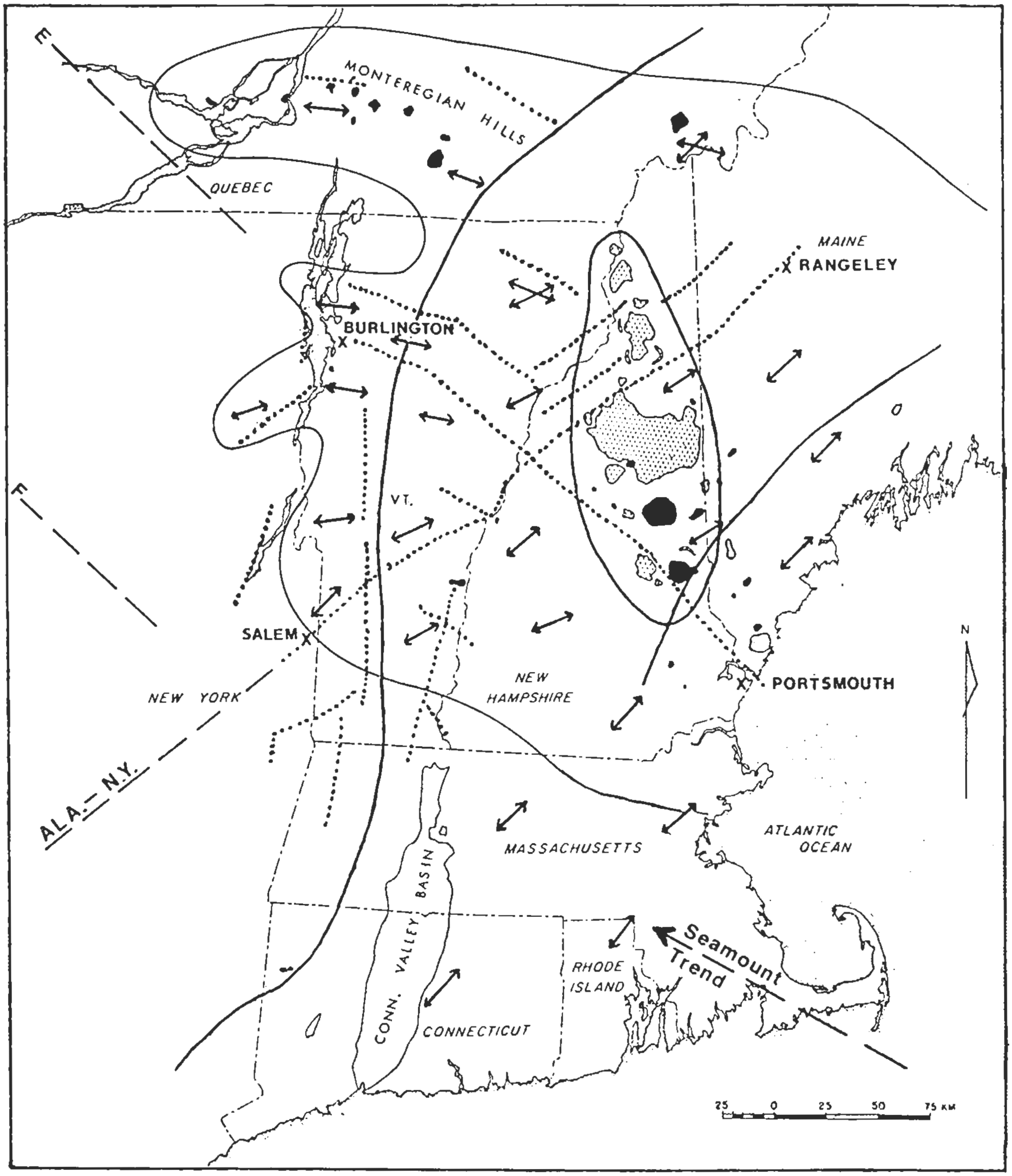

Fig. 25-3. Mesozoic igneous province boundaries (solid lines), generalized dike trends (double-ended arrows), and major geophysical and topographic lineaments (dotted lines) of New England and adjacent areas of New York and Quebec. Lines *E* and *F* are gravity-based lineaments described by Diment et al. (1980). Solid lines are igneous province boundaries from Fig. 25-2 and described by McHone and Butler (1984).

