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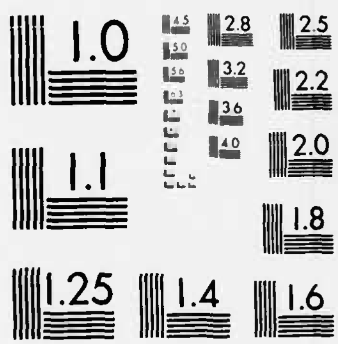

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19. ABSTRACT (cont)

This multidisciplinary and interdisciplinary project involved investigations of: (1) Geophysical properties of the shallow crust underlying the Appalachians of southern New England by means of dispersion of Rg waves and electromagnetic methods; (2) deeper geological structure by interpretation of multichannel seismic reflection lines in the onshore and offshore portions of New England; and (3) by analysis of the geology of the region in the light of data from our own site specific and regional studies as well as from published sources. The results of our studies are detailed below, but major contributions include the following: (1) southern New England has been subdivided into Rg wave dispersion regions and, to the extent possible, correlations with tectonostratigraphic divisions of the region were established. In those cases that lack correlations on the scale of our observations, explanations have been offered. These studies were carried out using Boston College's New England Seismic Network. (2) electromagnetic studies, using Boston College's magnetic observatory installations and VLF meter, and analysis of existing aeromagnetic maps, suggest that major fault zones in eastern MA constitute part of a series of stacked thrust faulted duplexes. (3) Analysis of multichannel seismic reflection lines collected by the U. S. Geological Survey in the Gulf of Maine and on the Long Island Platform gave rise to revisions of previous interpretations of the large scale geology of the region. Such revisions include our interpretation that the Fundy Fault of the Bay of Maine should be correlated with the Blue Hills fault south of Boston that is traced and/or extrapolated through Rhode Island as an easterly dipping thrust fault, the newly mapped Smithfield fault zone of Alleghanian or early Permian age; (4) large scale overthrusting and underthrusting has been produced throughout the region as a result of continent-island arc, island arc-island arc, and continent-continent collisions; and the resulting structures have been modified by those produced by rifting tectonics.

FINAL TECHNICAL REPORT

Multidisciplinary Geophysical Study of the Earth's Upper Structure

Grant No. AFsor-85-0177

Principal Investigator: James W. Skehan, S.J.
Co-Principal Investigators: John F. Devane, S.J.
Alan L. Kafka

December 27, 1988

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MULTIDISCIPLINARY GEOPHYSICAL STUDY OF THE EARTH'S UPPER STRUCTURE

by

James W. Skehan, S.J., Principal Investigator
John W. Devane, S.J., Co-Principal Investigator
Alan L. Kafka, Co-Principal Investigator

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ABSTRACT Investigations were made of: 1)

This multidisciplinary and interdisciplinary project involved investigations of: (1) Geophysical properties of the shallow crust underlying the Appalachians of southern New England by means of dispersion of Rg waves and electromagnetic methods; (2) deeper geological structure by interpretation of multichannel seismic reflection lines in the onshore and offshore portions of New England; and (3) by analysis of the geology of the region in the light of data from our own site specific and regional studies as well as from published sources. The results of our studies are detailed below, but major contributions include the following: (1) southern New England has been subdivided into Rg wave dispersion regions and, to the extent possible, correlations with tectonostratigraphic divisions of the region were established. In those cases that lack correlations on the scale of our observations, explanations have been offered. These studies were carried out using Boston College's New England Seismic Network. (2) electromagnetic studies, using Boston College's magnetic observatory installations and VLF meter, and analysis of existing aeromagnetic maps, suggest that major fault zones in eastern MA constitute part of a series of stacked thrust faulted duplexes. (3) Analysis of multichannel seismic reflection lines collected by the U. S. Geological Survey in the Gulf of Maine and on the Long Island Platform gave rise to revisions of previous interpretations of the large scale geology of the region. Such revisions include our interpretation that the Fundy Fault of the Bay of Maine should be correlated with the Blue Hills fault south of Boston that is traced and/or extrapolated through Rhode Island as an easterly dipping thrust fault, the newly mapped Smithfield fault zone of Alleghanian or early Permian age; (4) large scale overthrusting and underthrusting (was) ~~has been~~ produced throughout the region as a result of continent-island arc, island arc-island arc, and continent-continent collisions; and the resulting structures have been modified by those produced by rifting tectonics. (etc)

1. INTRODUCTION

This project was a multidisciplinary study in which we investigated the geological and geophysical properties of the Appalachian mountains in southern New England. We analyzed lateral and vertical variations in the geology, and we investigated the extent to which those variations are related to lateral and vertical changes in both the seismic velocity structure of the shallow crust and the electromagnetic properties of the crust. The Appalachians of southern New England have undergone a complex geological evolution (e.g. Skehan, 1988; Skehan and Rast, 1983; Robinson and Hall, 1980). Based on recent geophysical studies, including this project and related research activities, lateral and vertical variation in earth structure beneath the New England Appalachians have been revealed. Our studies focused on understanding the relationship between surface geology, shallow crustal structure, and deeper earth structure. The research questions addressed in this study were designed to further our understanding of the extent to which a detailed knowledge of the surface geology of a region can be used to predict the presence of shallow to deep earth structures normally detected by geophysical methods.

This study was unique in several respects and it offers some original approaches to understanding the characteristics of the upper few kilometeres of the crust through an entire orogenic belt consisting of several accreted terranes. We utilized a combination of geological mapping, seismic studies of shallow crustal structure (using dispersion of short-period Rayleigh waves), interpretation of seismic reflection profiles, geomagnetic field studies, and interpretation of aeromagnetic data. Each of these methods has been known for some time and they have all been applied in various parts of the world. Prior to this investigation, however, these methods have rarely been combined into one interdisciplinary study. Shallow crustal studies using short period Rayleigh waves (Rg) and geomagnetic studies have been underutilized, or even neglected, in geological circles because they previously had been thought to have little relevance to the understanding of near-surface geological features.

This study was motivated by our prior seismological research on the dispersive properties of Rg waves (e.g. Kafka and Dollin, 1984). The results of that research suggested that lateral and vertical variations in the upper crust could be recognized by an analysis of seismograms of Rg waves generated by earthquakes and quarry blasts recorded by Boston College's 29 station seismic network (The New England Seismic Network, NESN). Weston Observatory also operated since 1958 the only geomagnetic observatory in the northeastern United States. Our studies of geomagnetic data have been used to define lateral and radial variations of electrical conductivity from near-surface to depths of several hundred km beneath adjacent geomagnetic stations in New Engalnd.

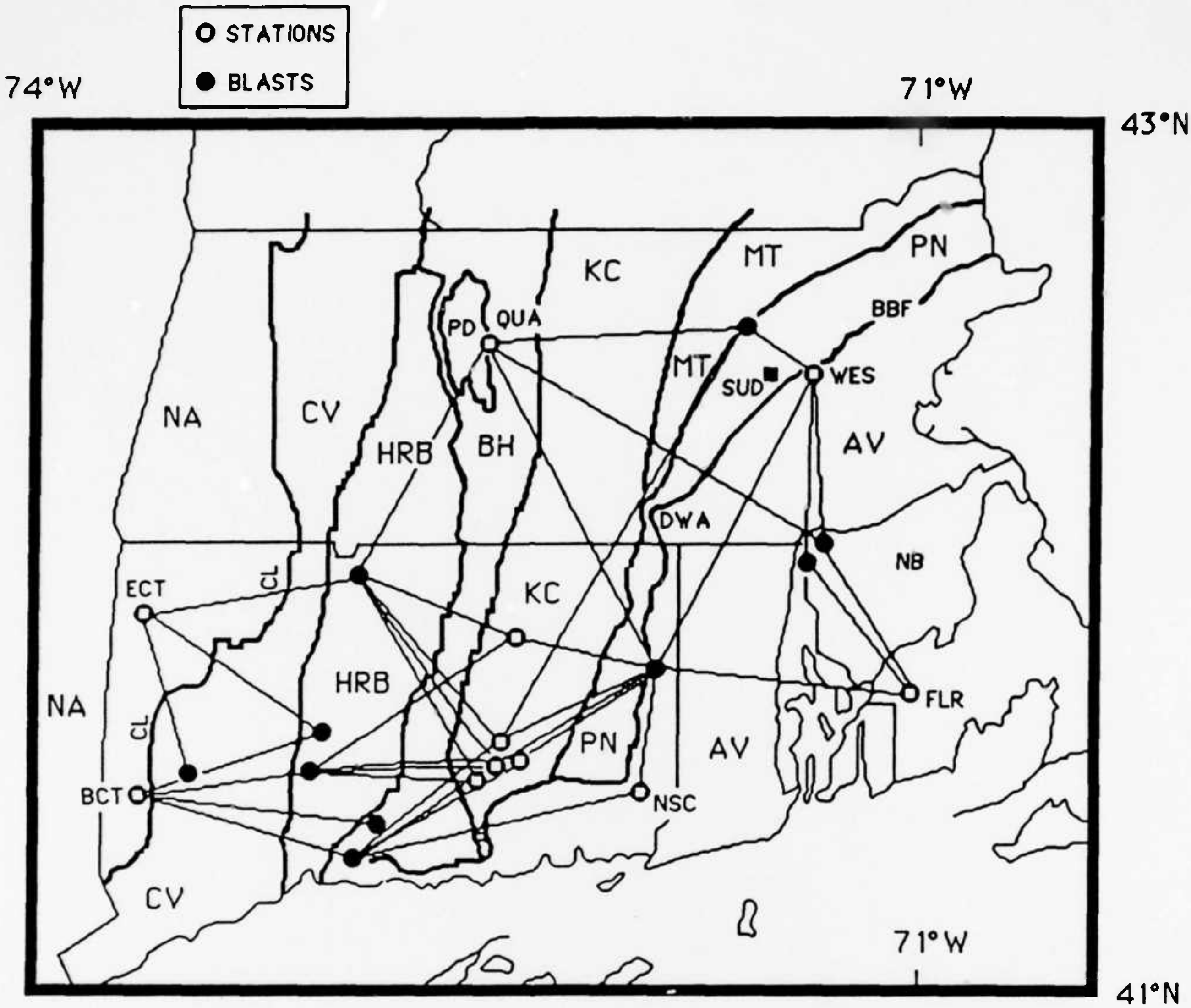
The northern Appalachian mountain system of southern New England is now known to consist of a number of "exotic" blocks or terranes that developed in different geological environments and, as the result of large-scale movements, have been sutured to one another. We considered it important to study shallow crustal as well as deep crustal features because these exotic blocks, believed to be sections of lithospheric plates (up to 150 km thick), interpreted to have been piled up to substantial thicknesses during ancient plate collisions that involved overthrusting and underthrusting of sheet-like masses of rock. Thus, blocks and sheets of rock formerly widely separated at the time of their formation have been juxtaposed. As part of this study we developed a methodology for lateral and vertical discrimination between such masses and sheets of rock to the extent that the characteristic rock properties permit such discrimination.

The results of this study are potentially applicable to mountain systems worldwide because the Appalachians of southern New England are interpreted to have been produced by multiple plate tectonic collisions involving continent-island arc, island arc-island arc, and continent-continent collisions. All of the geological features characteristic of subduction-related, transpressional, or extensional tectonic regimes are represented here as is also the case in many of the great mountain systems of Earth. We interpreted low angle overthrusting and underthrusting structures to be characteristic of large portions of the study region. Another major feature that suggests that the methodology of this study may be widely applicable to other mountain systems is that the tectonostratigraphic units comprising these mountains have been traced for vast distances along their trend. For example, the western margin of the Appalachians of North America (e.g. the Highlands of Western Connecticut) are interpreted (Skehan, 1988) to have continuations through the northern Appalachians of eastern North America, the northern British Isles, East Greenland, Svalbard and western Scandinavia. The eastern margin of the Appalachians (e.g. southeastern New England) are interpreted (Skehan, 1988) to have been continuous through the southern British Isles, western Europe, the Iberian Peninsula and West Africa. In addition to those mountain ranges noted above, for which there are direct correlations, one may expect that some level of correspondence in age and lithology of stratigraphic units, structures, metamorphism, plutonic and volcanic sequences and evolutionary history, could be established for other mountain systems having comparable tectonostratigraphic units and having undergone a basically similar geological evolution, such as the Ural mountains of the USSR.

One of the chief results of this study is that geophysical methods chiefly applicable to the shallow crust have ben used to address the question of what kinds of geological features can be recognized, and to what degree the recognition of these features can these contribute to an understanding of their evolution and that of the mountain belt. The geophysical methods utilized as research tools in the field, and data gathered by others and analyzed by us, are those that chiefly examine the upper crust of Earth and thus should include methods of greatest potential benefit in the solution of geological problems. Analysis of dispersive properties of Rg waves generated by quarry blasts and recorded on Boston College's New England Seismic Network (NESN) revealed lateral variations at depths ranging from very near surface down to a few kilometers in the crust. When the Rg dispersion results were compared with results of tectonostratigraphic studies from geology we were able to divide southern New England into dispersion regions, that, in part, correlated but, in part also, showed no clearcut correlations. However, the basis for correlations is more readily explained than lack of correspondence in most cases. Since this study of Rg dispersion is carried out, for the most part, with widely spaced seismic stations it seems probable that as it becomes possible to establish more closely spaced stations, the resolving power of the method will be increased.

Utilizing data from several multichannel seismic reflection lines collected by the U. S. Geological Survey in the Gulf of Maine, the Long Island Platform, and related parts of onshore New England we have been able to refine or revise geological interpretations by other workers, including our collaborators working with the primary data base.

Electromagnetic studies of the crustal structure of a part of eastern Massachusetts took place in three stages. The methodology that can be used successfully to define local conductivity structure was developed by this study. However, to be applied successfully, this methodology requires an array of stations recording simultaneously. During the present study, however, observations were made at our magnetic observatory at Sudbury, MA and when that station was discontinued, the equipment was installed at Weston Observatory. A second stage of the study provided for an analysis of aeromagnetic maps along three profiles over two major faults in eastern MA. This analysis indicates that the steeply to moderately west-dipping thrusts became nearly horizontal with distance to the west, indicating that these faults comprise a stacked sequence of ramp thrusts, an observation that represents a significant advance in the geological understanding of these regionally important fault zones. The third stage of the electromagnetic study of the near surface characteristics of the crust utilized a VLF meter using very low frequency (VLF) radio frequencies from 3 to 30 kc/s, that, in turn, utilized a magnetic field propagated by the U. S. Navy's transmitter in Cutler, ME. By means of four measurements, the electromagnetic properties of the near-surface rocks in a part of eastern MA were examined to a limit of 500 m. This method successfully delineated the lateral extent of the Bloody Bluff zone and in defining contacts between geological units. One of the most important by-products was the development of computer programs to model two dimensional conductivity structures.



NA = Proto-North American Terrane
CV = Connecticut Valley Synclinorium
CL = Cameron's Line
HRB = Hartford Rift Basin
BH = Bronson Hill Anticlinorium, Pelham Dome (PD)

KC = Kearsarge-Central ME Synclinorium
MT = Merrimack Trough
PN = Putnam-Nashoba Terrane
AV = Avalonian Superterrane

DWA = Douglas Woods Anticline
BBF = Bloody Bluff Fault Zone

Figure 1. Terranes and related structures of the southern New England Appalachians showing the distribution of Weston Observatory's seismic stations, location of quarry blasts, and the paths of Rg waves.

2. SIGNIFICANT ACCOMPLISHMENTS AND RESEARCH PROGRESS

2.1 Geology of the New England Appalachians

Although the Appalachian mountain system is one of the most extensively studied in the world, it is geologically one of the most complex and thus has yielded its evolutionary secrets slowly. Williams (1978) delineated several tectonostratigraphic divisions and Skehan and Osberg (1979) described five distinct terranes in the New England Appalachians. Research contributions in the meantime permit us to divide southern New England Appalachians (from west to east) into the following eight major composite terranes (Fig. 1):

(1) North American craton

(2) Connecticut Valley synclinorium

(3) Mesozoic basin

(4) Bronson Hill anticlinorium

(5) Kearsarge-Central Maine synclinorium

(6) Merrimack trough

(7) Putnam-Nashoba terrane

(8) Avalonian superterrane

Subdivisions of these terreanes and refinements in our understanding of them have resulted from this study and are described in the sections that follow.

