

# Crustal Profile of Mountain Belt: COCORP Deep Seismic Reflection Profiling in New England Appalachians and Implications for Architecture of Convergent Mountain Chains<sup>1</sup>

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## ABSTRACT

COCORP deep seismic reflection profiles from the New England Appalachians display some fundamental changes in crustal geometry from exterior to more interior parts of the mountain belt. Relatively shallow reflections from beneath the Taconic allochthon and Green Mountain anticlinorium are suggested to mark a zone of detachment that carries Precambrian Grenville basement of the Green Mountains in its upper plate. The data strongly suggest that tectonic thickening of the shelf sedimentary and synorogenic flysch sequence beneath the Taconic allochthon has occurred, and that major thrust-fault systems (Champlain thrust of western Vermont), which imbricate shelf lithologies, project downplunge into the seismic profile.

Eastward-dipping reflections beneath the east flank of the Green Mountains appear to project in the subsurface across the Connecticut River valley into New Hampshire. Because some of these reflections can be projected into an exposed zone of probable thrust-imbricated Precambrian Grenville basement and younger metasediments, there is a strong implication that similar rock types exist in the deeper crust beneath New Hampshire. The gross geometry of the eastward-dipping zone is one of a large thrust ramp

that facilitated faulting of continental basement in the Green Mountains to higher structural levels, thus suggesting the anticlinorium is a large hanging-wall structure or ramp anticlinorium. Highly deformed satellitic massifs of Grenville basement, such as the Chester dome, and sub-Silurian and Silurian-Devonian rocks of the Bronson Hill anticlinorium and Merrimack synclinorium are probably transported along intracrustal detachments as well.

Available geologic and geophysical data collectively suggest the possibility of a tectonically buried continental margin transition zone, much like that interpreted for the southern Appalachians. This zone would have been preserved from prior rifting of the proto-Atlantic ocean and its inherited geometry could have controlled subsequent convergent deformation during Appalachian orogenesis. Similar interpretations have been made for the Ouachita Mountains. Although regional deep seismic reflection profiling has not been carried out across the Alps, existing geologic and geophysical data imply that one might expect lateral changes in crustal reflection character similar to those observed in the Appalachians. Thus a large south-dipping step or ramp may be present at depth beneath the Pennine Alps north of the Insubric line, perhaps inherited from early continental margin structure of the European plate, and the root zone for the Pennine nappes might then have acquired its steep geometry as a result of thrust sheets riding over this ramp. The growing body of deep seismic reflection data from convergent mountain belts raises the possibility of such preserved transition zones beneath transported rocks, and provides an alternative interpretation to lithosphere-penetrating "sutures" in explaining lateral geologic and geophysical contrasts in the crust.

## INTRODUCTION

At present, the Appalachian mountain belt is perhaps one of the best studied in the world on a crustal scale, there being a wide variety of geologic and geophysical data available. Several near vertical incidence seismic reflection surveys exist, which transect the orogene at different latitudes from Québec to Georgia (Figure 1). Some of these surveys include reflection information from depths at which other studies place the crust-mantle transition (Moho). Two such transects are the COCORP southern Appalachian study (Cook et al, 1979, 1981) and the COCORP northeastern traverse (Ando et al, 1983; Brown et al, 1983).

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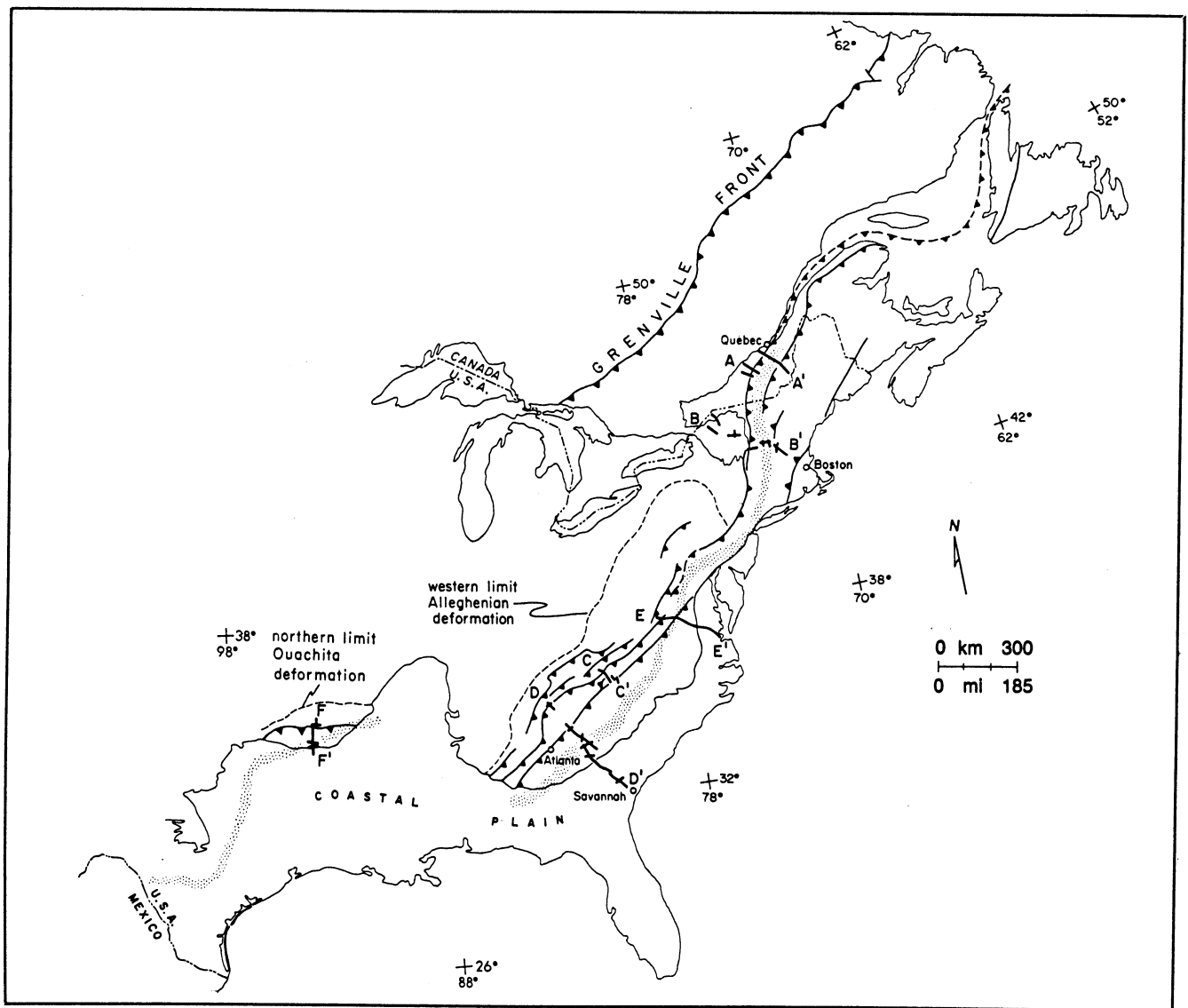


Figure 1—Map of Appalachian and Ouachita orogens showing locations of regional seismic lines collected to date. Select parts of lines BB', DD', and FF' are treated in text. AA' = Québec Appalachian data collected for Ministère des Richesses Naturelles du Québec; BB' = COCORP northeast transect (Adirondack Mountains and New England Appalachians, parts I and II); CC' = U.S. Geological Survey Grandfather Mountain survey in North Carolina and Tennessee; DD' = COCORP southern Appalachian transect, parts I and II; EE' = U.S. Geological Survey central Appalachian survey; FF' = COCORP Ouachita Mountains transect. Dotted pattern along strike of mountain belts = Appalachian Bouguer gravity gradient and Ouachita-Marathon gravity gradient discussed in text.