1986). West-northwest trends through the area are found for extensions of magnetic lineaments to the west (Diment et al., 1980) and for the New England seamount chain of the adjacent Atlantic basin (McHone and Butler, 1984). A major topographic line, the Burlington-Portsmouth lineament, crosses Vermont and New Hampshire in the same orientation (Fig. 25-3). Cretaceous dikes and plutons (the Monteregian Hills) trend about parallel to these cross-lineaments in the western and central Appalachians of northern Vermont and adjacent Quebec.

Northeasterly topographic, structural, and dike trends become more common nearby and southeast of the the Salem – Rangeley lineament, a topographic line that apparently extends from the New York – Alabama geophysical lineament of King and Zietz (1978). The Salem – Rangeley line marks a directional change of at least 70° for NEQ dikes, apparently marking a stress trend boundary for the Cretaceous intrusions despite no apparent control on the earlier Jurassic plutons and dikes. In the model developed by Roper (1980) and described in a later section, this border may be a zone where tensional drag from subcrustal mantle flow under the southeastern continental margin becomes the direction of compression to the northwest.

Notre Dame Bay igneous province

Two gabbroic stocks and more than a hundred lamprophyre dikes are found in a zone approximately 70 km by 100 km across the shorelines and islands of Notre Dame Bay (NDB), northern Newfoundland (Fig. 25-2). The dikes trend generally to the northeast except near the Budgell Harbor stock, where they appear to be more radial in orientation if not distribution. Despite Late Jurassic dates (139 – 155 Ma, K-Ar) on the Budgell Harbor stock, the dikes have Early Cretaceous radiometric and paleomagnetic ages (Lapointe, 1979).

The intrusions of the NDB province are very similar to members of the NEQ province in age and petrology. Situated within the most northerly of the Appalachian mobile belts, the NDB province is on line with the Charlie-Gibbs fracture zone, a major transform fault of the northern Atlantic. Detailed orientation diagrams of NDB dikes are not available, but the dominant NE trend mentioned by Strong and Harris (1974) implies NW – SE extension in Cretaceous time apparently like the Early Jurassic stress pattern, except in the area of plutons.

Modern stresses and paleostresses

Estimates of the modern state of stress in eastern North America show a diversity of principle stress directions, mainly derived with shallow (less than 6 km) focal mechanisms for recent earthquakes, and observations of bedrock deformations in drill holes, quarries, and glaciated surfaces (Sbar and Sykes, 1973; Zoback and Zoback, 1980; Gephart and Forsyth, 1985). In general, minimum compression is nearly vertical, as expected near the surface. Maximum and intermediate compression are not easily distinguished. Maximum compression directions may trend E – W, NE – SW, or SE – NW and could vary nonsystematically across the Appalachians, especially in the New England region (Gephart and Forsyth, 1985).

Sbar and Sykes (1977) suggest that a boundary between stress domains extends through western New England and southeastern New York, and preexisting (Mesozoic?) faults and other crustal fabrics seem to affect strain patterns related to the recent stresses (Graham and Chiburis, 1980). Gephart and Forsyth (1985) calculate that a single stress pattern can be responsible for the many strain directions found for recent seismicity in New England, influenced by active zones of weakness in the region. Many of the same crustal heterogeneities seem to have existed during Mesozoic tectonism and magmatism, as shown by patterns of intrusions.