2.1.1 The Avalonian Superterrane: a Volcanic Arc and Back Arc Basin

In the beginning of this project, Skehan and others (1985) proposed that several of the late Proterozoic units of the Avalonian terrane of southeastern New Engalnd formed as olistrstromal deposits (submarine slump deposits). For over a decade, parts of the northern Appalachians have been interpreted to have a close relationship to the geology of western Europe and West Africa (Schenk, 1971; Skehan, 1973; Rast and others, 1976). However, it is only more recently that specific correlations have been made (O'Brien and others, 1983; Skehan and Rast, 1983; Rast and Skehan, 1983; Skehan and Pique, in press 1988) such that the Avalonian terranes of eastern North America are now generally interpreted to have consisted of a volcanic archipelago lying offshore of West Africa during the Late Proterozoic and early Paleozoic (Fig. 2). The olistostromes of eastern Massachusetts and Rhode Island (Fig. 3) contain distinctive olistoliths of quartzite and carbonate that are interpreted to have been derived from the West African continental shelf of Gondwanaland (Skehan and others, 1985). In the resulting paper (Bailey and others, 1989), we have assembled evidence in support of the concept that the Avalonian Superterrane within the region of the present study, at least, originally consisted, in part, of carbonate and quartzite deposits similar to those of the West African continental

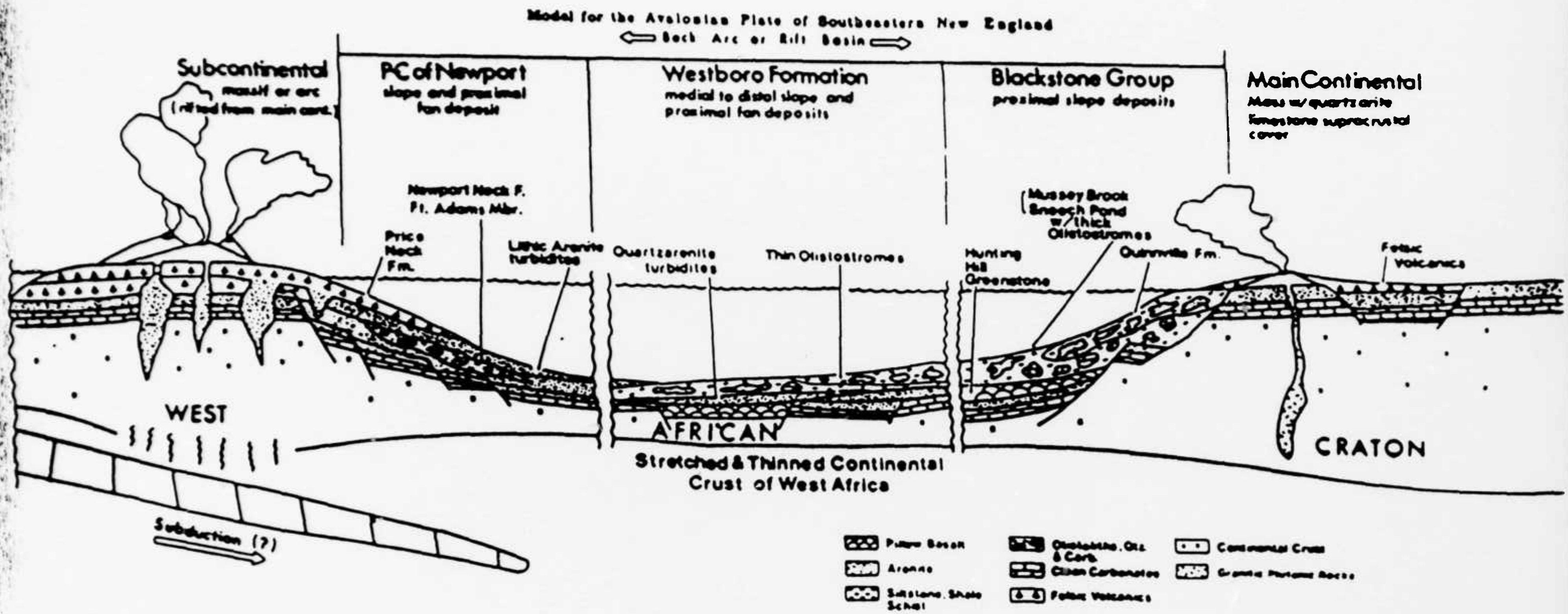


Figure 2. A cross-sectional reconstruction of possible tectonic environments for the olistostromes of the Avalonian Esmond-Dedham Terrane of southeastern New England showing their interpreted relationships to the volcanic arc and back arc basin to the older West African continental shelf deposits and the West African Craton on which they were deposited (Bailey and others, in press 1988).

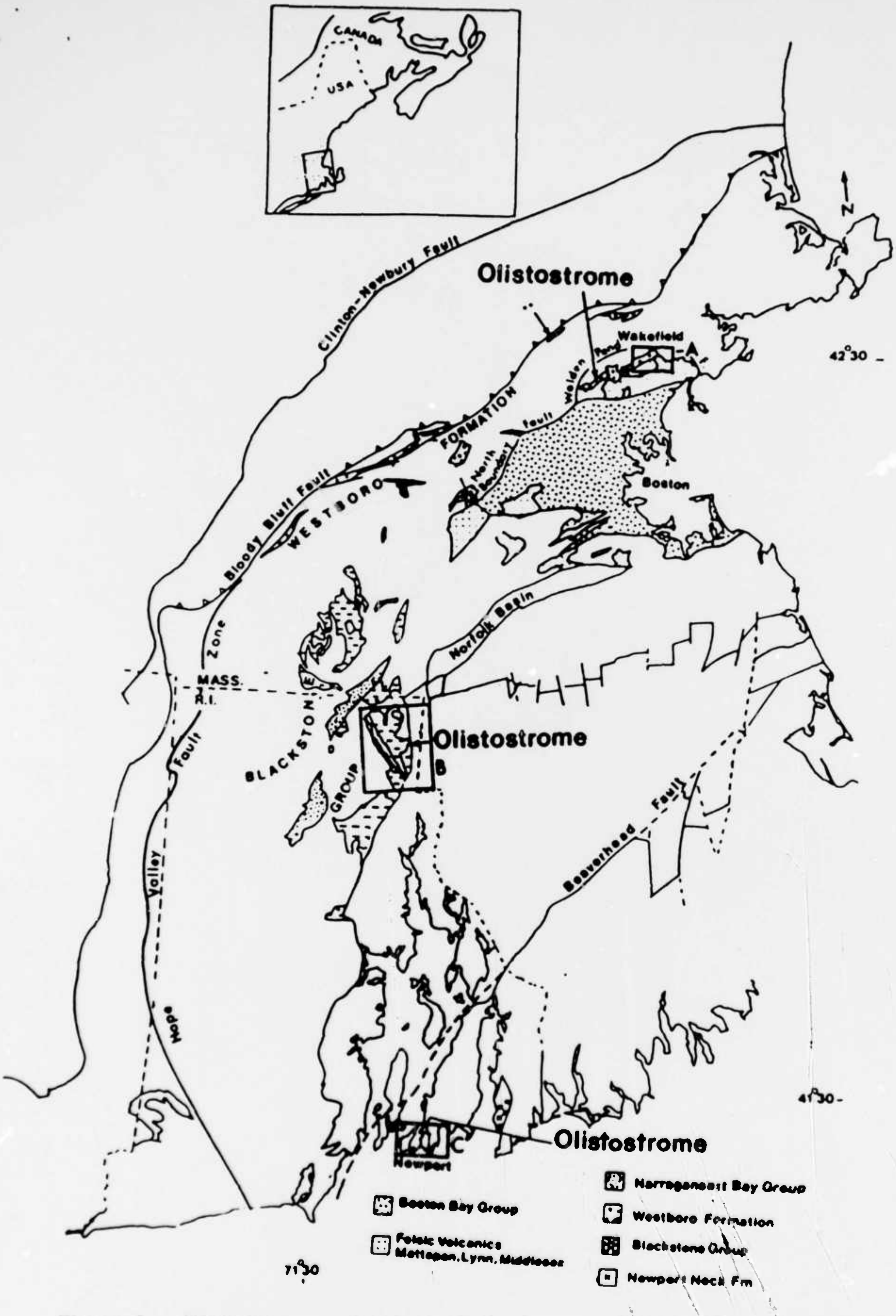


Figure 3. Regional map of the Avalonian terranes showing olistostrome deposits; the Hope Valley Shear Zone marking the terrane boundary between the HVSZ and the D-E terranes and the Bloody Bluff F.Z. that form the eastern margin of the P-N Terrane (Bailey and others, in press (1988).

shelf, but that, in part also, the deposits of southeastern New England represent that collapsed continental shelf and that olistostromes formed in the resulting back arc basin. These olistostromes are now represented by the Westboro Quartzite north of Boston, the Blackstone Group of Rhode Island, and the Fort Adams Formation of Newport, Rhode Island. This study suggests strongly that the Avalonian Superterrane (Skehan and Rast, in press 1988) represents a Late Proterozoic volcanic arc and back arc basin and that the early Paleozoic Avalonian composite terrane consisted of these earlier formed volcanic islands with fringing shelf deposits ranging from fossiliferous sandstone and shale to carbonate of Cambrian age (Skehan and others, 1987).

2.1.2 Terrane Definition and Terrane Boundaries in the Avalon Superterrane

In order to characterize the Avalonian terranes of southeastern New England, Skehan and Rast, (in press, 1988) developed a systematic and thorough review of the lithology, stratigraphy, structure, metamorphism, plutonism, volcanism and geologic evolution of the two Avalonian terranes now recognized as comprising what we have named the Avalon Superterrane (Fig. 4). Skehan and Rast (in press, 1988) recognize that, with the proliferation of research on Avalonian terranes, the related terminology in the literature has developed certain ambiguities and imprecision. Thus we introduced the terms "Avalonian Superterrane" and "composite terrane" to refer to a late Proterozoic microcontinent, and to a fragment of the Superterrane that includes not only late Proterozoic but also a Paleozoic cover respectively. We now recognize the validity of the claim by O'Hara and Gromet (1985) that the Hope Valley shear zone (Fig. 4) separates the Avalon Superterrane into two, the Hope Valley Terrane and the Esmond-Dedham Terrane. Accordingly, our paper (in press 1988) summarizes all of the relevant data on these terranes and proposes an evolutionary model for both the Superterrane and for the composite terrane. We recognize the distinct possibility, indeed the strong probability, that accumulating evidence favors further subdivision of the Edmond-Dedham Terrane into two and possibly more terranes.

The above study has implications for interpretations of Rg dispersion studies in the Avalon Superterrane specifically, but also in the Putnam-Nashoba terrane, in the Kearsarge-Central Maine synclinorium and in the Bronson Hill anticlinorium. If a given terrane is geologically and/or geophysically inhomogeneous on a scale that is much smaller than either the wavelength of the Rg waves or the station spacing, the Rg dispersion method will tend to average out any of the geological variations. On the other hand, an increased understanding of the degree of geological inhomogeneity, coupled with more detatiled Rg experiments, including closer station spacing, may allow us to identify subtle differences in the geology that correleate with variations in geophysical properties.

2.1.3 Comparative Study of southeastern New England Avalonian Terrane with the Pan-African of Morocco

A further effort to understand the evolution of the Avalon Superterrane and to focus attention on unsolved problems has resulted in the preparation of a paper by Skehan and Pique (in press, 1988) on the comparative evolution of the Avalon Superterrane of New England and its interpreted counterpart, the Pan-African orogenic belt of West Africa (Fig.5). The latter author is an authority on the geology of Morocco and was visiting professor at Boston College this past year. The objective of this paper is not only to compare and describe those aspects of the geology that we have recognized as being similar or identical, but especially to recognize those

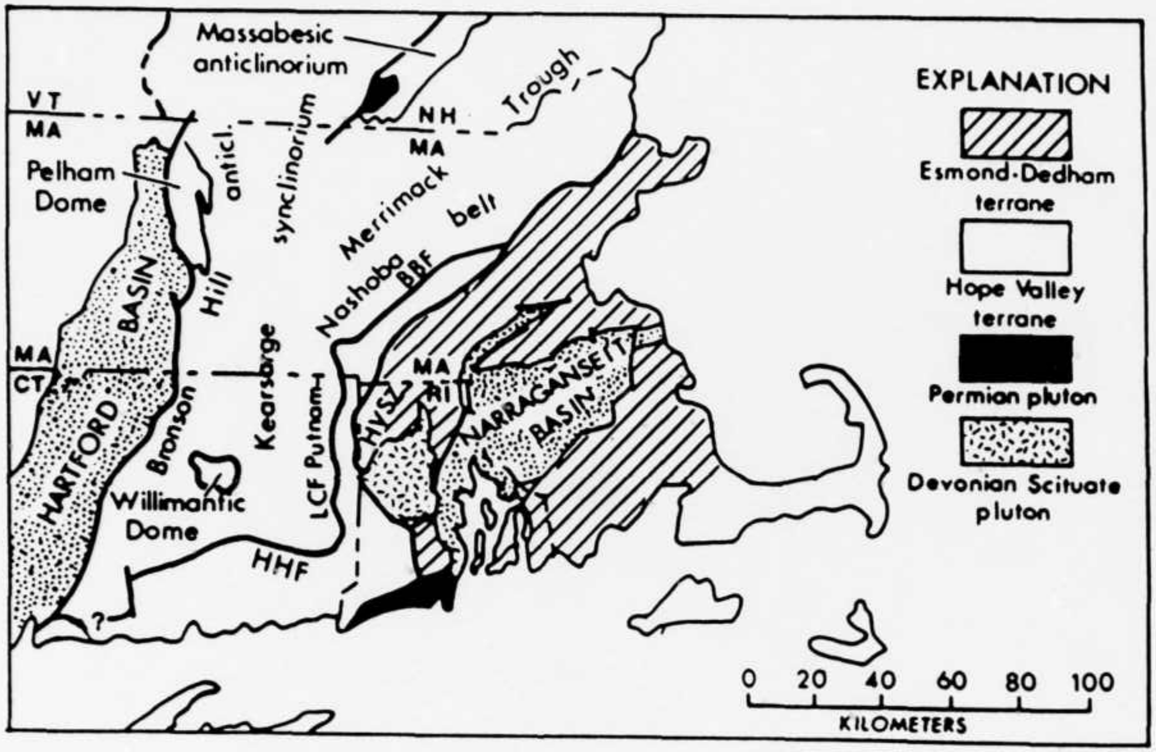


Figure 4. Generalized geologic map of a part of southeastern New England, showing terranes comprising the Avalon Superterrane, including several sub-divisions of the Esmond-Dedham Terrane, and other tectono-stratigraphic divisions of the region. HHF = Honey Hill fault zone; LCF = Lake Char fault zone; BBF = Bloody Bluff fault zone; HVSZ = Hope Valley shear zone (modified from Zartman and others, 1988, p. 377).

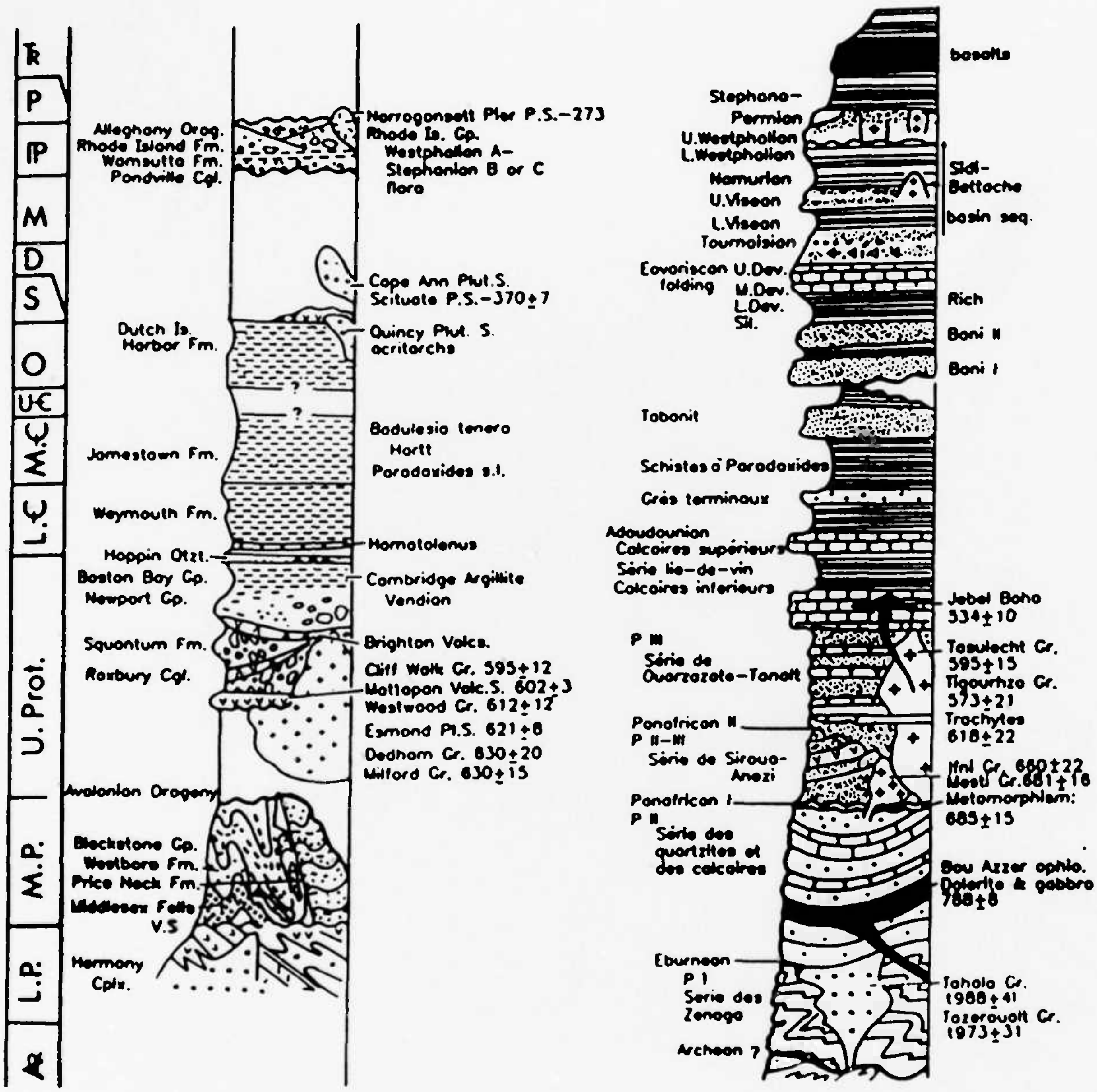


Figure 5. Stratigraphic columns for the Avalonian Esmond-Dedham Terrane of southeastern New England and for the Pan African of Morocoo indicating similarities and contrasts between the two (Skehan & Pique, in press 1988).

aspects that are dissimilar. These differences may represent real discrepancies or may reflect the fact that further investigation is needed to determine whether there is evidence in southern New England, not yet discovered, that may provide us with increased understanding of the evolution of these widely separated terranes that were united in late Proterozoic and possibly in early Paleozoic time [ca 800 to 350 million years ago (Ma)]. This research, of which Skehan's part only was supported by this study, has implications for geophysical studies for reasons that in part were noted above , but also because, to date, a basement to the Avalon zone has not been recognized, although its presence is suggested geochemically by Hermes and Zartman (1985) as well as by our own research cited above. Thus we expect that future geological and geophysical research may reveal a basement of ca 2000-3000 Ma Eburnean and older Archean gneisses, overlain by shallow water continental shelf deposits (Fig. 2). It is from the latter that we interpret the olistostromal deposits referred to above have been derived by submarine slumping in late Proterozoic time.