Regional deep seismic reflection data obtained by COCORP from the northeastern United States now extend from well within the craton (i.e., Adirondack Mountains of New York), across the frontal part of the New England Appalachians, to within the more highly deformed and metamorphosed internal parts of the mountain belt (Figures 1, 2). The combined data thus provide a crustal-scale image of a significant width of the Appalachians at this latitude and illustrate some important large-scale geometric changes at depth as one crosses from the foreland to a more internal tectonic position in the orogene.

Deep seismic reflection profiling from the internal parts

of the Appalachian orogene has revealed a strikingly similar deep crustal reflection geometry along its length, which contrasts markedly with the observed differences in surface geology. The exact nature of some of these reflections is not yet clear. However, the similarities in pattern on crustal scale are prominent and it is possible that many of these features are relict from an earlier, preconvergence (i.e., rifting) stage in the evolution of the continental margin. In particular, similar sets of eastward-dipping reflections are observed on both the southern and New England COCORP seismic traverses. These reflections lie east of a pronounced Bouguer gravity gradient that appears in part to mark a major lateral change in Moho depth and/or

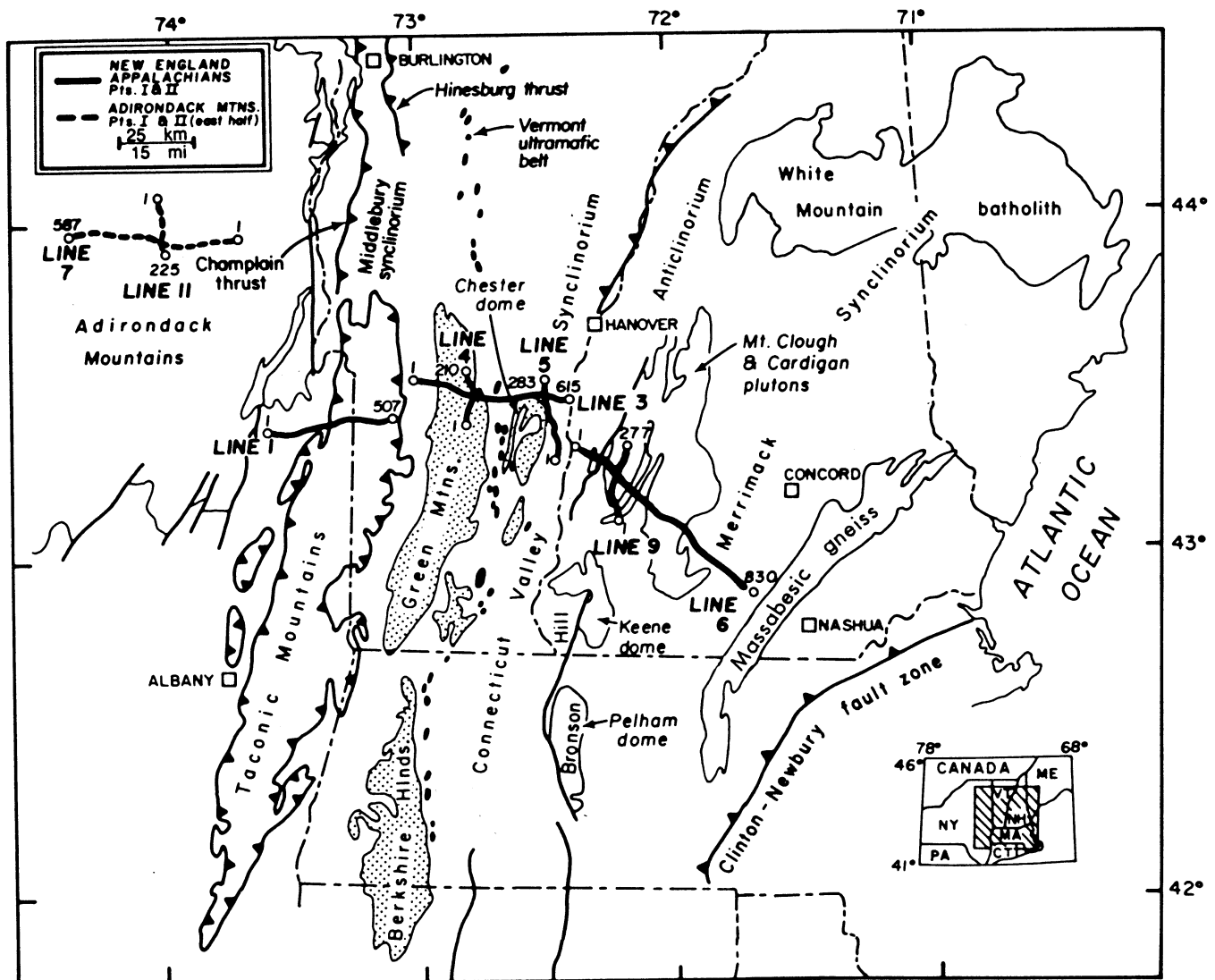


Figure 2—Location map for COCORP New England transect, showing major geographic and tectonic features; geologic contacts are from Williams (1978). Heavy solid lines are seismic lines discussed in text; heavy dashed lines are data collected by COCORP, but not treated in this paper; numbers along seismic lines are vibrator points (V.P.s) used for survey. Dot pattern = Precambrian basement massifs.

deep crustal density. At least one interpretation holds that this gravity gradient marks the approximate zone of transition from continental to rift stage or oceanic crust, perhaps preserved from the late Precambrian to early Paleozoic rifting of the Iapetus ocean (e.g., Cook and Oliver, 1981).

The purpose of this paper is multifold. We present new COCORP data from the New England Appalachians, in particular those from the phase II New Hampshire study, which have not yet been fully treated elsewhere. Because these data are part of a growing collection of deep seismic reflection information from orogenic belts, we also call attention to fundamental similarities that appear to exist among certain areas. In this context, inferential references will be made to such classic mountain belts as the Alps, which bear many surface similarities in deformational style to the New England Appalachians, but whose crustal studies have not yet benefited from regional deep seismic

reflection profiling.