Roper (1980) collected evidence for a model in which extension in eastern North America was replaced by compression in Cretaceous and later times. The most likely regional mechanism for initial extension is drag from mantle flow vectors that are faster than movement of the overlying lithosphere. Through time and with increasing distance from the new ocean ridge, the crust subsides along the thinned continental edge. Mantle flow lines compress against this margin and rise behind it, accounting for late Mesozoic and younger uplift of the Appalachian orogen (Roper, 1980, pp. 65 – 67). Regional change from widespread flow-parallel extension to a zone of flow-parallel compression may explain some of the switches in dike trends across the orogen described earlier in this paper.

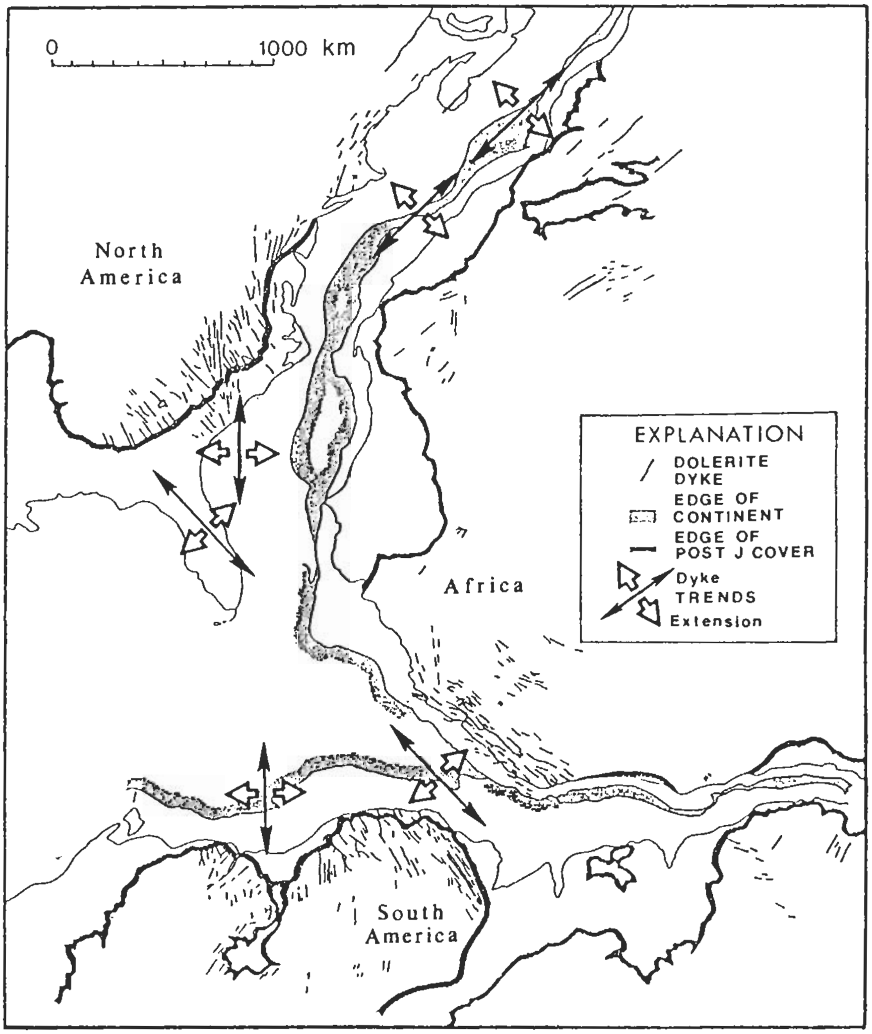

Fig. 25-4. Generalized map of Early Jurassic dolerite dikes around the proto-Atlantic basin, modified from Dooley and Wampler (1983) after May (1971), and extension directions inferred from the dikes during opening events of the North Atlantic.

Late Cenozoic mantle convection, intraplate volcanism, and deep-lithospheric stress patterns have been analyzed by Liu (1980) from global gravity data. Zones of volcanism consistently occur in linear regions of tension created by mantle flow, with magmas interpreted to follow translithospheric fractures in both continental and oceanic areas. The stress/intrusion patterns are similar to mechanical models discussed by Anderson (1951), Rittman (1962), and Roberts (1970), and to the 'hot-line' model of Bonatti and Harrison (1976).