2.1.4 Alleghanian age overthrusting and Mesozoic extension in Rhode Island

A geological investigation of rocks of the Harmony Complex of northern Rhode Island, that are considered candidates for some of these older basement rocks, has been undertaken by Watson (in progress) and by Watson and Skehan (in press 1988) as part of the present study. Quinn (1971) referred to these rocks as " Older gneissic rocks of northwestern Rhode Island". Skehan named them the Harmony Group (1983), but renamed them Harmony Complex (Skehan and Rast, in press 1988) to bring the nomenclature into accord with the North American Stratigraphic Code (1983). Significant results of our studies of the Harmony Complex (Figs. 6a and 6b) include: (1) the recognition that a substantial part of these rocks consist of highly deformed granitic plutons as well as a significant volcanic and volcaniclastic component; (2) deformed rocks in many parts of the area are characterized not only by a strong foliation but by a high degree of mylonitization; (3) two possibilities as to the age of the Harmony Complex seem reasonable, the first being that the plutonic rocks are largely equivalent to the Esmond Granite (ca 620 Ma) but much more intensely deformed than the latter. A second possibility is that the plutonic rocks are substantially older than the Esmond Granite, in the age range of between 660 to 800 Ma, the age of the Ifni or Mesti (681 Ma) granites, the age of metamorphism (685 Ma), and the intrusion of the Bou Azzer Ophiolite (788 Ma) of Morocco (Fig. 5). (4) overthrusting to a significant extent has been demonstrated in northern Rhode Island where outliers of granite, most probably Scituate Granite of Middle Devonian age, have been overthrust over sedimentary rocks of Pennsylvanian age in the North Scituate and Woonsocket basins as well as over older rocks of the Harmony Complex (Fig. 6a and 6b).

These results have implications for understanding the velocity structure and certain other geophysical parameters in this region. Since several parts of the Avalonian Superterrane are now known to be characterized by this type of low - angle overthrust structure (which may be characteristic of the geology of this region, rather than being the exception), one may expect that sheets of similar, nearly flat-lying rock units may be stacked one upon another. Throughout southern Narragansett Bay a number of thrust faults have been mapped (Skehan and Rast, in press 1988, and Fig. 7) which indicate that late Proterozoic rock masses have been overthrust upon Pennsylvanian rocks. This means that the thrusting took place in the Alleghanian orogeny during late Pennsylvanian to earliest Permian time. Thus large parts of the Avalonian composite terrane, especially the Esmond -Dedham Terrane that contains Pennsylvanian coal basins, may be much less homogeneous than thought prior to this study because of the presence of stacked thrust sheet

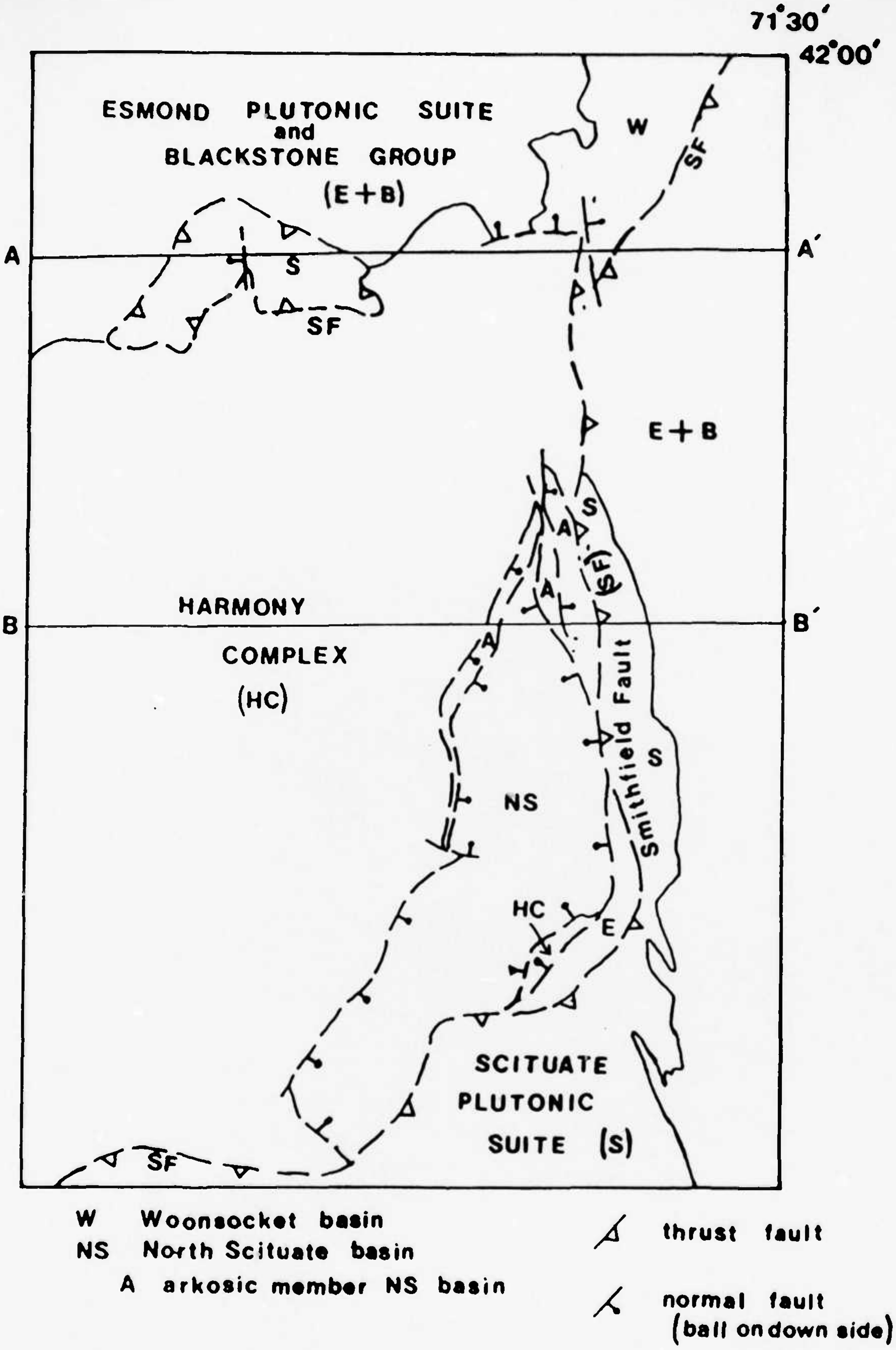


Figure 6a. Generalized geologic map of north-central Rhode Island showing the Smithfield fault, a possible continuation of the Fundy fault, undifferentiated pre-Pennsylvanian and Mesozoic normal faults, and Late Proterozoic rock units, as well as Pennsylvanian basins, overthrust by the Smithfield fault (Watson and Skehan, in press 1988).

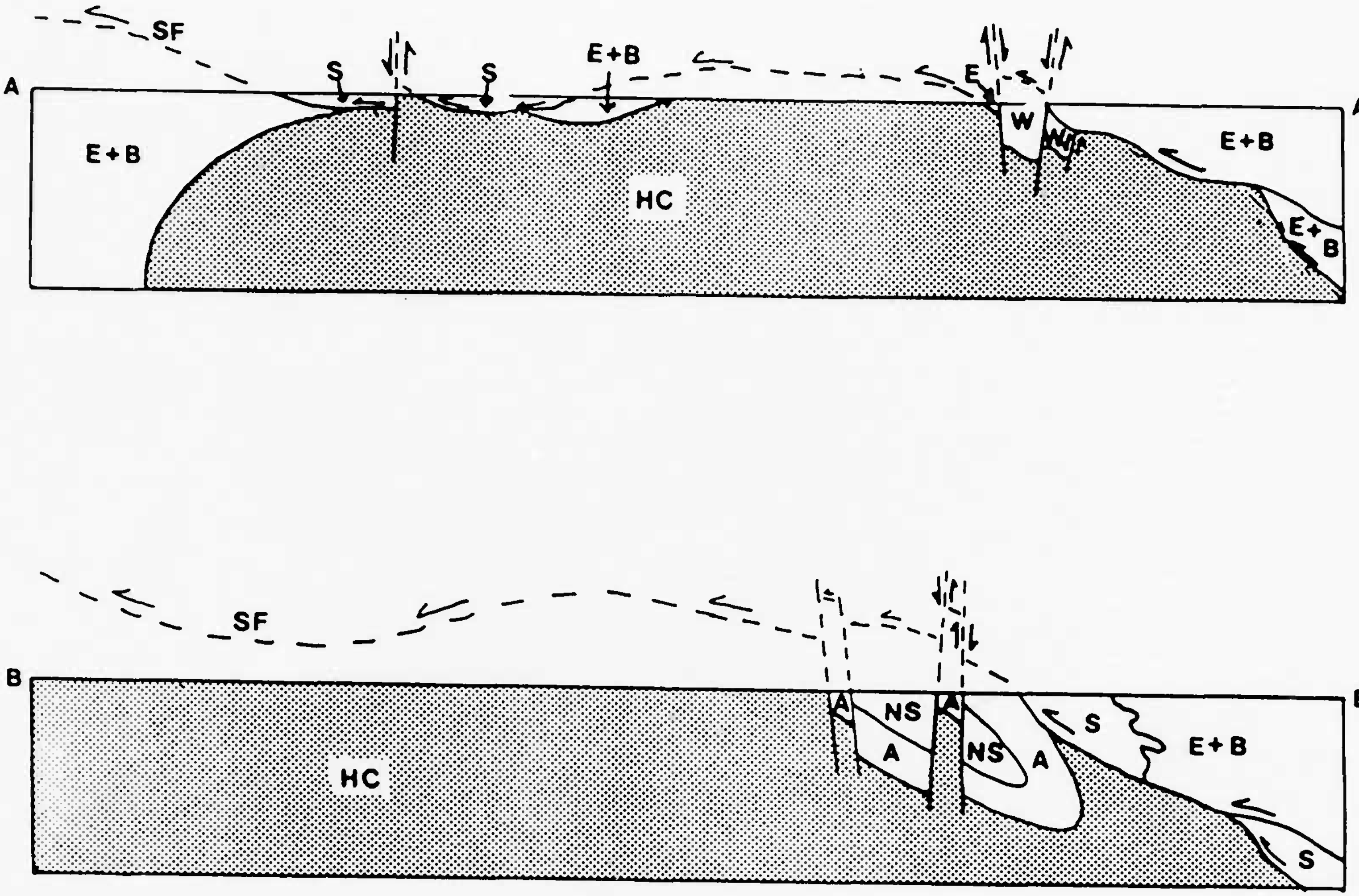


Figure 6b. Geologic cross sections from the generalized map (Figure 6a), showing overthrusting of Scituate, Esmond, and Balckstone rocks along the Smithfield fault (Watson and Skehan, this report).

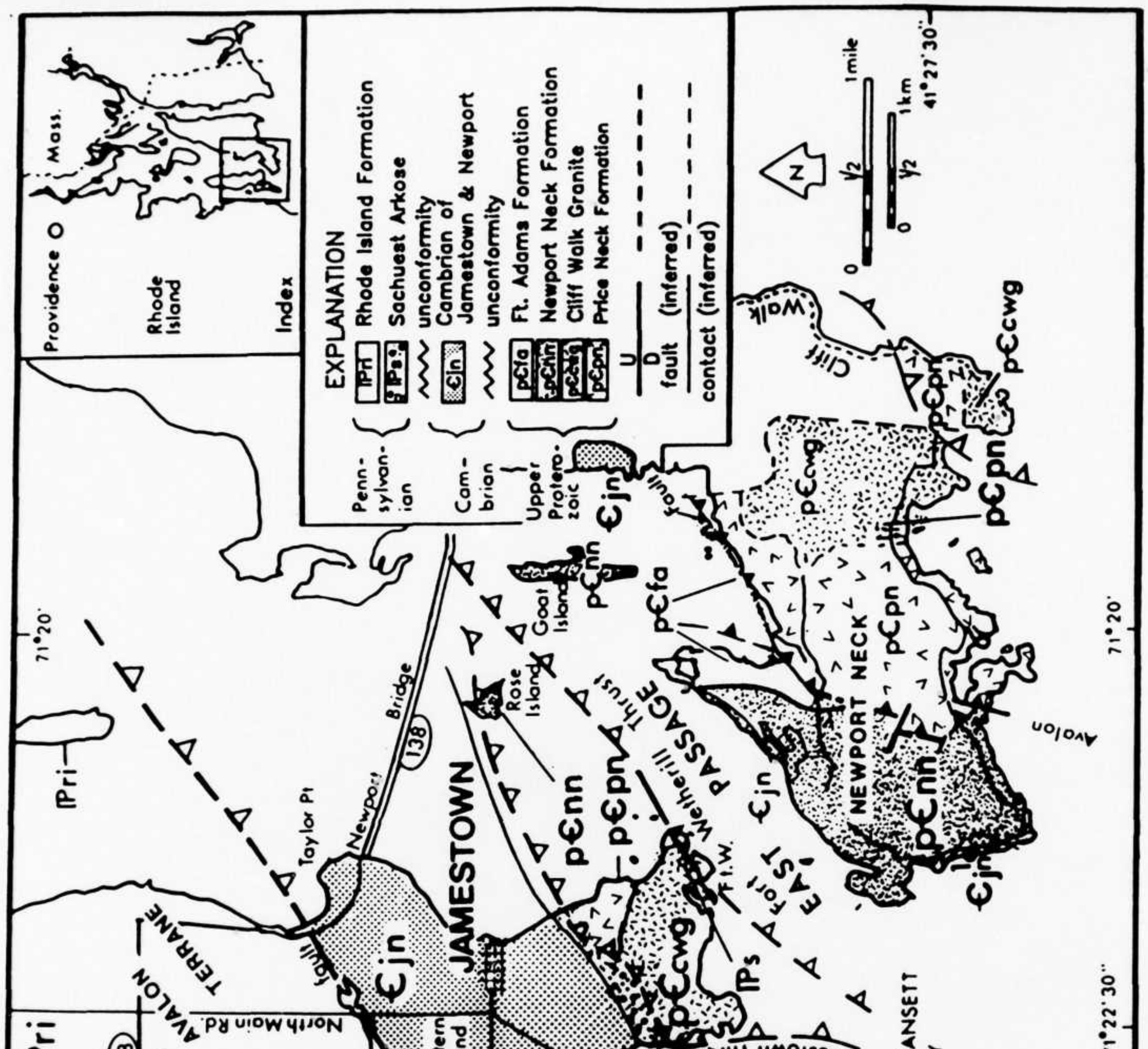


Figure 7. Geologic map of the Newport Basin showing distribution of major rock units of the Newport Basin and major thrust faults (modified from Skehan and others, 1987, Figure 1, p. 196).

duplexes. These duplexes may contain, in addition to a variety of granitic and volcanic rocks of Late Proterozoic and Devonian age, also sedimentary sequences of Cambrian and Pennsylvanian age. Geophysical methods for probing the crust to depths beyond the range of the Rg dispersion studies may be required to identify these deeper structures such as the duplexes interpreted from the geology and from geomagnetic studies (see Section 2.3).

2.1.5 Overthrusts involving the North American craton in Vermont

It has been long known that the rocks of western New England and of eastern New York experienced a westward directed tectonic transport during the early Ordovician Taconic orogeny. However, the qualitative and quantitative extent of that transport has only gradually become known. In the mapping of southern Vermont , western Massachusetts, and western Connecticut, Doll and others (1961), Skehan (1961, 1969), and Zen, (1968, 1987) and Rodgers (1986) recognized thrust faults that implied substantial shortening of the crust and large amounts of westward transport of rock masses. However, it was not until the validity of plate tectonic theory was field tested extensively that the great magnitude of tectonic transport has become semi-quantitatively recognized. It is now generally accepted that the amount of overthrusting must be measured in hundreds of kilometers rather than in lesser distances (Stanley and Ratcliffe, 1985).

As part of this study, a portion of the Wilmington-Woodford area of southernmost Vermont, originally studied by Skehan (1961), was remapped by Hawkins (1986a) to identify major overthrusts and to evaluate in qualitative and semi-quantitative terms the tectonic transport due to the Taconic and Acadian orogenic episodes that affected that part of the North American craton and its margin. This study identified three, or possibly four, major thrust blocks or slices, the Stamford block, the Heartwellville slice, and the Hoosac Mountain slice. The fourth, the Readsboro block, may be a separate slice, but our study suggests that it is probably a part of the Stamford block (Figs. 8a and 8b) (Hawkins and Skehan, 1985; Hawkins, 1986a, 1986b).

The Stamford block forms the southeastern margin of the Green Mountain Massif, and the Readsboro block may represent a tectonically elevated continuation of the Stamford, uplifted by folding, or it may be tectonically elevated by thrusting along a fault as yet not recognized. The upper boundary of both the Stamford and Readsboro blocks is interpreted to be the Heartwellville thrust, that also marks the base of the overlying Heartwellville slice (Figs. 8a and 8b). Both the Stamford and Readsboro blocks contain Proterozoic basement rocks overlain by a rift facies clastic cover that may possibly range from Middle Proterozoic to Cambrian in age. The Heartwellville slice is comprised dominantly of marble-bearing metashales, the latter representing a more proximal or westerly derived rift clastic sedimentary facies. The uppermost tectonic package within the study area is the Hoosac Mountain slice that is separated from the slices below by the Hoosac Mountain thrust. The Hoosac Mountain slice is comprised dominantly of metagraywackes, metashales, and metavolcanics, representing a more distal or easterly rift clastic facies derived from the North American craton.