COCORP data from the New England Appalachians were collected in two phases, the first of which extends from Oneida Corners, New York, to Windsor, Vermont, and was completed in the fall of 1980. The second phase, completed in the fall of 1981, extends from just south of Claremont, New Hampshire, southeastward to the village of Mont Vernon, New Hampshire (Figure 2). The combined traverses thus cross from the southeastern Adirondack Mountains eastward over the Taconic allochthon, Green Mountains and Chester dome of eastern New York and Vermont, and the Bronson Hill anticlinorium and Merrimack synclinorium of New Hampshire. These seismic traverses are part of the larger COCORP study of the northeast, which also includes transects within exposed Grenville Province rocks of the Adirondack Mountains. Results of the part I New England Appalachian traverse (lines 1-5, Figure 2) are discussed by Brown et al (1983) and

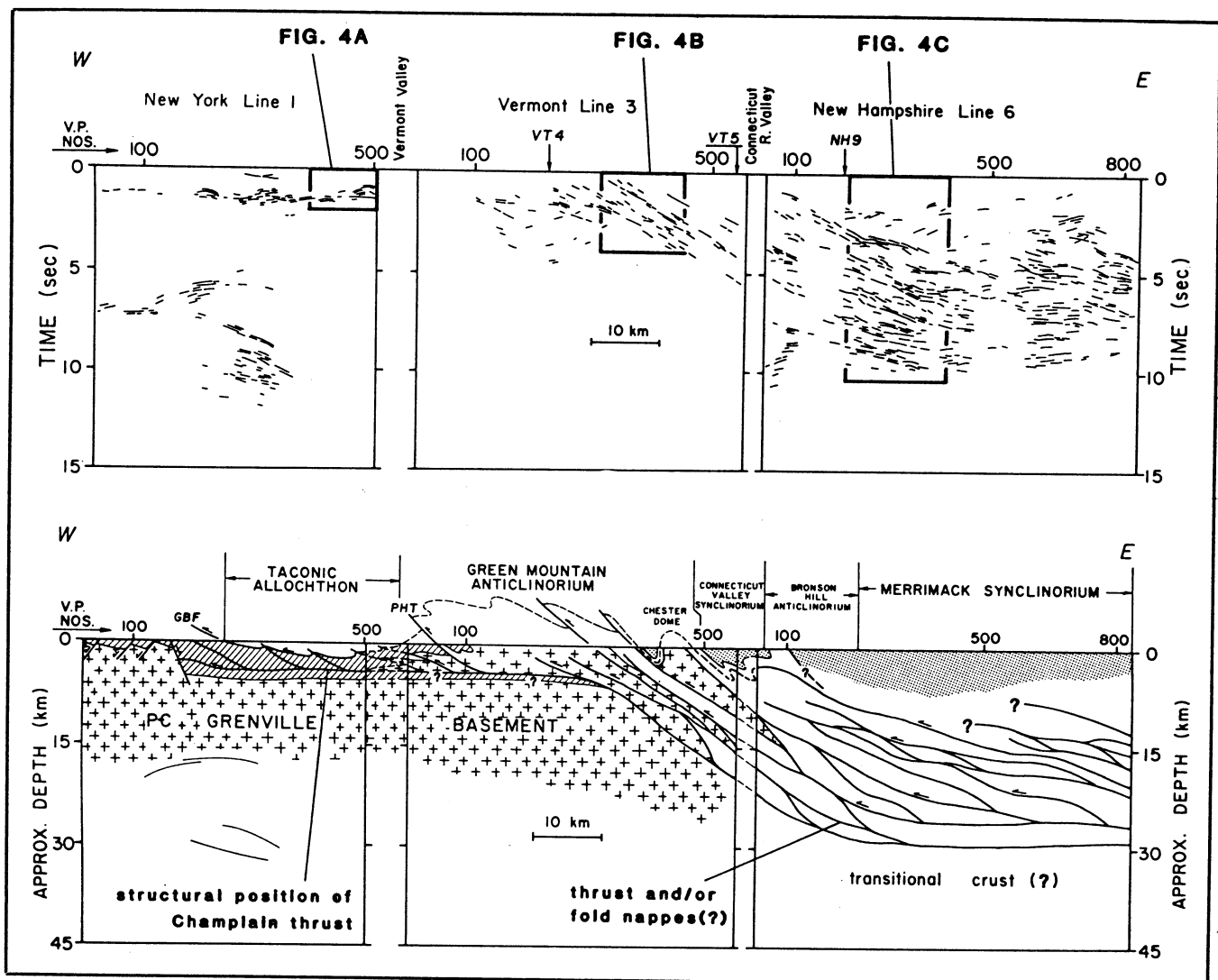


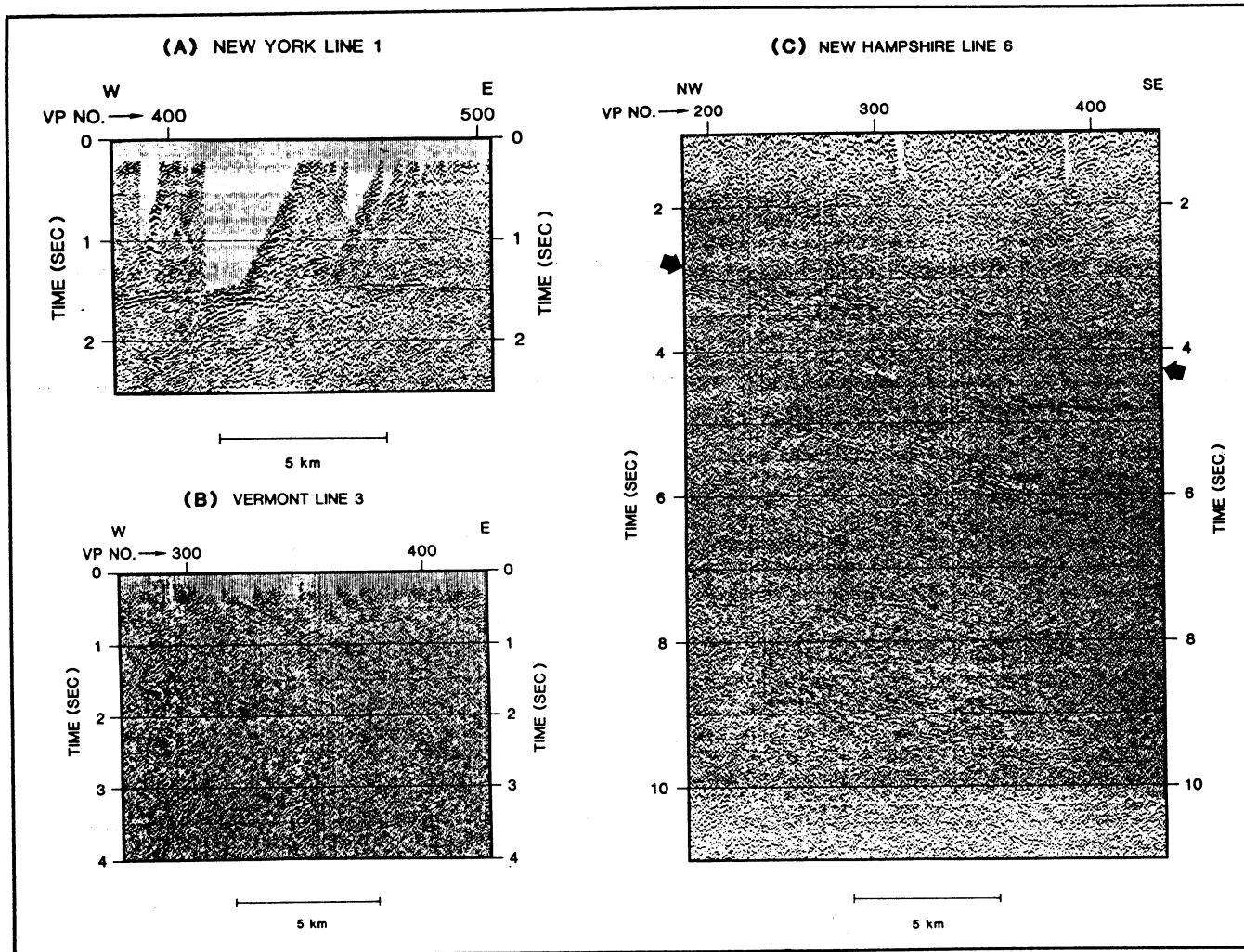
Figure 3—Interpretation for New England transect. Upper panel is line drawing of seismic data, showing locations of data gaps, cross lines (VT4, VT5, and NH9), and positions of excerpts of actual data shown in Figure 4; vertical scale in seconds of two-way travel time. Lower panel is simplified tectonic cross section (in part schematic) based on seismic data and surface geology; vertical scale is depth in kilometers (section has a vertical:horizontal ratio of 1, assuming an average crustal velocity of 6.0 km/sec). V.P. numbers are vibrator stations (100 stations  $\approx$  10 km). Plus pattern = Precambrian Grenville basement; ruled line pattern = mostly lower Paleozoic shelf to miogeoclinal carbonates and clastics, and synorogenic flysch; blank pattern = transported off-shelf rocks of Taconic allochthon in western part of section, plus thrust and/or fold-imbricated rocks (basinal facies metasediments and crystalline basement?) at east flank of Green Mountains and in subsurface of New Hampshire; dot pattern = mostly Silurian, Devonian, and Ordovician(?) high-grade metasediments and Devonian synkinematic plutons (pattern meant to indicate surface outcrop, not necessarily accurate subsurface distribution). GBF = Giddings Brook fault of Taconic allochthon; PHT = Pine Hill thrust. Imbricate faults in subsurface of eastern Vermont and New Hampshire are meant to depict a possible style of deformation rather than actual geologic contacts. Zone of transitional crust(?) = zone east of New England Bouguer gravity high which may represent lateral increase in deep density from lower values on west to higher values on east. Cross section not necessarily balanced.

Ando et al (1983). The discussion presented herein focuses in greater detail on part II of the COCORP study (lines 6 and 9, Figure 2).

Seismic recording and processing parameters are not discussed at length here, except where critical to the interpretations. Recording parameters for the part I transect are listed by Brown et al (1983) and the general processing stream applied to the data is identical to that reported by Schilt et al (1979). The data are presented as line drawings with excerpts of actual data as separate figures. They are

in unmigrated form, although hand and constant velocity migrations have been used as interpretive aids. Because many of the reflection events (especially near the eastern part of the transect) are dipping, it is clear that precise migrations will enhance details of the data.