Mesozoic paleostress patterns

The ENA dike trends are similar to those of Early Jurassic dolerite dikes across the present North Atlantic in maps of pre-rift configurations, as pointed out by May (1971) and shown by Figure 25-4. Dolerite dikes on the eastern side of the Atlantic have ages indistinguishable from ENA dikes (Dalrymple et al., 1975). The northeast-trending dolerites and associated basalts are also chemically similar across the ocean basin (Bertrand and Coffrant, 1977), and in general, the Early Jurassic magmas are considered to be precursors of the forthcoming Atlantic ridge basalts (Bryan et al., 1977).

The three major trends of the ENA dikes are repeated by dikes in western Africa and northeastern South America (Fig. 25-4). It is apparent that Early Jurassic dikes were formed parallel and generally adjacent to the final rifts that separated the continents and opened the North Atlantic Ocean. Figure 25-4 also shows extensional stress directions derived from the Early Jurassic intrusions. Because dike ages are similar, it appears that three overlapping stress patterns operated in Early Jurassic time along the more than 3000 km of the initial Atlantic rift zone. May (1971) related this pattern to radial strains developed by early rift doming of the Blake Plateau (Fig. 25-4). However, assuming that the extension followed

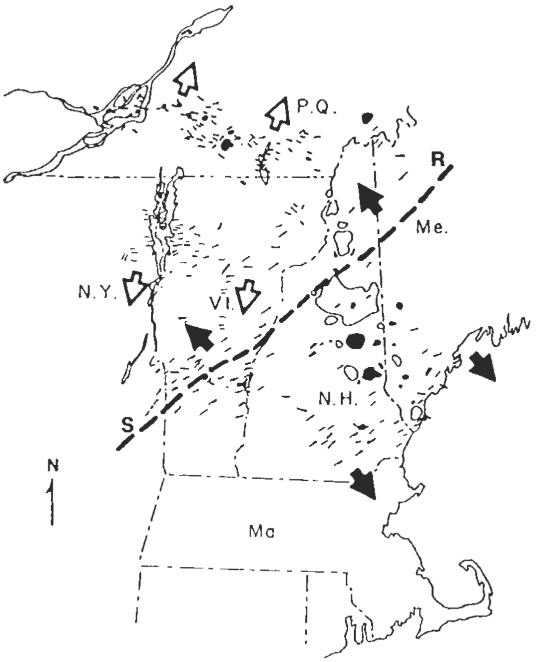

Fig. 25-5. Extensional stress directions inferred from Cretaceous dike trends of New England. Dotted line = Salem – Rangeley *(S – R)* lineament discussed in the text. Solid arrows = extension dominant to the southeast of the S – R lineament; empty arrows = extension dominant to the northwest of the S – R lineament.

mantle patterns of movement, several zones of upwelling and horizontal flow, or convection cells, must be responsible for the dike trends. Individual 'hot spots' or mantle plumes cannot be responsible for the Early Jurassic tectonic and magmatic pattern. As discussed by de Boer (1967) and Lindholm (1978), the Triassic – Jurassic basin margin faults formed during Atlantic rifting may not be closely related to deep stress patterns shown by the dikes, but rather may follow more-shallow crustal anisotropies.

Additional details of younger extensional patterns are best shown in New England because of the big range in distribution and ages of the dikes in that region, and because their orientations are well mapped (McHone, 1984). Northwest-southeast extension throughout the Mesozoic Era may be related to modern northeast compression in the Northern Appalachians, but it also appears from the New England patterns that distinct strain boundaries have long been present. North – south to northeast – southwest extension may have dominated much of the western side of the Appalachians in the Cretaceous and possible later, controlling alkalic magmas during a shift or rotation of the new North American plate movement that also opened the North Atlantic Ocean northward from Newfoundland (Lapointe, 1979). Much more detail can be added to paleostress/strain models through future work on magmatic patterns in eastern North America.

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