Three folding events and two garnet grade metamorphic events, separated by a pervasive chlorite retrogression, were recognized within the Hoosac Mountain and the Heartwellville slices. Two folding events and two biotite grade metamorphic events were recognized within the Stamford thrust block. These tectonic features are interpreted to have developed dominantly as a result of Taconic compressional

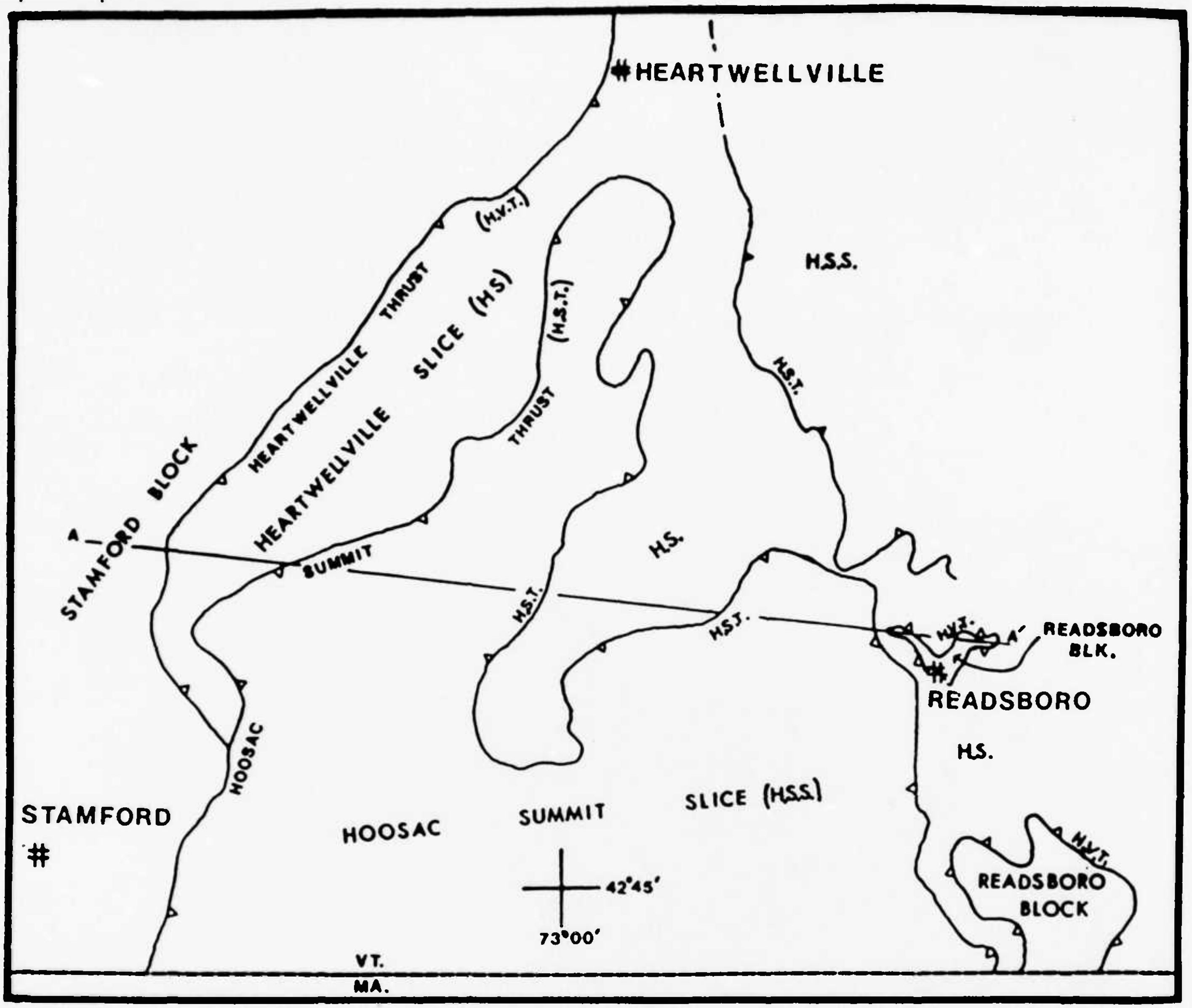


Figure 8a. Map of the southern Vermont area showing the distribution of major thrust blocks and slices and their boundary thrust faults (after Hawkins & Skehan, in press 1988).

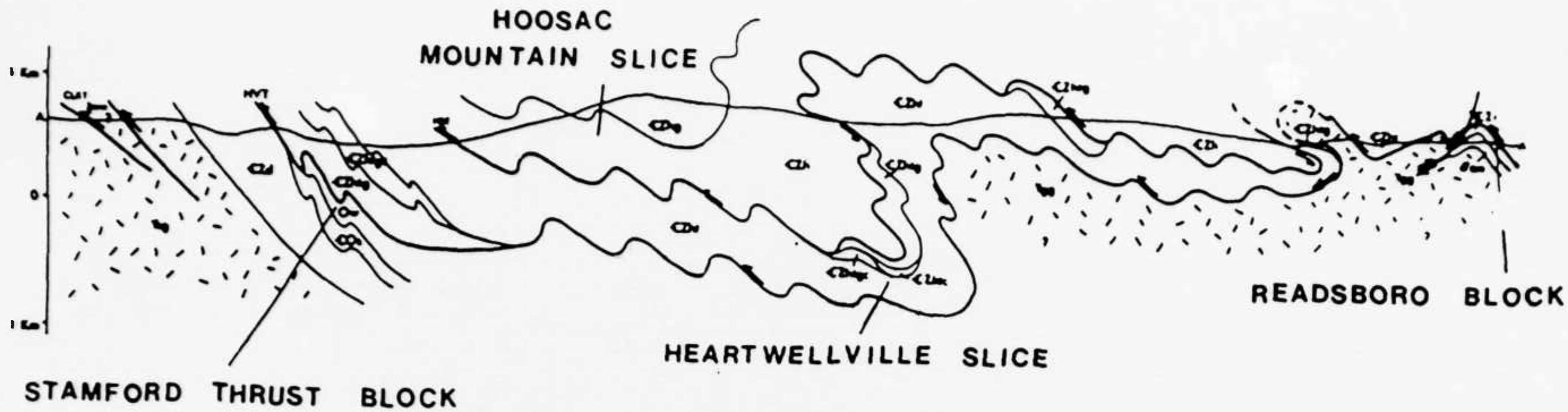


Figure 8b. Cross section of the southern Vermont area showing the distribution of major thrust blcoks and slices and their boundary thrust faults (after Hawkins and Skehan, in press 1988).

deformation processes of Ordovician age and subsequently were deformed by additional but less intense compressive deformation of the Acadian orogeny (of Devonian age). The latter tectonic effects are considered to be responsible for structures associated with the formation of retrograde metamorphic minerals.

In Section 2.2 we discuss our results of Rg dispersion studies. Rg dispersion studies have as yet not been carried out in southern Vermont or adjacent northwestern Massachusetts. However, this geological study will be used to make tentative predictions as to the dispersion characteristics we might expect to encounter in future dispersion studies there. We found that Rg group velocities were relatively high in the area surrounding the Waterbury Dome of southwestern CT, the Waterbury Dispersion Region of this study. Our interpretation is that the Waterbury Dispersion Region (Fig. 13a) is of very high velocity because it contains a substantial amount of Grenvillian crust as well as being associated with a strong gravity high, the latter implying an abundance of relatively near-surface gabbroic to ultramafic rocks. If so, at least the Stamford block, and possibly the Readsboro block, should have relatively high Rg group velocities (i.e. similar to those of the Waterbury DR) because, as least in the Green Mountain massif, both conditions seem to be met.

2.1.6 Tectonic Evolution of the crust of offshore and onshore New England

Hutchinson and others (1988) and Phiney (1986) provided an interpretation of several important multichannel seismic reflection lines collected by the U. S. Geological Survey as part of an assessment of the Eastern U. S. continental margin for oil and gas, in the Bay of Maine and on the Long Island Platform respectively. Skehan, Hutchinson, Hussey and Rast (1987) collaborated on a project that Skehan reported on at the International Geological Correlation Project Symposium in 1987 in Mauritania, that has implications for correlations between eastern North America and West Africa. This project was concerned with a reinterpretation of certain parts of the seismic lines (Fig. 9a and 9b) in the light of what is known about relationships between the onshore and offshore geology of New England.

Our main conclusions, based on data summarized in Skehan and others (1987) concerning the sequence in which exotic terranes of southern New England came into collision with one another are as follows: (1) The collision of the composite Merrimack Trough-Putnam-Nashoba Terrane-Hope Valley Terrane of Gondwanan or African affinities with the Bronson-Kearsarge-Central Maine terranes produced the resulting Taconic collision of the latter with the North American craton (Fig. 9b, Block C2 with C3); (2) the collision of the Esmond-Dedham Avalonian Terrane with the Hope Valley Terrane gave rise to continued underplating in the Devonian Acadian orogeny; and (3) the Alleghanian collision of the Meguma Terrane with the previously amalgamated terranes affected chiefly southeastern coastal and offshore New England (Skehan and others (1987).

Additional conclusions by these same authors (in preparation, 1988) include the following:

(1) Hutchinson and others (1988) interpreted the Ponkapoag fault, that forms the southern boundary of the Norfolk Basin (Fig. 9a) as the probable onshore continuation of the Fundy fault that cuts across the Bay of Maine. On the basis of onshore geology, it is now our opinion that the Blue Hills fault, which occurs just north of the Ponkapoag fault and of the Quincy Granite, and which probably is continuous with the Smithfield fault zone (Fig. 6a and 6b) that forms the western

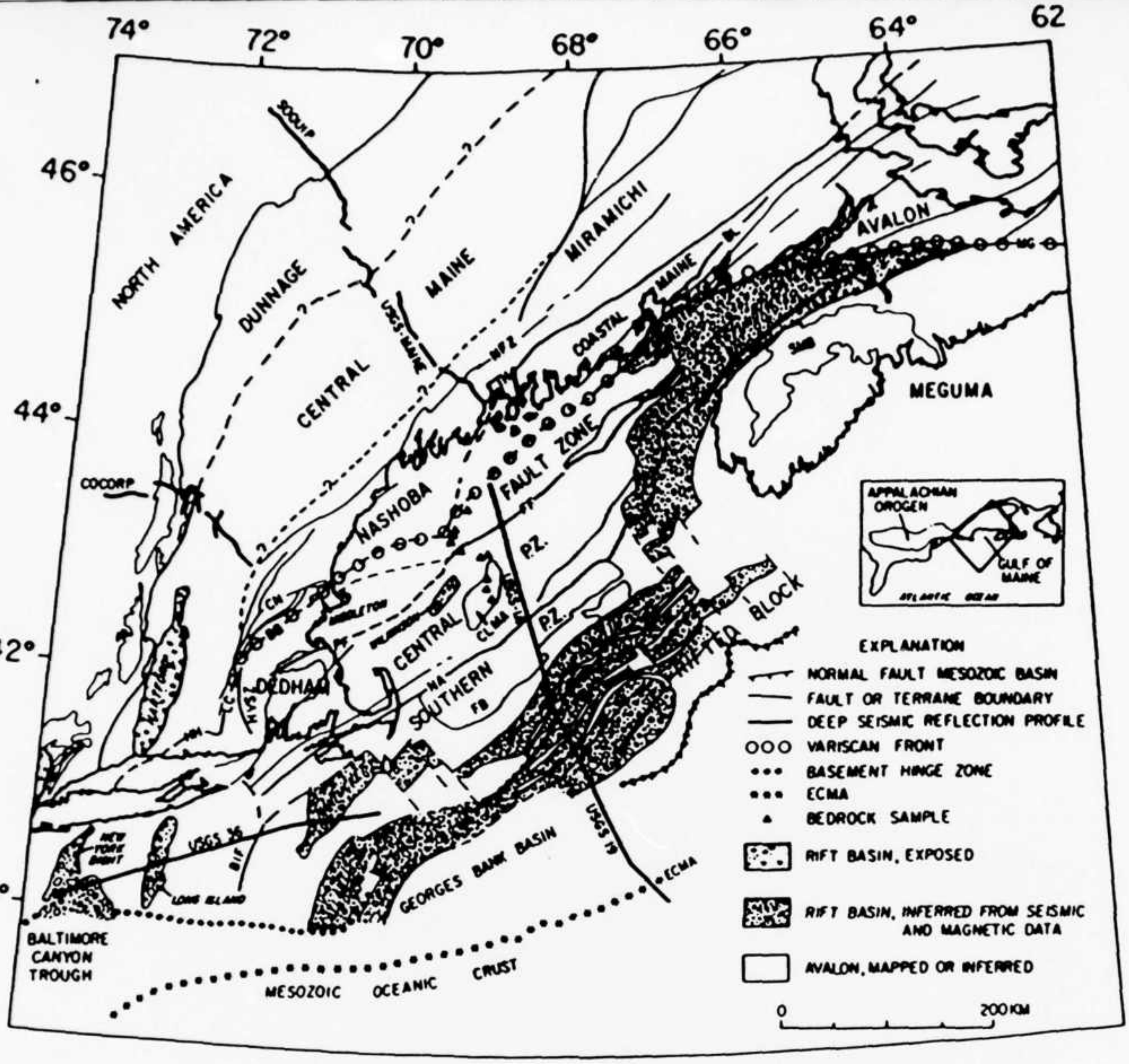


Figure 9a. Tectonic map of the Gulf of Maine and surrounding region, showing generalized terranes of the Appalachian orogen, the configuration of the continental margin, and location of the Quebec-Maine-Gulf of Maine-Georges Bank (U.S.G.S. 1A, 19) and the Long Island Platform (U.S.G.S. 36) seismic transects. Terrane boundaries are simplified from Williams and Hatcher, 1983; Zen, 1983; Zartman and Naylor, 1984; Keppie, 1985; O'Hara and Gromet, 1985; and D.B. Stewart and others, unpub. data. Abbreviations are: NFZ, Norumbega fault zone; TH, Turtle Head fault zone; BL, Belle Isle fault zone; VF, Variscan front; MG, Minas geofracture; CN, Clinton-Newbury fault; BB, Bloody Bluff fault; LC, Lake Char fault; HH, Honey Hill fault; HVSZ, Hope Valley shear zone; PF, Ponkapoag fault; FF, Fundy fault; CLMA, Cashes Ledge magnetic anomaly; NA, Nauset anomaly; BIF, Block Island fault; South Mountain batholith; FB, Franklin batholith; ECMA, East Coast magnetic anomaly; PZ, Plutonic zone (from Hutchinson and others, 1988).

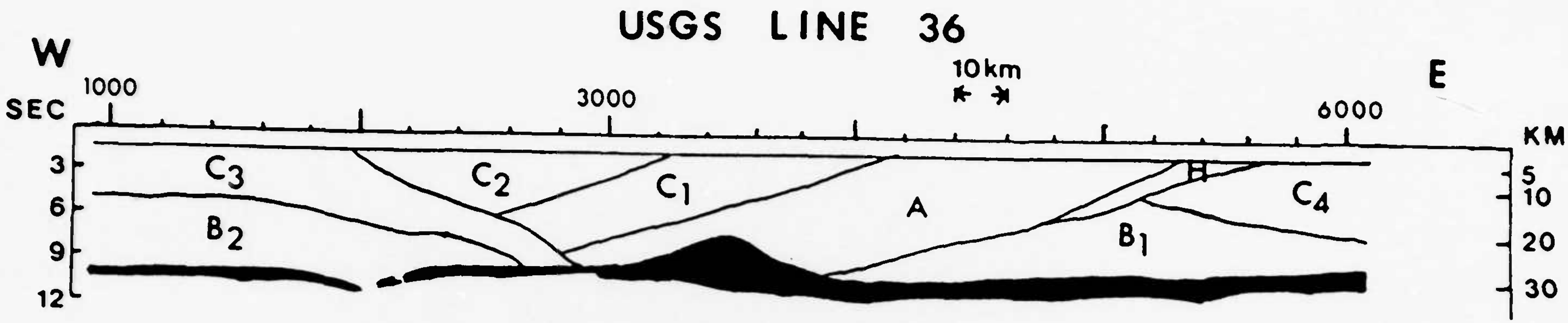


Figure 9b. Generalized interpretation of U.S.G.S. seismic line 36 (modified from Phinney, 1988).

margin of the Scituate Granite of northern Rhode Island (Watson and Skehan, in press 1988).

(2) All of the tectonostratigraphic zones from the Bronson Hill anticlinorium eastward through the Putnam-Nashoba Terrane are truncated in southernmost Connecticut against the east-northeast trending Avalonian gneisses (Fig. 9a). However, Phinney's (1986) interpretation of the U. S. Geological Survey seismic profile (Fig. 9b) indicates that terranes that probably correspond to the Bronson Hill through Putnam-Nashoba Terrane are represented on the Long Island Platform. However, the intervening occurrence of older Avalonian rocks in southern CT precludes the uninterrupted continuation of the Bronson Hill-Putnam -Nashoba sequences into the Long Island Platform. Thus we can interpret this to mean only that Long Island Sound must be underlain either by an east-northeasterly trending, southwesterly plunging anticlinorium, or by a major east-northeasterly striking fault zone that has dragged the Avalonian gneisses upward on the north side of the fault.

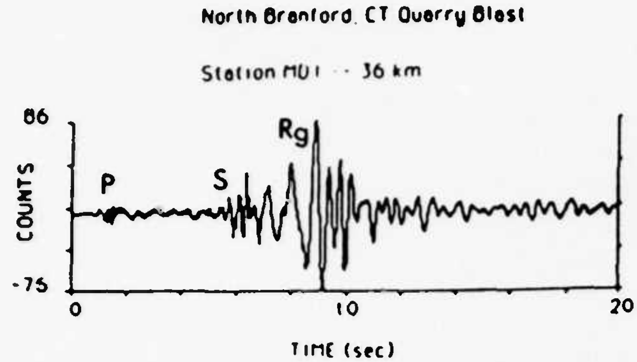
(3) Phinney (1986) interpreted the westerly dipping wedge (Fig. 9b, Block A) as the Avalonian Terrane underthrust beneath the Kearsarge- Central Maine synclinorium. However, on the basis of projections of the terranes of southern Connecticut southward, and on other considerations of the regional geology, it appears that Block A cannot be Avalonian terrane but must represent the Meguma Terrane and that the Avalon Superterrane must be represented by Block C1 (Fig. 9b) which we have reinterpreted from Phinney's seismic profile as having underthrust the Kearsarge-Central Maine synclinorium (Block C2 of Fig. 9b).