In general, the quality of the data is variable, and on some seismic lines, a low signal-to-noise ratio has hampered interpretations. The reasons for the low ratio of signal to noise of some of the data are not yet entirely clear. However, a somewhat surprising result is that very good



**Figure 4—Seismic reflection data panels for COCORP New England transect. Panels are keyed to line drawing in Figure 3. Vertical scale is in seconds of two-way travel time; V.P. numbers are vibrator stations (100 stations  $\approx$  10 km). (A) New York line 1, subhorizontal reflections at 1.5 sec is probably from relatively in-place shelf sediments beneath transported shelf rocks and Taconic allochthon. (B) Eastward-dipping events on Vermont line 3 are interpreted to be detachment zones within Precambrian Grenville basement and metasedimentary cover at east flank of Green Mountain anticlinorium. (C) New Hampshire line 6 shows complex dipping reflections to about 30 km (about 18.8 mi) beneath Bronson Hill anticlinorium and Merrimack synclinorium of western New Hampshire; arrows indicate prominent dipping zone of reflections above which seismic dips are discordant.**

deep data were obtained from New Hampshire, where rocks at the surface are multiply deformed and reach high metamorphic grades.

#### TACONIC ALLOCHTHON

Rocks of the Taconic allochthon of eastern New York and western Vermont constitute a complexly imbricated tectonic klippe, lying atop a coeval carbonate to clastic shelf and synorogenic flysch sequence. The Cambrian(?) to Middle Ordovician, dominantly deep-water clastic rocks of the allochthon are disposed in a series of fault-imbricated slices (e.g., Zen, 1967), and have been interpreted as the off-shelf continental-rise facies equivalents of the shelf rocks they lie structurally above (Bird and Dewey, 1970). The units that comprise the allochthon are preserved in the core of the south-plunging Middlebury

synclinorium (Figure 2), a major regional structural feature in western Vermont. A tectonic model currently favored by many relates westward emplacement of the allochthon to development of an accretionary wedge and collision of an offshore island arc with an east-facing passive continental margin during the Taconian orogeny (Chapple, 1973; Rowley and Kidd, 1981). Current models have tended to treat the structural imbrication of the allochthon as an evolving thrust belt.

The COCORP reflection survey (line 1, Figure 2) began on Grenville ( $\pm$  1.0 Ga) crystalline basement of the southeastern Adirondack Mountains and crossed eastward over exposed shelf lithologies (Potsdam, Beekmantown, Black River, and Trenton units) and the Taconic allochthon with its underlying blanket of flysch. The Giddings Brook fault (generally considered to be the basal fault of the allochthon) was crossed by the traverse at about V.P. 260. Proba-

bly the most prominent feature on the seismic profile is a subhorizontal zone of reflections between vibrator points (V.P.) 200 and 500 at a two-way travel time of about 1.5 sec (Figures 3, 4A) corresponding to a depth of 2.8 mi (4.5 km), assuming an average crustal velocity of about 19,700 ft/sec (6.0 km/sec). This zone exhibits local complexities in reflection pattern suggesting disruption, and almost certainly represents the subcrop of the Paleozoic carbonate to clastic shelf sequence lying structurally beneath the Taconic allochthon. West of V.P. 200, shallow reflected energy is not abundant. The probable explanation for this is that just west of V.P. 200 the basal units of the shelf sequence and the flysch are exposed at the surface, with the unconformity between these rocks and the Grenville gneisses not far west of the beginning of line 1.