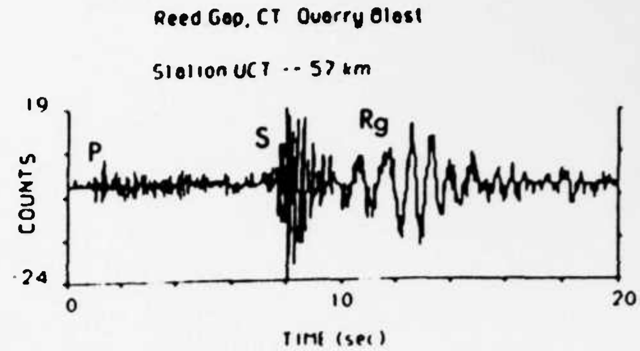
Such large scale correlations based on a combination of onshore geological and geophysical data combined with seismic profiles, such as those available in the Bay of Maine and on the Long Island Platform, may assist in resolving some of the important unanswered questions of geological and geophysical correlations.

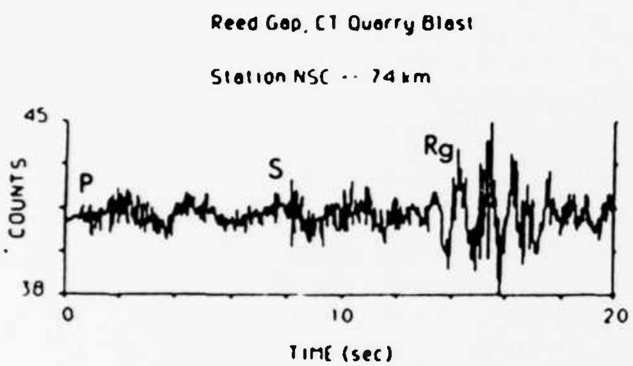
2.2 Rg Wave Dispersion, Shallow Crustal Structure and Deeper Earth Structure

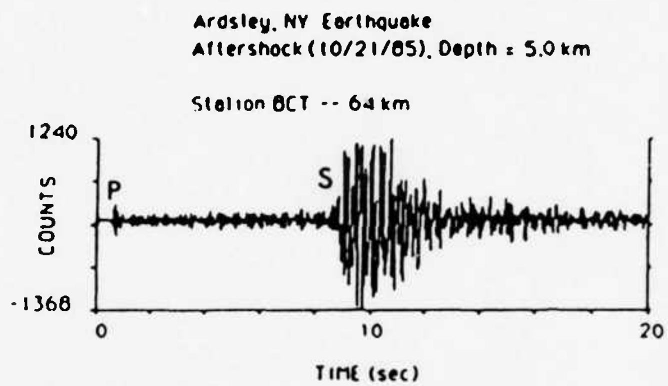
This aspect of our study was an investigation of the seismic velocity structure of the shallow crust underlying the New England Appalachians. Lateral variation in the shallow crust was analyzed using observed dispersion of Rg waves (e.g. Kafka and Dollin, 1985; Kafka and Reiter, 1987). The methods used for this part of our study are short-period analogues of surface wave techniques that have been developed for studies of long-period surface waves (e.g. Dziewonski and Hales, 1972). Computer programs for analyzing short-period Rg waves have been developed over the past few years at Weston Observatory with support from AFOSR and other agencies. The seismograms analyzed in this research are generated by quarry blasts, refraction blasts, and very shallow-focus earthquakes recorded at stations of the NESN.

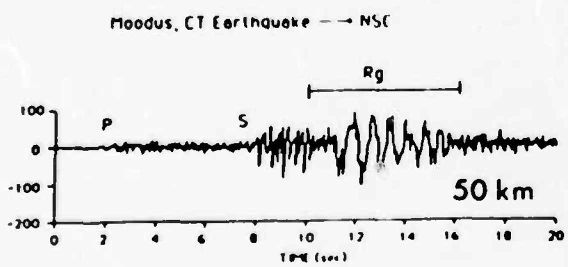
Figure 10 shows examples of Rg waves recorded from quarry blasts and shallow-focus earthquakes in New England. Rg waves recorded by the NESN range in period from about 0.2 to 2.5 sec, with the strongest signals being in the 0.5 to 1.5 sec period range. Thus, analysis of the dispersive properties of Rg reveals lateral variations at depths ranging from very near the surface down to a few kilometers in the crust. Rg dispersion studies complement other types of geophysical studies in New England that constrain physical properties in deeper parts of the earth, such as: reflection and refraction surveys (e.g. Klemperer and Luetgert, 1987), analysis of











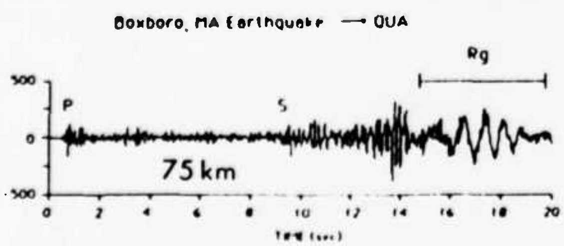


Figure 10. Seismograms of quarry blasts and earthquakes recorded in southern New England showing examples of Rg waves. The three examples of quarry blasts have prominent Rg waves because the sources are at the earth's surface, but the 5 km deep Ardsley, NY earthquake did not generate Rg waves. Since the Moodus, CT earthquake was very shallow (about 2 km), Rg waves are observed from that event. There are not enough stations located near the Boxboro, MA earthquake to constrain its depth, but the Rg waves recorded from that event suggest that it occurred in the upper few km of the crust.

teleseismic residuals (e.g. Taylor and Toksoz, 1979), and analysis of regional gravity and magnetic anomalies (e.g. Coblentz and Reidy, 1988).

The method that has been used for most of the Rg wave research at Weston Observatory involves measuring group velocity dispersion of Rg waves (e.g. Kafka and Dollin, 1985; Saikia et al., 1986; Kafka and Reiter, 1987; Kafka, 1988). Group velocity is measured using a narrow band-pass filter analysis (Dziewonski et al., 1969). The observed group velocities are inverted for shallow crustal structure using both trial-and-error as well as linearized least squares inversion (e.g. Backus and Gilbert, 1970; Der and others, 1970). Based on that methodology, we have found significant lateral variation in the shallow crustal structure underlying various parts of New England. Our results suggest that in some parts of the region, lateral variation in shallow crustal structure correlates with variation in geology, but in other parts, lateral variation in shallow crustal structure is not correlated in any obvious way with variation in geology.

We have also been investigating the possibility of applying the two-station method (Brune and others, 1960) to measure phase velocities of Rg waves recorded in New England. The results indicate that both phase and group velocities of Rg waves could be obtained for specific paths by installing portable seismic stations at appropriate points along paths from quarries that blast frequently. By combining group and phase velocities from such experiments, lateral variations in Rg velocities could be delineated in greater detail, and thus more detailed information about lateral variation of the shallow crust could be obtained.

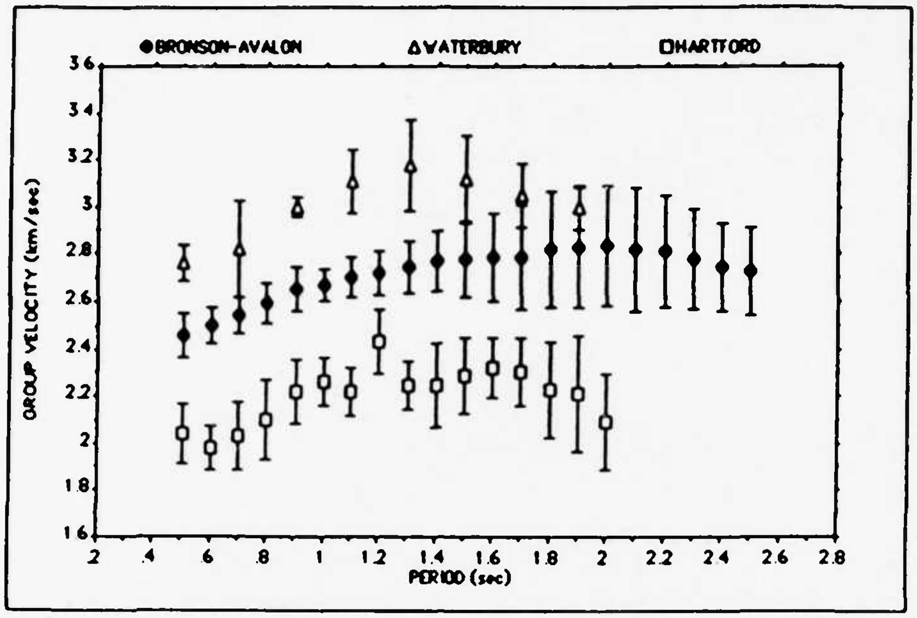
2.2.1 Group Velocity Dispersion

During the past several years, a number of studies of lateral variation of Rg wave dispersion in New England have been undertaken at Weston Observatory (e.g. Kafka and Dollin, 1985; Kafka and McTigue, 1985; Saikia and others, 1986; Kafka and Reiter, 1987; Kafka 1988). One area that has been investigated is southeastern Maine (Kafka and Reiter, 1987). Using Rg waves generated by USGS refraction blasts, we found evidence for lateral anisotropy in the shallow crust beneath southeastern Maine. Rg wave group velocities were found to be faster in the direction parallel to the structural grain of the Appalachians and slower in the direction transverse to the grain.

The area that has been most extensively studied as part of this research is southern New England (SNE). In SNE, we have found no evidence for lateral anisotropy in the shallow crust, but we did find evidence for lateral heterogeneity. Since most of the research for this project was concentrated in SNE, a thorough review of our results from that area is presented in the remainder of this section.

Figure 1 shows the paths of Rg waves from a number of studies in SNE. The results of Rg dispersion studies in SNE are summarized in Figures 11, 12a, 12b, and 13. As those figures demonstrate, there appear to be some parts of SNE in which the shallow crust is very homogeneous (geophysically) across a wide geographical area, but in which geological mapping has discriminated between a wide range of geological structures. On the other hand, some regions appear to be characterized by systematic lateral variations in Rg dispersion.

The following regionalization is our current interpretation of the results of our Rg studies in southern New England (Kafka and Skehanm in review 1988). It is a



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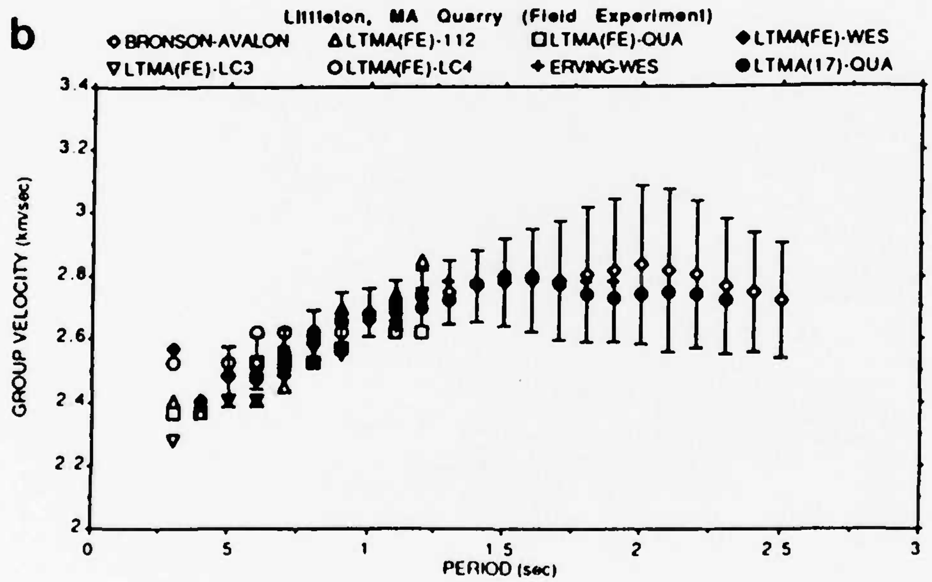

Figure 11. (a) Mean and standard deviation of Rg group velocities for paths contained within three dispersion regions in southern New England. Dispersion regions corresponding to these data are shown in Figure 12(a). The data used for these statistics are from the higher quality Rg signals analysed by Kafka and Dollin (1985), Kafka (1985), Kafka and McTigue (1985), McTigue (1986), Saikia et al. (1986), and Gnewuch (1987). These statistics represent a subset of the paths shown in Figure 1. However, all of the data from the paths shown in Figure 1 are consistent with the classification shown here and in Figure 12(a). (b) Group velocity results from the Littleton, MA quarry field experiment LTMA(FE), the Erving, MA earthquake, and an additional quarry blast from the Littleton, MA quarry. Paths for the Littleton, MA quarry blast experiment are shown in Figure 17. Open diamonds and error bars indicate the mean and standard deviation for the Bronson-Avalon dispersion region.

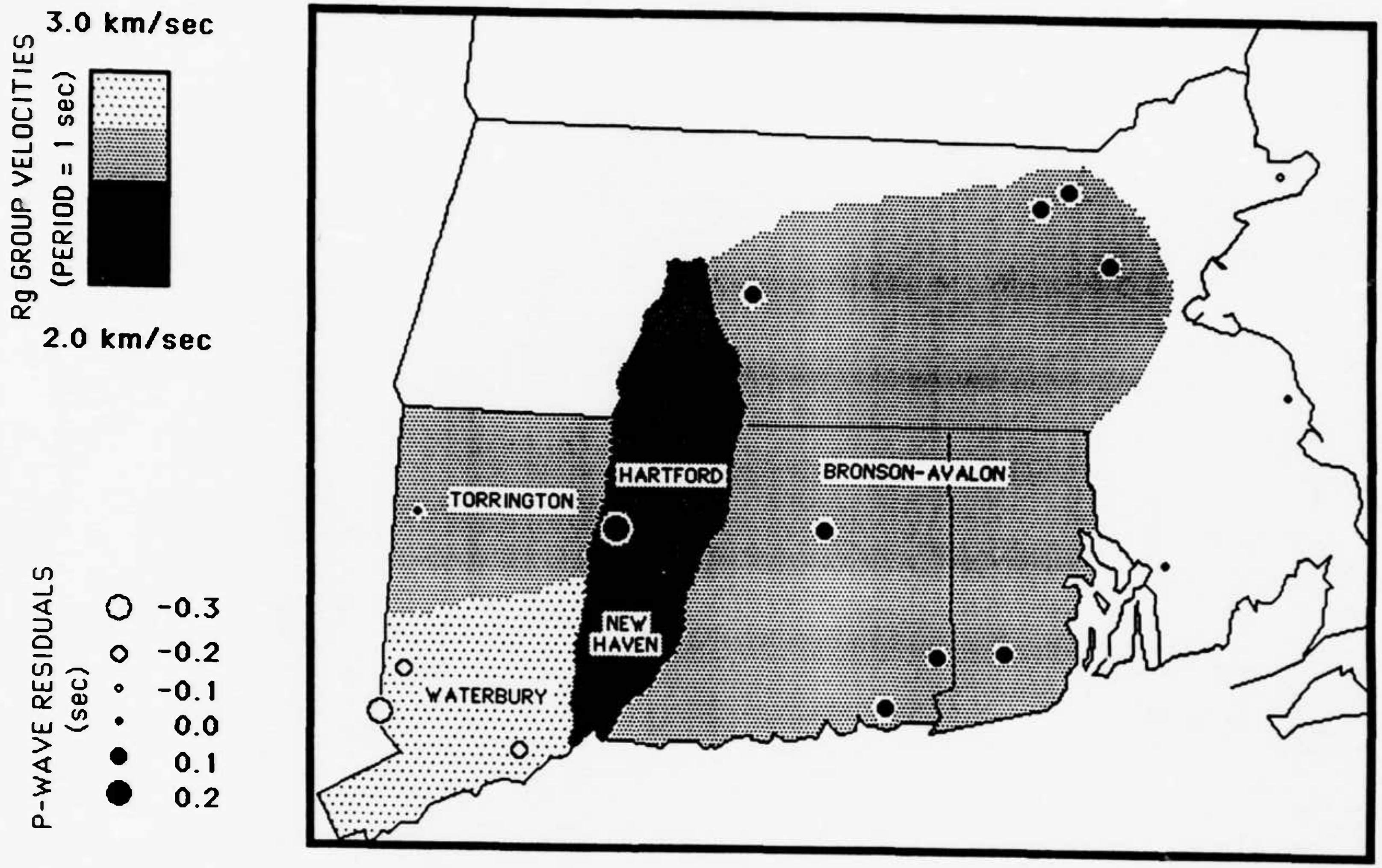

Figure 12(a). Rg dispersion regions and teleseismic residuals in southern New England. Dispersion data are from Kafka and Dollin (1985), Kafka (1985), Kafka and McTigue (1985), McTigue (1986), Saikia et al. (1986), and Gnewuch (1987). The names given to the dispersion regions are from Skehan and Kafka (1987). Teleseismic residuals are from Taylor and Toksoz (1979) and Peseckis and Sykes (1979).