At travel times of less than 1.5 sec, reflections are present but not abundant. None can be unequivocally traced to outcrop. However it is likely that these reflection events are produced by lithologic contrasts, faults, or both within the allochthon, and as such represent internal details within it. The synorogenic flysch situated between the allochthon and the underlying shelf carbonate sequence is highly deformed (Zen, 1961; Bosworth and Vollmer, 1981; Rowley and Kidd, 1981). This coupled with the known internal structural complexity of the allochthon would suggest that the lack of abundant, strong reflections from above the autochthonous shelf carbonate sequence (above 1.5 sec) is a result of the rocks being effectively homogeneous to the input seismic signal.

If those reflections that do occur above 1.5 sec are fault zones, they may be produced by lithologic contrasts peculiar to the zones themselves. It has been recognized for many years that some of the fault zones that separate slices of the Taconic allochthon contain slivers of the underlying shelf carbonates (e.g., Craddock, 1957; Shumaker, 1967; Zen, 1967). It seems possible that the contrasts necessary to generate the observed reflections within flysch and allochthon could be produced by fault zones that are decorated with such slivers.

At travel times between 6.0 and 12.0 sec on New York line 1 (Figure 3), arcuate to dipping reflections are observed. It has been suggested that these events represent discontinuities (or diffraction patterns therefrom) of probable Grenville ( $\pm 1.0$  Ga) age within the basement (Brown et al, 1983). Because these events cannot be traced to the surface, their interpretation is of course ambiguous. It is thus possible that these reflections represent structures of post-Grenville age, perhaps related to Paleozoic tectonism. A less equivocal interpretation awaits the acquisition of more data.

#### GREEN MOUNTAINS AND CHESTER DOME

The Green Mountain massif of central Vermont is a north-south elongate structural culmination exposing Precambrian metamorphic rocks (Mount Holly complex of Doll et al, 1961) which have yielded radiometric ages up to 1.0 Ga (Tilton et al, 1960; Faul et al, 1963). These rocks, plus those in the cores of satellitic domes immediately east of the Green Mountains (e.g., Chester, Athens, and Sadawga domes) which have yielded similar ages, are gen-

erally considered to be Grenville basement. Excluding rocks that have yielded distinctly older ages (Chain Lakes massif of Maine,  $\pm 1.5$  Ga, Naylor et al, 1973), they are the easternmost exposures of such basement in the New England Appalachians.

Crystalline metamorphic rocks of the Berkshire Highlands to the south (Figure 2) have also yielded Grenvillian ages ( $\pm 1.0$  Ga, Tyringham gneiss, Ratcliffe and Zartman, 1976). These and other massifs in the Appalachians lie along a trend of basement-cored anticlinoria called the Blue-Green-Long axis by Rankin (1976). Significantly, many of the Precambrian basement rocks coring these anticlinoria have been shown to be overprinted by younger deformations. Field mapping and radiometric dating in the Berkshire Highlands (Middlefield thrust zone) have shown that basement-involved thrust faulting there began as early as the mid-Ordovician Taconic orogeny (Ratcliffe and Harwood, 1975; Ratcliffe and Mose, 1978; Ratcliffe and Hatch, 1979), and that an eastward-increasing overprint of Devonian (Acadian) age is also present in some of these same rocks (Hatch, 1975; Norton, 1975; Stanley, 1975).

These overprinting relationships also apply to rocks of the Green Mountain massif. Recent work on Precambrian and Cambrian rocks of the southeastern Green Mountains (Karabinos, 1982) documents thrust faulting and metamorphism of Acadian and probable Taconian age. In addition,  $^{40}\text{Ar}/^{39}\text{Ar}$  and K/Ar dating in Precambrian and Paleozoic rocks from the southern Green Mountains and northern Berkshire Highlands strongly suggests a post-Grenville metamorphism within these massifs of Ordovician (Taconian) age, with a retrogressive overprint near their eastern flanks of Devonian (Acadian) age ( $465 \pm 5$  Ma and  $376 \pm 5$  Ma, respectively, Sutter et al, in press).

COCORP line 3 (Figure 2) extends from west of Chippenhook, Vermont, about 8 mi (13 km) north and 3.7-4.3 mi (5.9-6.9 km) east of the termination of line 1, to the town of Windsor, Vermont, on the Connecticut River. The profile begins east of the outcrop of the Taconic klippe, transecting deformed and metamorphosed lower Paleozoic shelf rocks of the Champlain Valley sequence exposed west of the Green Mountains. Eastward, the profile traverses the Green Mountain anticlinorium, the Townshend-Brownington syncline of Doll et al (1961), and the northern part of the Chester dome, passing just north of Mount Ascutney. Two roughly north-south cross lines were also completed; one along the axis of the Green Mountains, and another along the eastern flank of the Chester dome (lines 4 and 5, respectively, Figure 2).

Unfortunately, data quality on Vermont line 3 was poor in comparison to the other New England lines. The reflections are neither prominent nor abundant. Nonetheless this line provides important geometric information, especially when put into regional context with the other seismic data and the surface geology.

Between V.P.s 100 and 325, a weak subhorizontal zone of reflections is present at 1.5 sec (Figure 3), in general correlating in time with the zone of reflections at 1.5 sec on New York line 1 (Figure 3). This correlation in time suggests the possibility that shelf sediments, which are undoubtedly present beneath the Taconic allochthon, may extend, per-

haps as slices, for some distance eastward beneath crystalline basement rocks of the Green Mountains. Alternatively, these discontinuous reflections may represent zones of high strain (i.e., ductile fault zones) within the basement massif. In either case, a zone of detachment(s) beneath the Green Mountains is strongly implied. A further possibility is that these events could in some way reflect early formed layering within the Grenville gneisses, in which case their correlation in time with New York line 1 and their subhorizontal attitude would be fortuitous.

Beneath the eastern flank of the Green Mountain anticlinorium (V.P.s 250-450, Figures 3, 4B), an east-dipping zone of reflections extends downward in the crust to about 4.5 sec or 8.4 mi (13.5 km) for an average velocity of 19,700 ft/sec (6 km/sec) at the eastern end of line 3. These reflections have unmigrated dips of 30°-35° and apparent plays project to the surface both within Grenville age gneisses of the Green Mountain massif, and the garnet zone metasedimentary cover flanking it to the east. Hand migration of events in this east-dipping zone suggests that their true dip is about 40°. In three dimensions the geometry of these reflections is more complex. The zone appears on Vermont cross-line 5 (for location see Figure 2) as a set of roughly subhorizontal events at about 4.0 sec. Individual reflections within this sequence, however, exhibit local dips and appear to crosscut one another. Reflections with the same characteristics also occur on line 5 above 4.0 sec. Projecting plays of this dipping reflection zone to the surface within Grenville basement and metasedimentary cover implies that they may represent lithologic layering and/or zones of concentrated strain within those rocks.

No obvious reflections from within rocks of the Chester dome are present on Vermont line 3. This is perhaps due to the internal complexity of the dome. Both Grenville basement rocks in the core and the sediments flanking it have been multiply deformed (Thompson, 1950; Rosenfeld, 1968; Nisbet, 1976), and overprinted by high-grade synkinematic metamorphism (Thompson and Norton, 1968; Downie, 1980).

In addition, no identifiable seismic expression of Mesozoic plutons cropping out near the Vermont transect is seen on the profiles. Both the Mount Ascutney and Cuttingsville stocks of probable Cretaceous age (Foland and Faul, 1977) are located slightly off the Vermont line 3 traverse to the south (near V.P.s 150 and 570, respectively). Intrusive contacts of the stocks are apparently steep, and reflections that can be readily interpreted as internal structure, layering, or contacts with the host rocks of these plutons have not been identified.

#### BRONSON HILL ANTICLINORIUM AND MERRIMACK SYNCLINORIUM

East of the Connecticut River valley in New Hampshire, the surface geology is significantly different from that in Vermont. Most of the rocks in the area surveyed by COCORP are Silurian or younger and have been deformed and metamorphosed to high grades. Older rocks appear in the cores of the "Oliverian" gneiss domes of the Bronson Hill anticlinorium (Figure 2) and have been overprinted by at least two phases of synkinematic meta-

morphism (Thompson and Norton, 1968). Complexities are due in part to the fact that this is a position in the New England Appalachians where early formed Taconian structures have been severely overprinted by later (Devonian) deformation and metamorphism of the Acadian orogeny.

The Bronson Hill anticlinorium is the eastern of two gneiss dome belts in western New England described by Thompson et al (1968), the western belt being those domes such as the Chester and Athens, which are cored by Grenville basement. In contrast to the western belt, the domes of the Bronson Hill are cored by layered to massive gneisses, metasedimentary, and metavolcanic rocks, and flanked by a carapace of pre-Silurian amphibolitic metavolcanic rocks plus Silurian and younger metasediments. The oldest core rocks are suggested to be late Precambrian, but are chiefly Ordovician (e.g., Naylor et al, 1973), whereas the oldest flanking carapace rocks in the central Connecticut valley are regarded as Middle Ordovician based on paleontologic ages of possibly correlative rocks in Maine (Berry, 1968; Naylor, 1968).

The rocks of the Bronson Hill anticlinorium have long been regarded as the remnants of volcanic islands (Hitchcock, 1883; Kay, 1951) or an island arc assemblage (Naylor, 1968; Rodgers, 1970). Tectonic syntheses of western New England have treated these rocks as a terrane floored by basement which is distinct from Grenville age basement exposed to the west in the Green Mountains and Chester dome. The arc and its basement were thus "sutured" to the proto-North American continent during early Paleozoic plate convergence, broadly coeval with emplacement of the Taconic allochthon (Bird and Dewey, 1970; Osberg, 1978; Robinson and Hall, 1980; Rowley and Kidd, 1981).

The Merrimack synclinorium lies east of the Bronson Hill anticlinorium (Figure 2), and extends from central Maine to southeastern Connecticut. In New Hampshire, the synclinorium is occupied mostly by clastic metasediments of Devonian, Silurian, and Ordovician(?) ages (Billings, 1956; Hatch et al, 1981), and Devonian plutons (Lyons and Livingston, 1977). The structural and stratigraphic relationships between basement and cover rocks in the Bronson Hill anticlinorium and adjacent strata within the Merrimack synclinorium are extremely complex (e.g., see Dixon and Lundgren, 1968; Osberg et al, 1968; Thompson et al, 1968; Rodgers, 1981). The Oliverian domes are apparently late features that were preceded by development of large nappe structures accompanied by high-grade (sillimanite-K-feldspar) metamorphism (Thompson and Norton, 1968; Thompson et al, 1968). In the area of the COCORP transect (line 6, Figure 2) the early phase recumbent nappes, which involve rocks as young as Devonian, are thought to have verged westward (Thompson et al, 1968). In the synclinorium proper, uncertainties in stratigraphic and structural relationships along strike do not allow a unique solution to the geometric development of the structures, which evidently involved stages of backfolding as well as late doming following initial nappe formation (e.g., compare Dixon and Lundgren, 1968; Thompson et al, 1968; Robinson, 1979).

COCORP New Hampshire line 6 (Figure 2) extends from south of Claremont near the Connecticut River

southeastward to the village of Mont Vernon. The survey thus transects the Unity dome of the Bronson Hill anticlinorium (for description, see Chapman, 1942; Thompson et al, 1968), the Devonian Mount Clough and Cardigan plutons (Bethlehem Gneiss and Kinsman Quartz Monzonite), and metasedimentary rocks (mostly Silurian and Lower Devonian metasediments) in the central part of the Merrimack synclinorium.

In contrast to Vermont line 3, New Hampshire line 6 exhibits numerous prominent deep reflections (Figures 3, 4C). At the western end of the survey a pronounced eastward-dipping zone of events gives way to flatter events farther east. This zone in general dips 20°-30° (unmigrated) and becomes subhorizontal beneath V.P. 500 (Figure 3). Strong reflections are observed beneath the surface locations of both the Bronson Hill anticlinorium and Merrimack synclinorium, and are present vertically in time to about 10.0 sec (or about 18.6 mi  $\approx$  30 km for an average velocity of 19,700 ft/sec  $\approx$  6 km/sec). Some of the east-dipping events on New Hampshire line 6 project westward beneath the Connecticut River valley to line up with dipping events on Vermont line 3, and may therefore be continuous with them.

A particularly strong band of reflections marks the top of the eastward-dipping zone and separates the lower sequence of abundant strong reflections from an upper, largely transparent zone (see Figures 3, 4C). This seismic boundary, which is also very prominent on cross-line 9 (see Figures 2, 5), dips eastward from about 1.0 sec near V.P. 100 (Figure 3) to 5.0 sec beneath V.P. 525. Above this boundary, weak west-dipping reflections occur and are largely discordant with it. East of V.P. 525 strong reflections are observed from about 2.0 sec down to 10.0 sec; most dip eastward but local west dips are seen above 4.0 sec.

In two dimensions, the internal complexities of the strongly reflective zone on line 6 are manifested by changes in dip and crosscutting character.