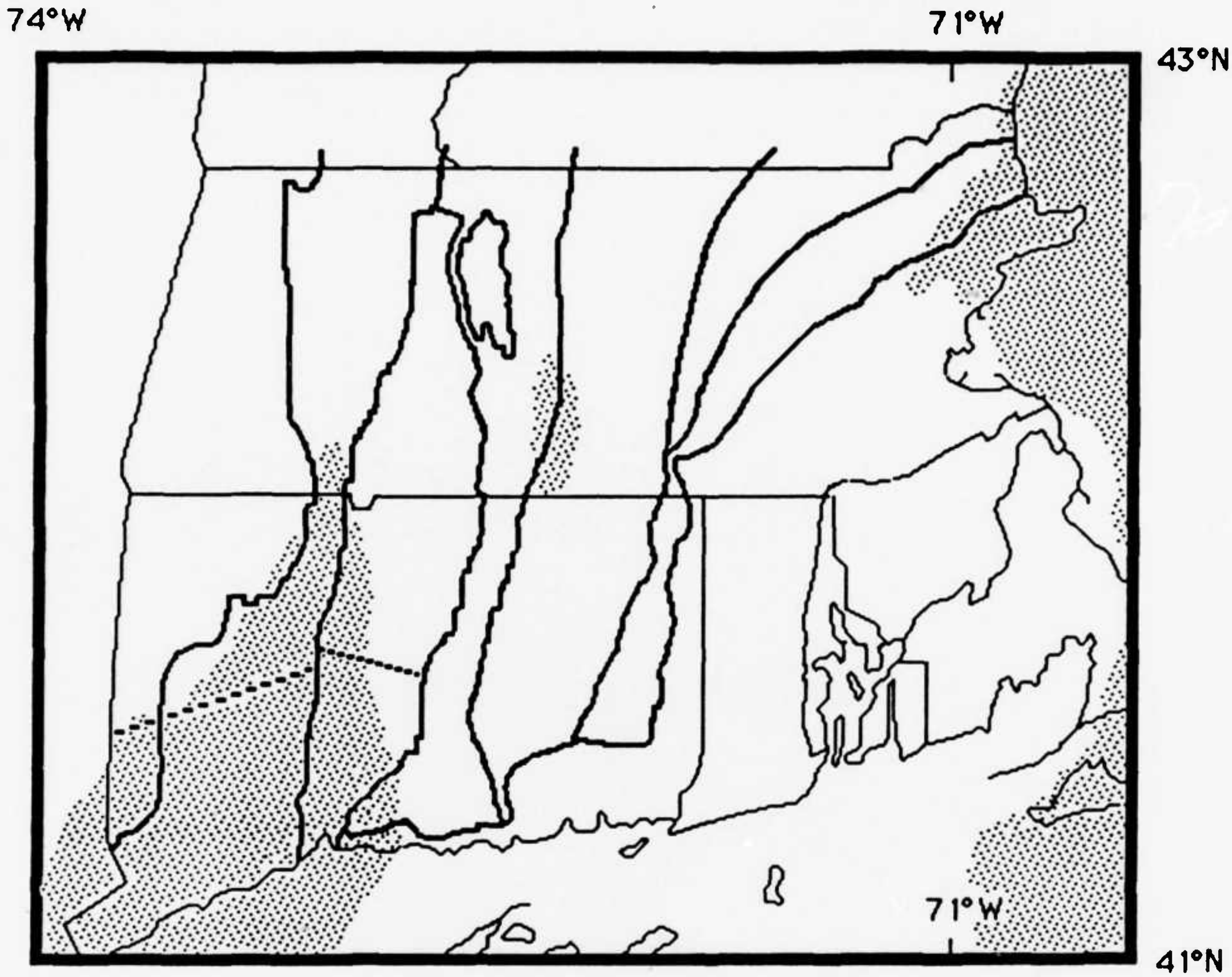

Figure 12(b). Relationship between gravity anomalies, dispersion regions and major geologic structures in southern New Enland. Shaded areas represent areas where Bouguer gravity anomalies exceed +10 mgal (adapted from Haworth et al., 1980).

presented here as a working hypothesis for our studies of the relationship between geology, shallow crustal structure, and deeper earth structure:

(1) There are only minor variations of Rg group velocities across a large part of southeastern New England, extending from the Bronson-Hill anticlinorium to the Avalonian Superterrane. Based on that similarity in Rg dispersion and the geology of that area, Skehan and Kafka (1987) named that part of SNE the Bronson-Avalon dispersion region (BADR, Figure 12a). The shallow crustal structure appears to be quite homogeneous throughout the BADR.

(2) The northern part of the Hartford Rift Basin is characterized by very low Rg group velocities. These low velocities are not surprising since that area is covered by glacial lake sediments overlying the lithified sedimentary rocks of the Hartford Rift basin. However, in the southern part of the basin, Rg velocities are nearly as high as in the crystalline basement provinces to the east (Kafka and Dollin, 1985). Skehan and Kafka (1987) suggested that these higher velocities are probably due to a combination of a larger volume of basalt and to the presence of crystalline bedrock at relatively shallower depths (ca. 1.5 km on average) in that area than is present in the Hartford area where the average depth to crystalline bedrock is ca 2.5 km (Fig. 14).

(3) The shallow crust in southwestern Connecticut is characterized by significantly higher seismic velocities than in the BADR. Skehan and Kafka (1987) suggested that these high velocities were a result of the shallow crust of the Connecticut Valley synclinorium being enriched in oceanic type crust (ophiolites).

The higher frequency Rg waves do not sample material at depths greater than a few kilometers, but studies of teleseismic residuals suggest that lateral variations observed in the Rg studies extend deeper into the crust. The pattern of lateral variation of Rg dispersion is nearly identical to the pattern of positive and negative teleseismic P-wave residuals (Figure 12) from studies by Taylor and Toksoz (1979) and Peseckis and Sykes (1979). It is difficult to say how deep these variations penetrate, but a minimum depth can be roughly estimated by comparing the Rg and teleseismic residual results. In the 0.5 to 1.5 sec period range, where Rg signals are the strongest, the group velocities in the Waterbury dispersion region are about 12% higher than in the BADR. If the same percentage of difference between the two regions is assumed for P wave velocities at depth, then it would be necessary to extend that lateral variation down to about 15 km to explain the observed differences in teleseismic residuals (0.3 sec). As a rough estimate of the maximum depth of lateral variation, Taylor and Toksoz (1979) concluded that lateral variations revealed by their analysis of teleseismic residuals may extend to depths as great as 200 km.

Further evidence for a deep-seated crustal feature that correlates with the higher velocities found for the Waterbury dispersion region and for the New Haven dispersion region is found in the pattern of gravity anomalies in SNE. A prominent Bouguer gravity high is found in southwestern Connecticut [Figure 12(b)], in the same region where we observed higher Rg velocities and where negative teleseismic P-wave residuals are observed.

Models of the seismic velocity structure of the shallow crust beneath various parts of New England have been found by inverting the Rg wave group velocities for shear wave velocities using a linearized least squares inversion (e.g. Saikia et al., 1986; Kafka and Reiter, 1988). Examples of shallow crustal models corresponding to several Rg dispersion regions in SNE are shown in Figure 13.

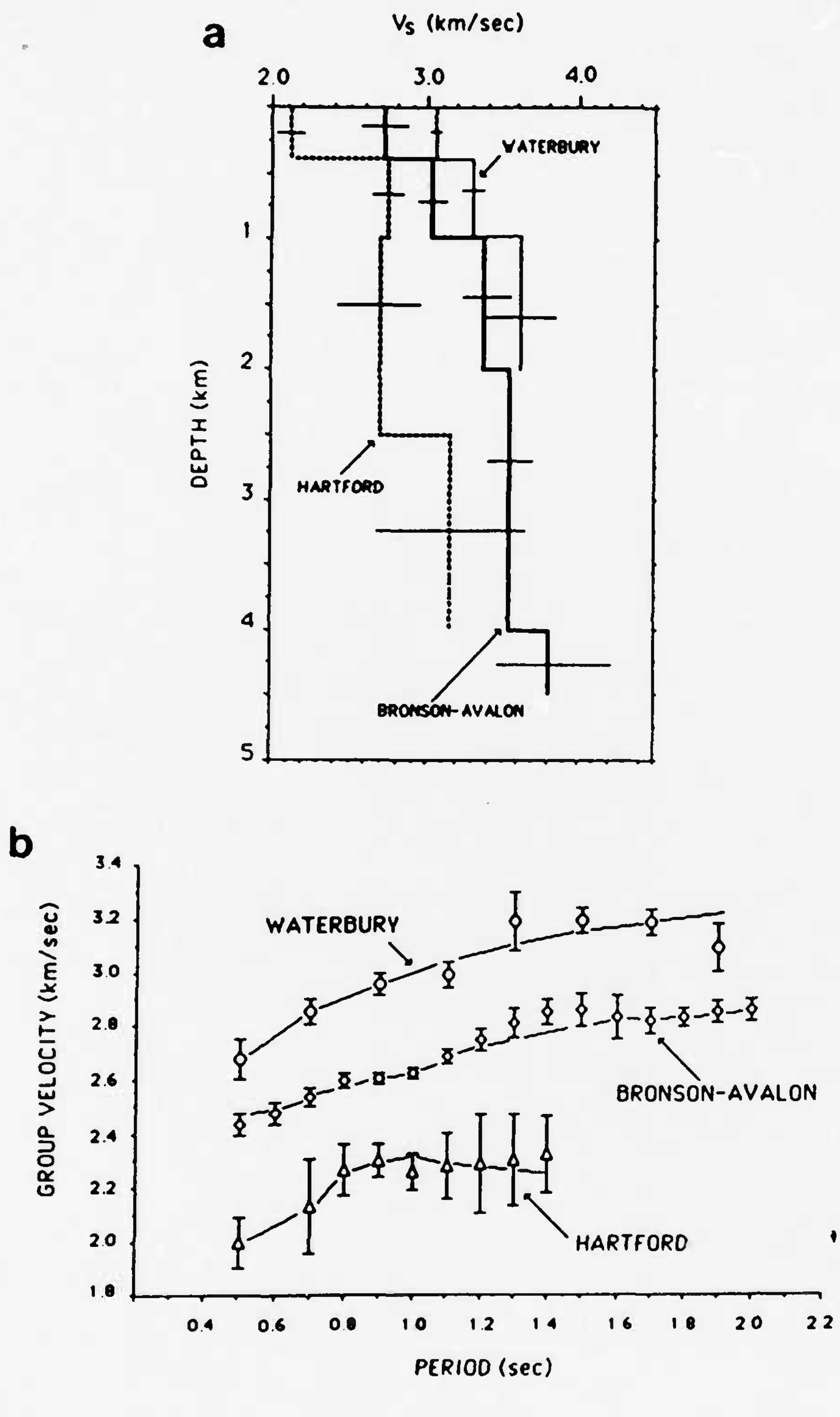

Figure 13. (a) Models of the shallow crustal structure obtained from linearized inversion of Rg group velocities for subsets of paths contained within the hypothesized dispersion regions (DR's) in southern New England (from Saikia et al., 1986; Gnewuch, 1987; and Kafka and Reiter, 1988). (b) Mean, standard deviation and calculated dispersion corresponding to models shown in (a). The data shown for the Waterbury DR are for paths from the North Branford, CTquarry to station BCT. The data shown for the Bronson-Avalon DR are for paths from the Wauregan, CT quarry to the Moodus array. The data shown for the Hartford DR are for portions of paths traversing the Hartford DR (after removing the effect of the Bronson-Avalon DR, using an approach described by Kafka and Dollin, 1985).

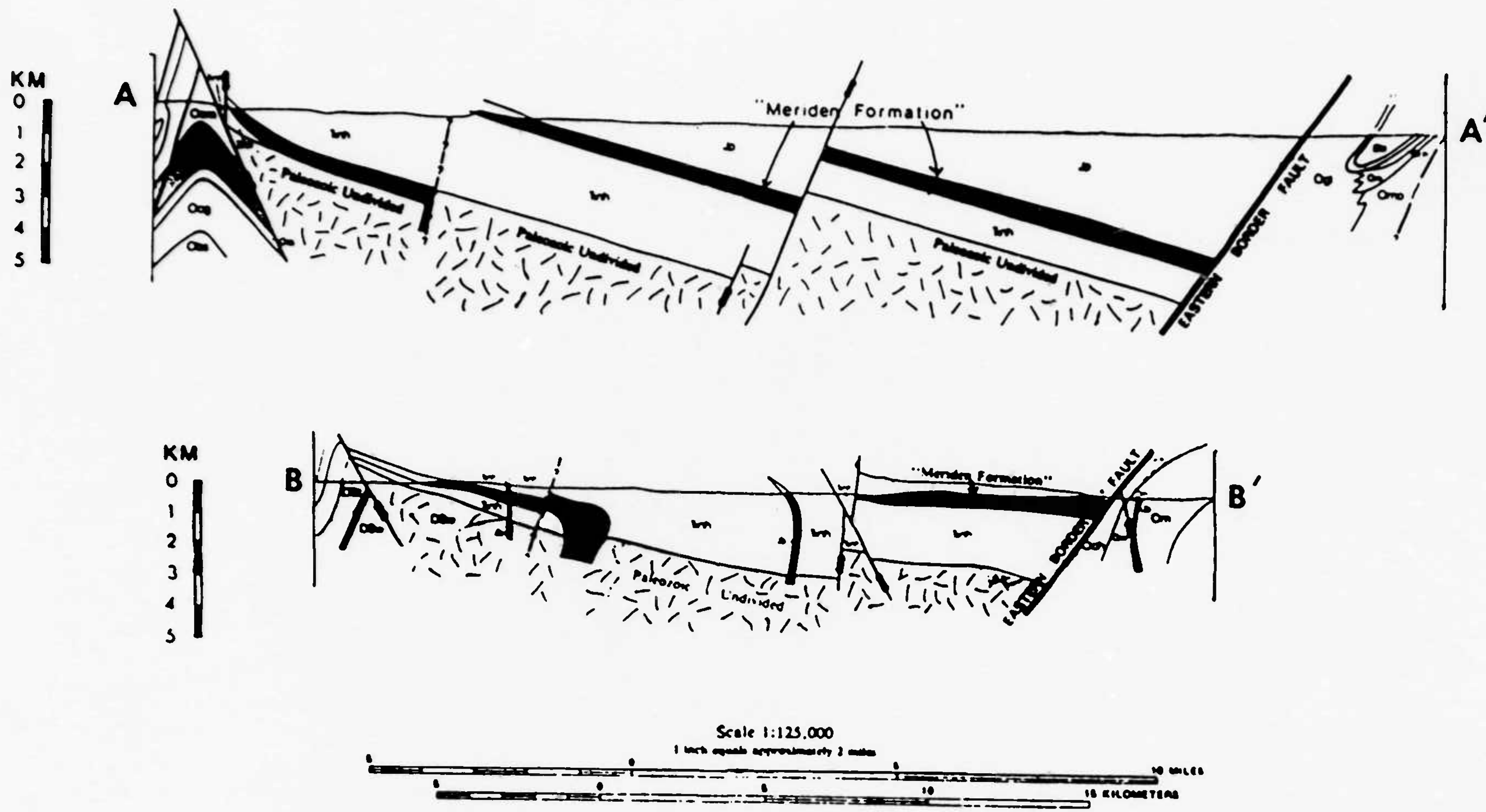

Figure 14. Geological cross sections through the northern and southern parts of the Mesozoic Hartford Basin. It shows fault blocks with (a) a relatively thick sedimentary cover and enclosing basaltic rocks overlying Paleozoic basement; and (b) a similar but thinner sequence of Mesozoic rocks above Paleozoic basement.

2.2.2 Phase Velocity Dispersion

Our research to date on phase velocities of Rg waves has focused on how precisely and accurately phase velocities can be measured for the short-period Rg waves recorded in New England. The two-station method (Brune et al., 1960) has been used for these phase velocity experiments. The accuracy and precision of these phase velocity measurements depends on a number of factors, including: (1) the accuracy and precision of phase measurements, (2) the distance between the two stations (relative to the wavelength being studied), (3) the extent to which the fundamental mode has been isolated well enough so that higher modes (or other seismic waves) do not interfere with the phase measurements, and (4) the extent of lateral variation in the shallow crust between the two stations.

The wavelengths of Rg waves with periods between 0.5 and 2.5 sec are about 1 to 6 km. Thus, station spacings of much greater than about 10 to 15 km yields very little control on phase velocities (except for the longer periods). For station spacings that large, the fraction of a complete phase cycle that is actually measured is only a small percentage of the total number of wavelengths between the two stations. The signal is weak for the longer periods, and thus the phase can be difficult to measure for the longer periods. Furthermore, any significant lateral variation in structure might be expected to be greater for shorter periods than for longer periods. Thus, the station spacing appropriate for phase velocity experiments must result in the proper combination of all the factors associated with measuring phase velocity if the experiment is to be successful.

We have used the array of six stations in the vicinity of Moodus, CT (Fig. 15) as well as field data from portable seismic stations installed near Weston Observatory as an empirical test for measuring phase velocity. Initially, we found that there was so much scatter in the observations that only very limited information could be obtained from such studies [Fig.16(a)]. However, we were able to greatly improve this methodology by using a time variable filter (Landisman et al., 1969) to extract the fundamental mode Rayleigh wave from the seismogram [Fig.16(b)]. The precision is greatly improved by applying the time variable filter to the data (in that all measurements across the Moodus array give nearly the same result). In addition, this experiment gives some indication of the accuracy of the phase velocity results, since there is general agreement between the observed phase velocities and phase velocities calculated from the seismic velocities observed in the Moodus borehole (Kafka and Reiter, 1988; and Dan Moos, personal communication). Apparently, the most serious factor causing the scatter in the Rg phase velocity measurements was that higher modes (and perhaps other wave types such as body waves and/or scattered wave energy) were interfering with the fundamental mode.

The ability to measure phase velocities in addition to group velocities should greatly enhance these Rg studies. Stations can be installed at specific sites to investigate whether specific geologic structures are characterized by distinct seismic velocities in the shallow crust. Specific hypotheses regarding lateral variation in the shallow crust can be tested in this way.

2.3 Electromagnetic Characteristics of Geological Structures

The electromagnetic investigation of the crustal structure of a part of eastern Massachusetts had three stages. Seismic investigations take advantage of the

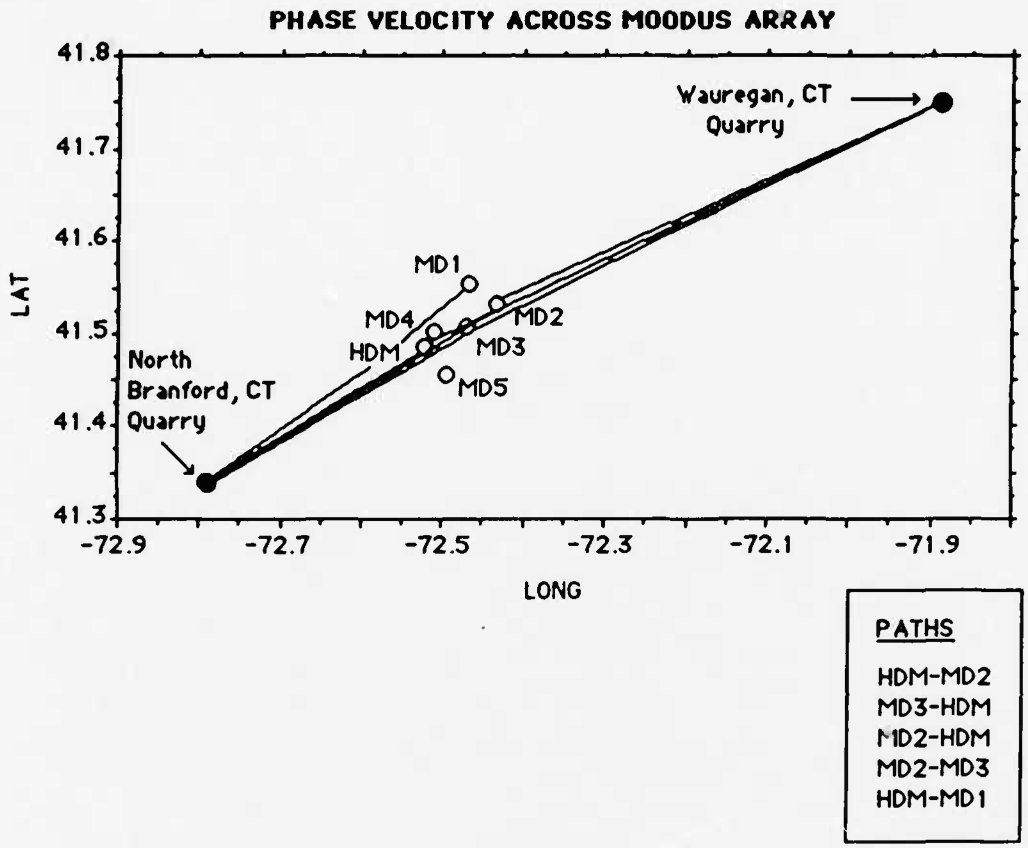

Figure 15. Locations of quarry blasts and stations used for the phase velocity experiments discussed in this report.