The same geometric character is seen on cross-line 9 (Figures 2, 5), which crosses line 6 at a high angle. It thus appears on the unmigrated time sections, where some three-dimensional control exists, that lenticular or lozenge-shaped "packages" of reflections are present in the subsurface (Figure 5).

On New Hampshire line 6 (see line drawing, Figure 3), two subvertical panels of poor data quality occur between V.P.s 100 and 175, and 475 and 575. A number of factors singly or in concert could have contributed to degraded data quality in these positions (e.g., noisy recording conditions, near-surface attenuation, poor coupling). At the present time the cause of the poor data is not known.

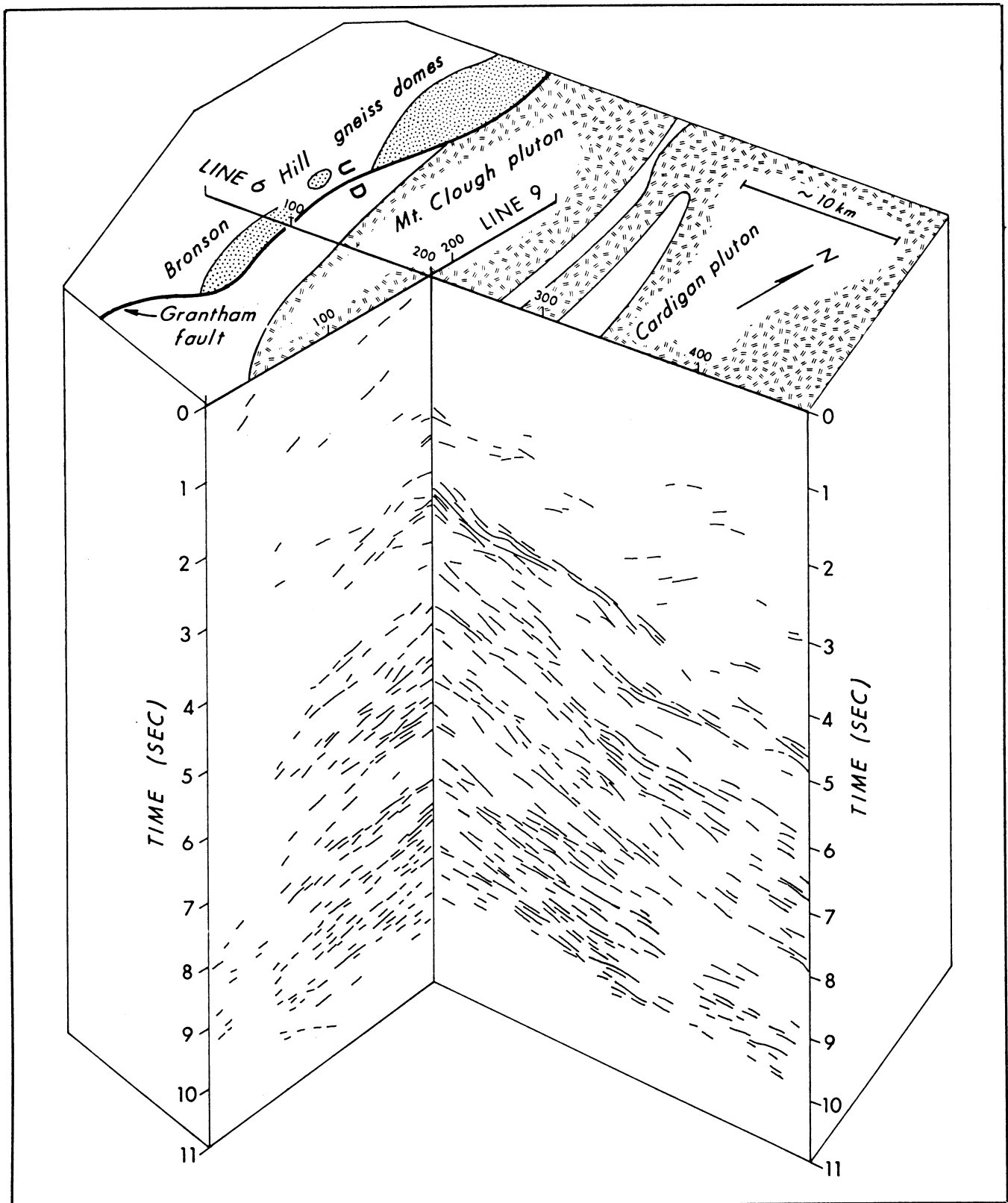
### INTERPRETATION

A significant aspect of the reflection pattern on New York line 1 and Vermont line 3, when viewed together, is the correlation in time of events at 1.5 sec (Figure 3). On New York line 1, this zone almost certainly represents shelf sedimentary rocks lying beneath the allochthonous Taconic sequence. The nature of the correlative sequence beneath the Green Mountains on Vermont line 3 is more

equivocal. As discussed earlier, these reflections can be interpreted to mark a zone of detachment beneath the Green Mountain anticlinorium, which may or may not contain slices of shelf-type sedimentary rocks. The zone of detachment may continue westward beneath the Vermont valley to the Taconic Mountains, where its subsurface position could be controlled by stratigraphic layering within the shelf sequence. The geometric complexities within the zone of reflections beneath the Taconic allochthon are perhaps due to splay or subsidiary faults which imbricate or otherwise involve the shelf sequence in deformation. Faults at the western flank of the Green Mountains (such as Pine Hill fault) (Wolff, 1891; Thompson, 1967) may also be splays from this detachment zone. Such a geometric style involving allochthonous Precambrian basement is very reminiscent of that described by Ratcliffe and Harwood (1975) and Ratcliffe and Hatch (1979) for the northern Berkshire Highlands not far to the south (Figure 2). There, it can be shown that Precambrian Grenville basement and the Paleozoic shelf sequence (mostly Stockbridge and Walloomsac carbonates and clastics) are structurally interleaved at the western flank of the Berkshire massif.

Because the zone of relatively continuous reflections on New York line 1 begins at 1.5 sec (2.5-2.8 mi = 4.0-4.5 km) (Figure 3), and because structural relationships suggest that the Taconic allochthon proper is relatively thin (about 1.2 mi = 2.0 km) (see Zen, 1961), there is likely a considerable thickness of shelf carbonates and syntectonic flysch beneath the allochthon. Between V.P.s 100 and 200, at the surface only a few kilometers west of the outcrop of the basal Taconic contact (Giddings Brook fault, GBF, Figure 3), the lowermost units of the shelf (Potsdam Sandstone, Beekmantown Group carbonates) lie depositionally on Grenville gneisses. Therefore, the thickness of the shelf and/or syntectonic flysch sequence must increase dramatically and rapidly to the east. We suggest that this thickening may be in large part structural, and explainable by thrust fault duplication. This is consistent with surface structural relationships along strike to the north, where thrusts of the Champlain-St. George-Orwell system (Coney et al, 1972) imbricate units of the shelf sequence. An important fact is that the Champlain thrust juxtaposes two different facies and thicknesses of coeval shelf rocks (Champlain lowland sequence of Welby, 1961, and Middlebury synclinorium sequence of Cady, 1945). Thus, the detachment zone we infer to exist beneath the Taconic allochthon and Green Mountains could represent the downplunge projection of the Champlain thrust system subcropping beneath the Taconic allochthon. Such a detachment system is in the same structural position as the Champlain thrust, but along the COCORP profile, occurs where allochthonous Taconic rocks are still preserved at higher structural levels in the core of the Middlebury synclinorium.