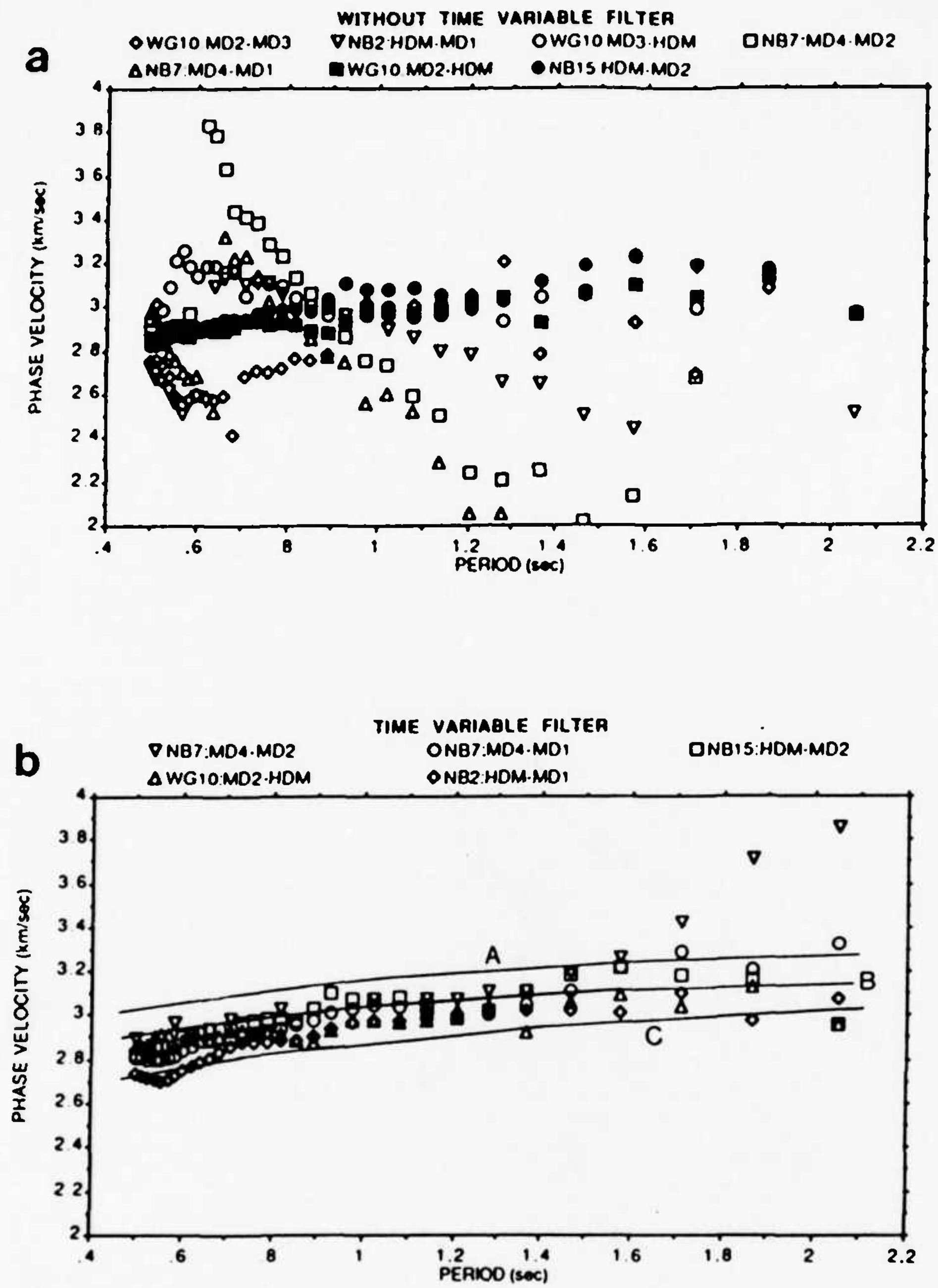

Figure 16. Measurements of pahse velocities of Rg waves propagating across the Moodus, CT seismic array. (a) Before applying time variable filter. Closed symbols are data from seismograms that had clearly recorded Rg waves, with little interference from noise or other phases. (b) After applying time variable filter. Data shown with closed symbols in (a) are unfiltered in (b). All other data in (b) are from filtered seismograms. Curve labelled A is the calculated phase velocity dispersion for the Waterbury DR model shown in Figure 13. Curve labelled B is the calculated phase velocity dispersion using the Vp and Vs values obtained from a 1.5 km deep borehole in the interior of the Moodus array (Dan Moos, personal communication). Curve labelled C is the calculated phase dispersion for the Bronson-Avalon DR model shown in Figure 13.

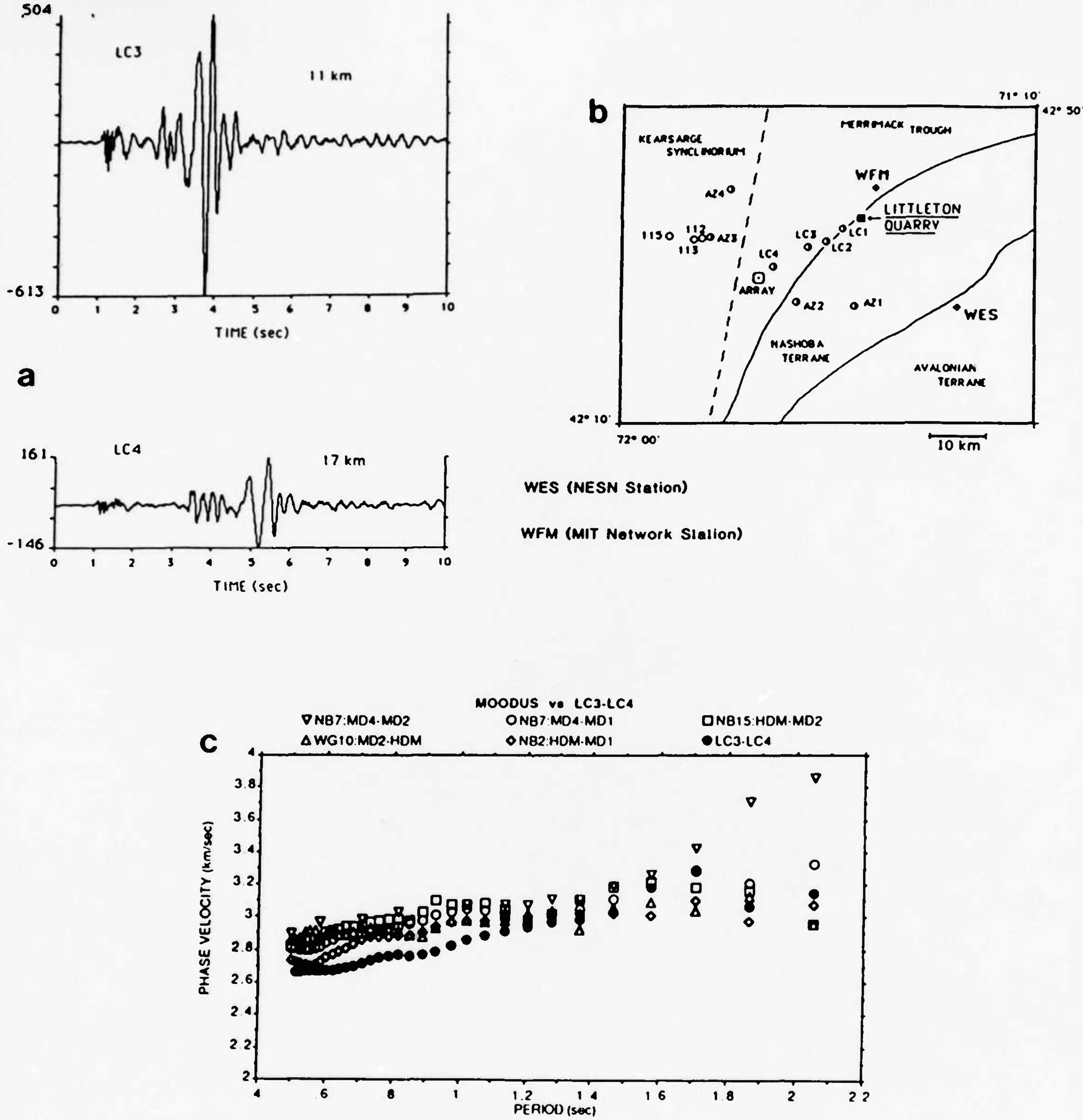

Figure 17. Field data recorded in summer of 1987 from a quarry blast located in Littleton, MA quarry. This experiment was a cooperative project involving personnel from Weston Observatory, Massachusetts Institute of Technology, Air Force Geophysics Laboratory, Southern Methodist University, and Air Force Weapons Laboratory. (a) Vertical component seismograms from stations LC3 and LC4. (b) Map showing locations of portable stations. (c) Phase velocities measured for the path from LC3 to LC4 compared with phase velocities measured for Rg waves propagating across the Moodus array (see Figure 16).

mechanical properties, the density and elasticity of earth materials. Electromagnetic methods depend on the magnetic permittivity and electrial conductivity of these same materials. The external time-varying magnetic fields induce electrical currents in the conducting earth. These currents generate internal magnetic fields. Magnetic field measurements at the surface of the earth are a combination of both internal and external fields. Methodologies to infer electrical conductivity depend primarily on the capacity to separate the internal and external fields. Geomagnetic observatory data must be separated into parts of external and internal origin. Aeromagnetic maps display only the effects of induction. The VLF methods make use of the simultaneous measurement of external magnetic field and the induced electrical and magnetic fields.

2.3.1 Processing Data from Sudbury and Weston Magnetic Observatories

Initially data from Boston College's magnetic observatory at Sudbury, MA, (Fig. 1) a component of the USAF continental USA network of magnetic observatories, was processed to develop induction arrows, indicative of electrical conductivity variation in the vicinity of the station. Single station data can be processed to identify the direction to conductive anomalies, but cannot yield the exact location and depth of the anomalous structure. This phase of our analysis, a combination of the methods of Schmucker (1970) and Everett and Hyndman (1967), concentrated on the daily variation of the magnetic field, since the available data was digitized at hourly intervals. Because external field source configurations cannot be specifically identified at a single station, the analysis was limited to the longest periods (24 hrs to 8 hrs) whose source field configurations can be assumed. After the Sudbury station was discontinued, the instrumentation was installed at Weston Observatory. Similar data processing of Weston data was conducted with the expectation that the depth of the conductive anomaly might be located by combining the induction arrows of the two sites. However, it proved to be impossible to separate source field effects (although we used the same months of the year) from subsurface anomalous effects, and thus the depth of the anomalous conductivity structure could not be defined. The induction arrows clearly demonstrated a strong electrical conductivity contrast across the Bloody Bluff fault zone, probably due to the mineralization and fluid content of the crushed zone. Local conductivity structure may be defined by this methodology, but it demands the use of an array of stations recording a the same time.

2.3.2 Defining the Geometry of the Bloody Bluff Fault Zone and Adjacent Structures

The purpose of the second phase of the study was to define the geometry of the Bloody Bluff Fault Zone (BBF) (Figs. 18, 19a and 19b) and adjacent geological structures from an analysis of aeromagnetic maps. The BBF is an important tectonic boundary separating highly metamorphosed, dominantly volcanic and volcaniclastic rocks of the Putnam-Nashoba Terrane and metasdimentary rocks of the Kearsarge-Central Maine synclinorium, from the Avalonian Superterrane (Fig. 1). The Putnam-Nashoba rocks are regarded by Skehan and Rast (1983) as a Late Proterozoic-early Paleozoic accretionary wedge and ocean floor deposits. These they interpret as having been associated with the western margin of African Gondwanaland and thus representing an exotic terrane, which has been welded onto the Bronson Hill volcanic arc that lay on the seaward or eastern side of the North American continent (Fig. 1).

The BBF consists of a 1 to 2 km wide zone of mylonites and intrusive bodies. While the zone is a significant regional structure, its geometry has been interpreted

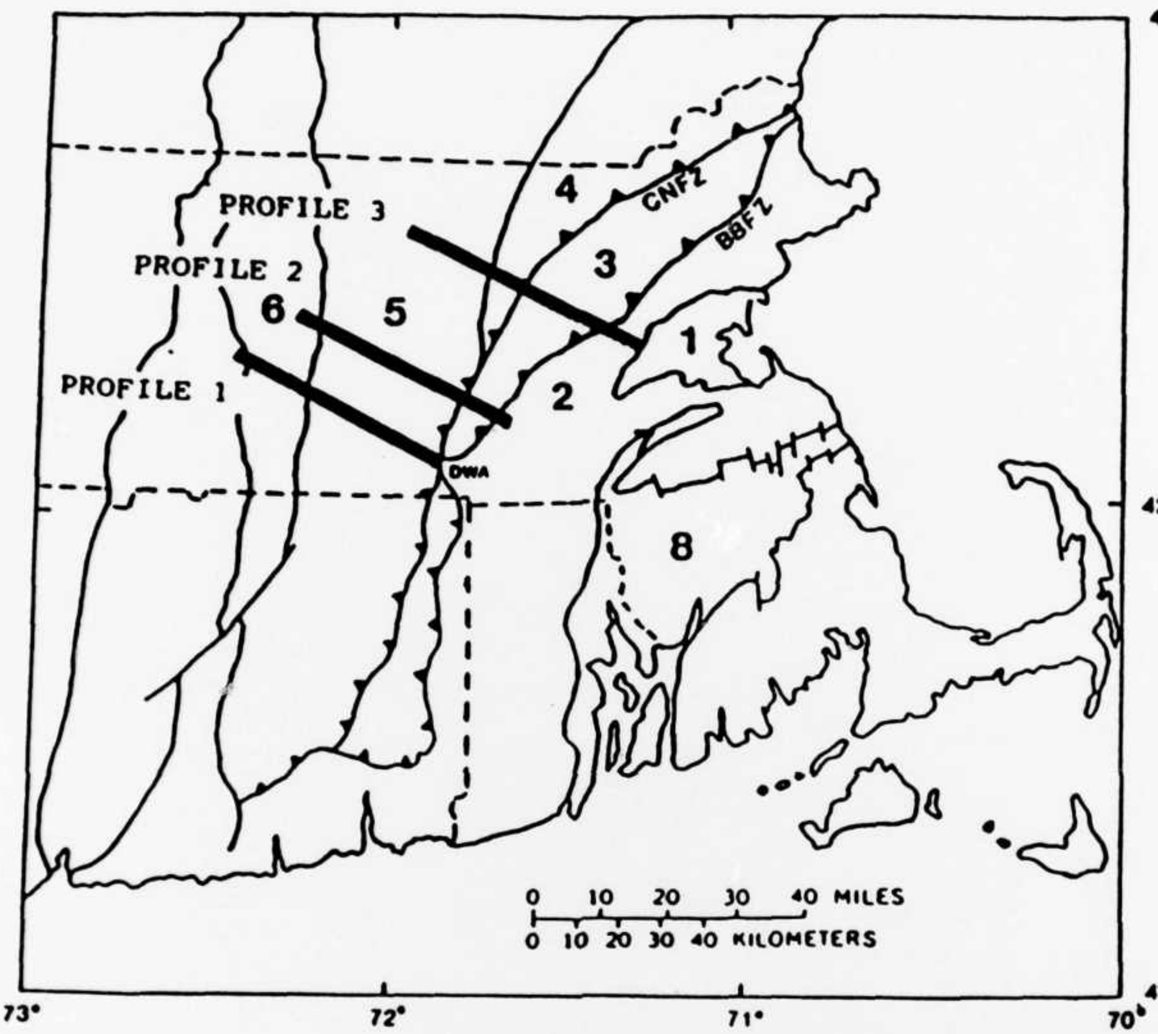

Figure 18. Regional tectonostratigraphic map with the pertinent terranes marked as well as the two regional thrust faults, the Bloody Bluff, and the Clinton-Newbury. The Aeromagnetic profiles which were modeled are also marked. The Avalonian Terane lies south of the Bloody Bluff fault.

1..........Boston Basin
2..........Esmond-Dedham Terrane
3..........Nashoba Block
4..........Kearsarge-Central Maine Synclinorium
5..........Merrimack Synclinorium
6..........Bronson Hill Anticlinorium
7..........Norfolk Basin
8..........Narragansett Basin
BBFZ....Bloody Bluff fault zone
CNFZ....Clinton-Newbury fault zone
DWA....Douglas Woods Anticline

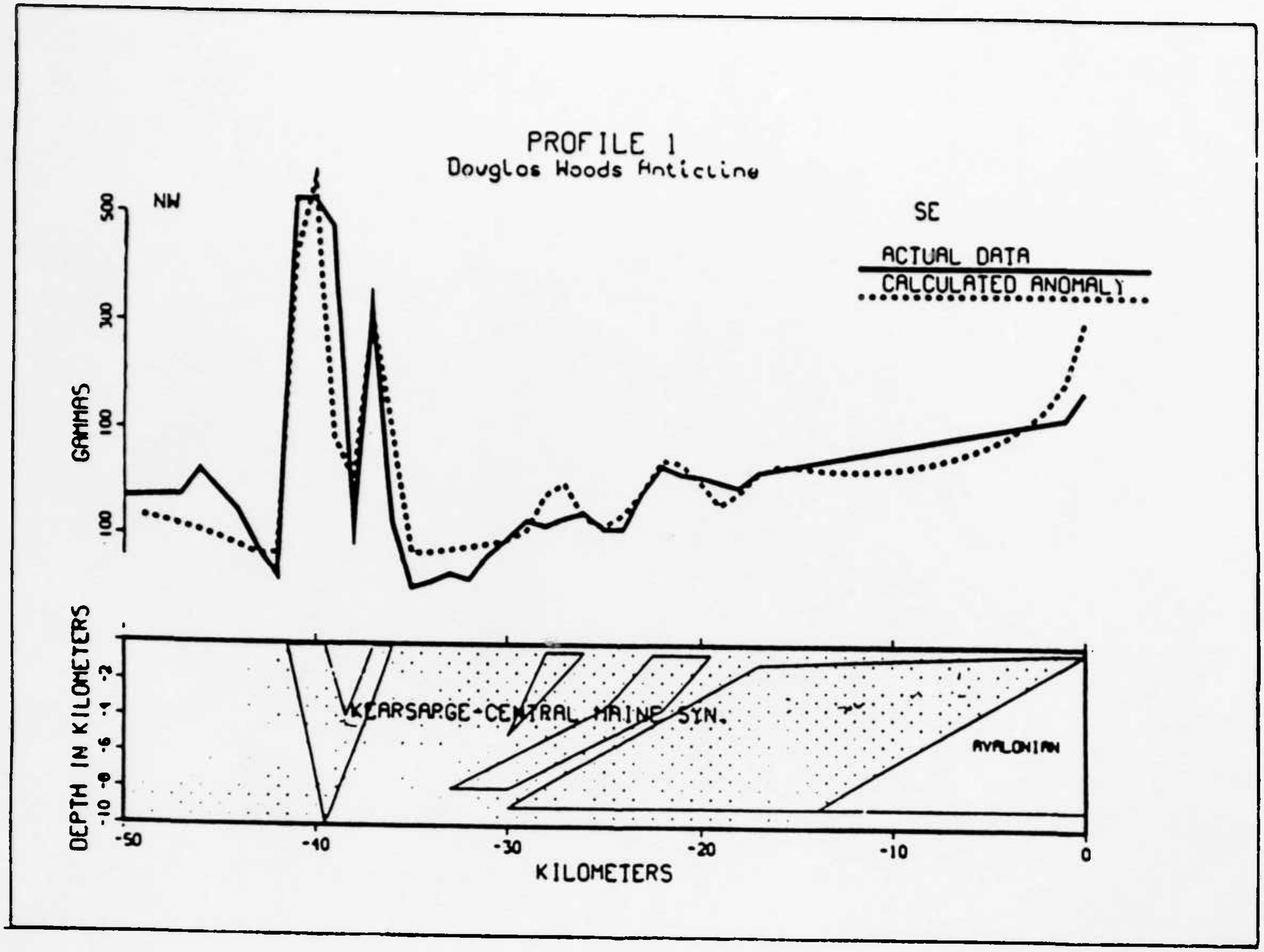

Figure 19(a). The fit of the model to the actual data along Profile 1 (Figure 17) showing the subsurface geology based on Zen (1983).

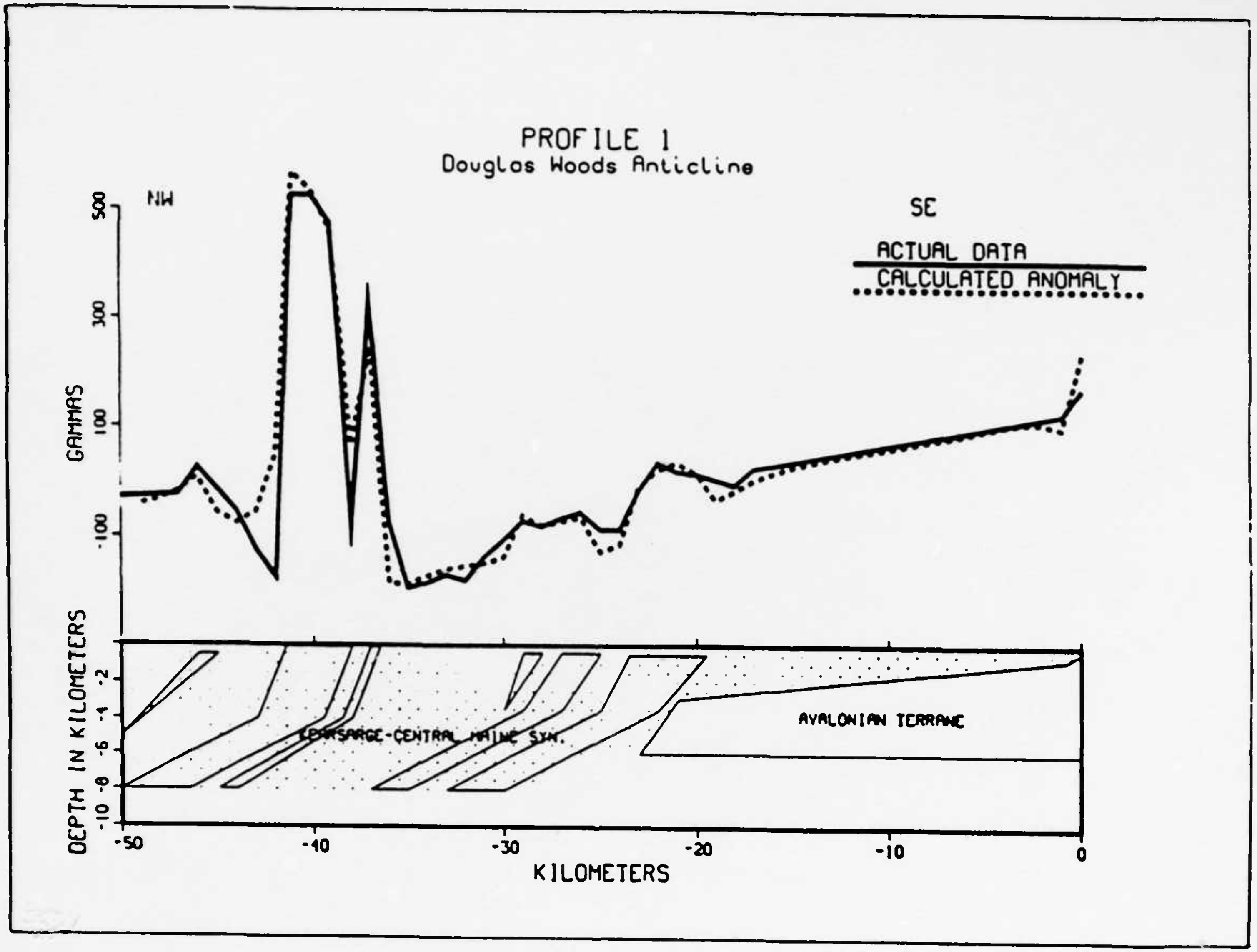

Figure 19(b). A fit of the model to the actual data along profile 1 (Figure 17) showing a better match than Figure 19(a) resulting from modification in the geology based on McTigue (1986).

as a west-dipping thrust with extensive strike-slip motion with an undetermined amount of displacement (Murray and Skehan, 1979). The area south of the fault is dominated by an extensive series of mafic bodies which have a high magnetic signature (Alvord et al., 1976). This contrast proved to be important in the construction of geologic models.

The analysis had two steps: 1) the spectra of three profiles (Fig. 18) were analysed to determine depths to source, and 2) this information was combined with the results of studies by Zen (1983), McTigue (1986) and Fisk (1985) to construct geologic models whose magnetic structure may be compared with existing aeromagnetic data, a forward modelling process.

Spectral analysis of aeromagnetic data has been used elsewhere to determine depth to basement (Spector and Grant, 1970) or depth to the Curie-point isotherm (Shuey and others, 1977). The method has normally been applied to two dimensional data; the depth is calculated from the slope of the log power spectrum. Treitel and others (1971) applied this technique to single profile data to determine the depth to basement in sedimentary basins where the basin-filling sediments have relatively no magnetic signature. We adopted this methodology in an attempt to determine the average depth to Avalonian gneisses of the Douglas Woods anticline (DWA of Figs. 18, 19a and 19b), the so-called "Avalonian Indentor" with the realization that computed depths may be somewhat smaller than actual depths due to the shielding of overlying magnetic rocks of the adjacent Marlboro and Nashoba amphibolites and gneisses of the Putnam-Nashoba Terrane and the metasedimentary schists and gneisses of the nearby Kearsarge-Central Maine synclinoroum.

Three profiles (Fig. 18) were digitized from the USGS aeromagnetic quadrangle maps. Spectral analysis yielded relatively shallow depths and suggested that the large scale magnetic sources were flat-lying. To distinguish between conflicting geological models of the subsurface structure, e.g. Zen (1983) and McTigue (1986), total magnetic field profiles of the structures were generated using the program of Won and Bevis (1987). A single example is shown in Figures 19a and 19b. The calculated profile of 19b is the better fit to the actual data. Detailed analyses of all profiles are contained in Luce (1988). The results of the analysis, Figs. 19a and 19b, suggest that thin-skinned tectonics, interpreted on the basis of the presence of brittle thrust features that are eastward verging, was the dominant process in the geological evolution of eastern Massachusetts. The foreland belt to the east of the BBF, is comprised of the Avalonian Esmond-Dedham Terrane. The presence of thrust faults vergent toward the foreland is typical of mountain belts in general, and in this case is one of the bases for the interpretation that Avalon was attached to the Gondwanan continent to the east. During the Acadian Orogeny, the Avalonian foreland of this continent was thrust beneath the sedimentary rocks of the basin to the west. The fault geometry is that of a ramp structure consisting of high-angle thrusts which flatten with depth to the NW. Consistent with this reional model is the initial high dip of the thrust faults (60-80 degrees), followed by low angles of 10 degrees at depths of only one to three km, thus indicating that the BBF constitutes a ramp structure.

In summary, we conclude that in a forward modelling mode, aeromagnetic data can be used to distinguish between conflicting geological interpretations of subsurface structure. If possible, such interpretation should be reinforced by ground traverses since details of geological contacts are sometimes blurred at the elevation of the flight-lines.

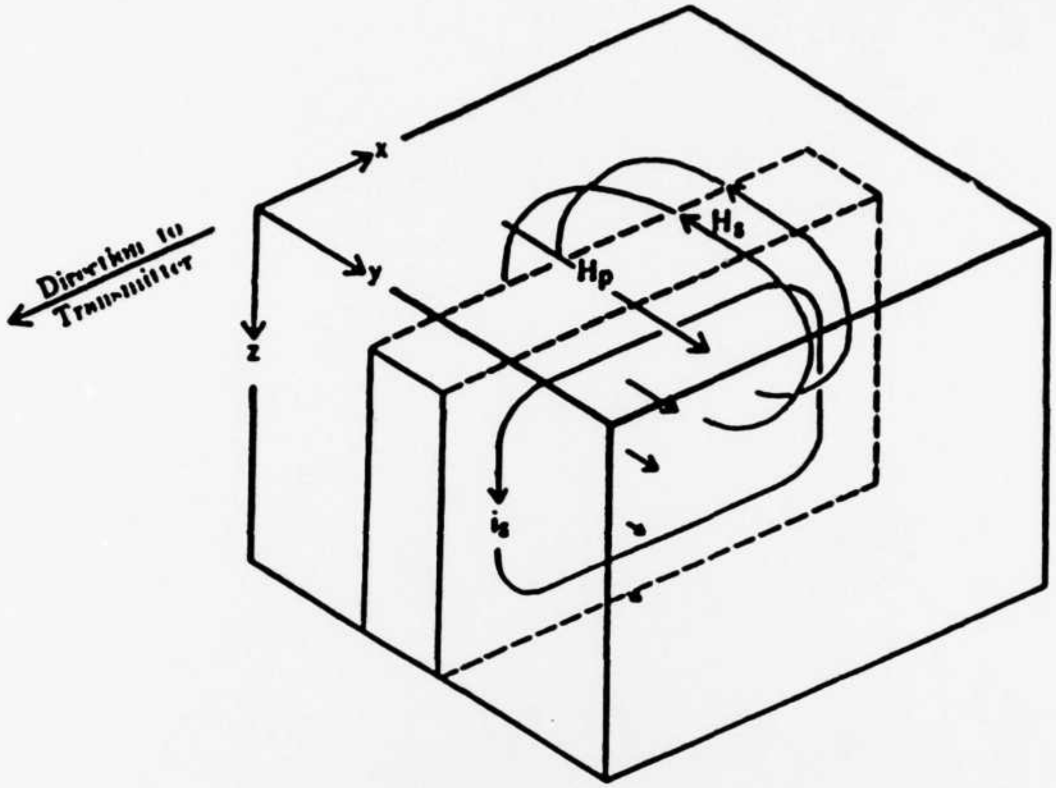

Figure 20(a). Induced current flow, i_S, in a subsurface conductor and subsequent generation of a secondary magnetic field, H_S, H_P is the primary magnetic field.

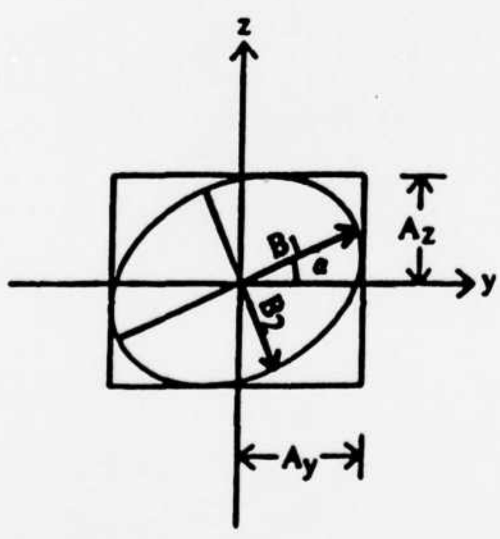

Figure 20(b). Geometry of the magnetic polarization ellipse.

2.3.3 Very Low Frequency (VLF) Meter

The acquisition by the Department of Geology and Geophysics of Boston College of a VLF meter opened another method of exploring the near surface electromagnetic characteristics of the crust. The very low frequency (VLF) band includes radio frequencies from 3 to 30 kc/s. The U.S. Navy operates one of the world's most powerful VLF transmitters in Cutler, Maine. The vertical antennae propagate a magnetic field which is horizontal and perpendicular to the azimuth of the transmitter. This is used as the primary magnetic field in the measuring scheme (Fig. 20). The total magnetic field observed at any location is the vector sum of this primary horizontal field and any secondary fields induced in the earth. The induced fields depend on the electromagnetic properties of the local geological structure. The combined magnetic fields, measured at the surface, form a polarization ellipse (Fig. 20). Using two sets of coils at right angles, the VLF instrument measures the tilt (alpha) and the ellipticity. A pair of ground electrodes permits the simultaneous measurement of the horizontal electrical field intensity. The ratio E/H then gives a measurement of the impedance of the ground, which can be expressed as an apparent resistivity and a phase angle by which the electrical field leads the magnetic field. These four measurements must then be inverted to describe the electromagnetic properties of the ground. Normally an area is surveyed by making many measurements on a rectangular grid.

To interpret the data, a model of the ground is constructed by assigning depth, horizontal dimension and electrical conductivity to rectangles. A computer program is used to calculate the surface values of apparent resistivity, phase and tilt, and in a least squares sense, adjusts the parameters of the rectangles until the model best fits the observed data. Details of the programs and measuring techniques are given in the related thesis by Sauchuk (1988).

Because of the frequency (24 kc/s) of the Cutler station, the depth of penetration is limited to approximately 500 m. Hence the method cannot help to resolve depths beyond that limit. However, the method is very efficient in delineating the lateral extent of fault zones or in defining contacts between geological units where these contacts are hidden by surficial cover, which is the usual case. The important contribution of the effort in this study was the development of computer programs to model two dimensional conductivity structures (Luce & Devane, in preparation, 1989) and these programs are available in Sauchuk (1988).

SUMMARY

This multidisciplinary and interdisciplinary project involved investigations of: (1) Geophysical properties of the shallow crust underlying the Appalachians of southern New England by means of dispersion of Rg waves and electromagnetic methods; (2) deeper geological structure by interpretation of multichannel seismic reflection lines in the onshore and offshore portions of New England; and (3) by analysis of the geology of the region in the light of data from our own site specific and regional studies as well as from published sources. The results of our studies are detailed above, but major contributions include the following: (1) southern New England has been subdivided into Rg wave dispersion regions and, to the extent possible, correlations with tectonostratigraphic divisions of the region were established. In those cases that lack correlations on the scale of our observations,

explanations have been offered. These studies were carried out using Boston College's New England Seismic Network. (2) electromagnetic studies, using Boston College's magnetic observatory installations and VLF meter, and analysis of existing aeromagnetic maps, suggest that major fault zones in eastern MA constitute part of a series of stacked thrust faulted duplexes. (3) Analysis of multichannel seismic reflection lines collected by the U. S. Geological Survey in the Gulf of Maine and on the Long Island Platform gave rise to revisions of previous interpretations of the large scale geology of the region. Such revisions include our interpretation that the Fundy Fault of the Bay of Maine should be correlated with the Blue Hills fault south of Boston that is traced and/or extrapolated through Rhode Island as an easterly dipping thrust fault, the newly mapped Smithfield fault zone of Alleghanian or early Permian age; (4) large scale overthrusting and underthrusting has been produced throughout the region as a result of continent-island arc, island arc-island arc, and continent-continent collisions; and the resulting structures have been modified by those produced by rifting tectonics.

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