A very speculative but significant point concerns the relevance of the COCORP data to palinspastic restorations. If relatively in-place shelf rocks are present in the subsurface as far east as V.P. 507 (zone of reflections at 1.5 sec, end of New York line 1, Figure 3), this is the westernmost place the inferred detachment at 1.5 sec could cut into Pre-



**Figure 5**—Isometric line drawing of junction between New Hampshire seismic lines 6 and 9 (for location, see Figure 2) showing aspects of three-dimensional reflection geometry beneath Bronson Hill anticlinorium and Merrimack synclinorium. Sketch geologic map modified from Thompson et al (1968) shows major surface features; stipple pattern = core rocks of Bronson Hill anticlinorium; Mt. Clough and Cardigon plutons are Devonian age synkinematic intrusions; white area = cover rocks of Bronson Hill gneiss domes and Merrimack synclinorium which have been involved in early phase west-vergent nappes and subsequent refolding; Grantham fault is probable Mesozoic normal fault (east side down) with about 6,500 ft (2 km) of throw (Thompson et al, 1968, their plate 1b).

Cambrian basement. This is a conservative estimate and would be consistent with the interpretation that there are no shelf or earlier sediments beneath the Green Mountain massif. The data quality at present does not allow this distinction to be made. Also, the oldest observed unit carried in the upper plate of the Champlain thrust is the Cambrian Dunham Dolomite (Doll et al, 1961). If structures do indeed correlate downplunge from the north into the COCORP traverse, the Champlain thrust (or its structural equivalent) may have initially ramped out of lower plate Cambrian units somewhere east of V.P. 507 (Vermont valley or eastward). This would suggest a minimum displacement on the Champlain thrust of about 12-16 mi (19-26 km) (measured in the plane of the COCORP cross section Figure 3).

Farther east on Vermont line 3 (east of V.P. 250, Figure 3), the zone of subhorizontal reflections steepens or is truncated by the zone of east-dipping events near the eastern flank of the Green Mountain massif. The projection of various splays of this zone into Precambrian gneiss of the massif and into the metasedimentary cover flanking it strongly suggests that the rocks are imbricated by thrust faults. Such relationships have been observed at the surface farther north in the Green Mountain and Lincoln Mountain massifs of central and northern Vermont (Thompson, 1972; Stanley et al, 1982; Tauvers, 1982) and the southern Green Mountains (Karabinos, 1982). An interpretation compatible with this and the steepening of dips is that the east-dipping zone is one of complex deformation associated with a large thrust ramp which facilitated faulting of Precambrian basement to higher structural levels. In this context the Green Mountain anticlinorium can therefore be regarded as a large ramp anticline.

If the interpretation of a subhorizontal zone of detachment beneath the Green Mountains is correct, it would suggest that uplift of the basement massif has been accompanied by significant horizontal translation, and is therefore not due to purely vertical upthrusting or buoyant upwelling. If the east-dipping reflections at the east flank of the massif do represent a large ramp structure, then the restored position of the basement rocks must lie east of this ramp. Many of the complexities in structural geometry observed at the surface in eastern Vermont and western New Hampshire may have resulted from thrust sheets riding over the ramp. The cross section in Figure 3 is geometrically consistent with the basement ramping following emplacement of the Taconic allochthon. Our interpretation is that the subhorizontal zone beneath the Green Mountains is a lower level of detachment, movement on which resulted in deformation of an earlier, higher level, thrust zone responsible for emplacing the deeper water Taconic sequence onto the shelf. Presumably, the earlier emplaced allochthon was continuous across the locus of the present Green Mountain axis prior to ramping of the basement. The timing of basement transport is not yet well enough constrained to document this interpretation. However, earlier cited work by Karabinos (1982), Ratcliffe and Mose (1978), and Sutter et al (in press) strongly suggests that basement-involved deformation in this region began as early as the Taconian orogeny. The Acadian over-

print indicates an additional increment of movement. At present, it is not clear to what extent the observed large-scale seismic geometries are a function of Taconic, Acadian, or younger events.

It has been recognized for some years that the axis of the Green Mountain anticlinorium coincides approximately with a sedimentary facies transition from shelf facies on the west to more basinal on the east (Rodgers, 1968). Although complicated by deformation, it can be shown for both the Green Mountain and Berkshire Highlands basement massifs, that flanking cover rocks on the west are largely shelf carbonates and clastics (Champlain Valley sequence, Thompson, 1967; Stockbridge and Walloomsac Formations, Ratcliffe and Harwood, 1975), and those on the east are mostly metapelitic and quartzofeldspathic wackes (Hoosac Formation and Moretown Member of Missisquoi Formation, Doll et al, 1961; Hoosac and Moretown Formations, Rowe Schist, Hatch et al, 1968). It appears, therefore, that the Green Mountain basement was initially detached from near the continental edge as defined by the shallow to deep water sedimentary facies transitions discussed by Rodgers (1968) and Cady (1968).

Important implications can be drawn from the possible correlation of east-dipping reflections on Vermont line 3 with similar events observed deeper in the crust on the western part of New Hampshire line 6 (Figure 3). Because some of the events on Vermont line 3 project to the surface within a zone of mostly pre-Silurian garnet-grade metasediments between the Green Mountains and Chester dome, it seems likely that the deeper reflections on New Hampshire line 6 represent similar lithologies. The anastomosing or lozenge-shaped reflection geometry observed in three dimensions on Vermont lines 3 and 5 and New Hampshire lines 6 and 9 (Figure 5) is reminiscent of detailed mapped geometries of thrust nappe zones. This suggests to us that if the interpretation of thrust-imbricated and/or folded basement and metasedimentary cover near the east flank of the Green Mountains is correct, such a structural style could extend in the subsurface for a considerable distance eastward beneath the Bronson Hill anticlinorium and Merrimack synclinorium.

Alternative interpretations for the reflections beneath New Hampshire include layered plutons or sills (perhaps related to late Precambrian? rifting of the proto-Atlantic ocean or to Triassic? rifting of the present Atlantic), or possibly a pervasive low-dipping to subhorizontal tectonite fabric in the crust. Other interpretations are undoubtedly possible. We suggest, however, that the strength of the interpretation that some of the east-dipping reflections represent thrust or fold nappe imbricated metasediments and basement lies in being able to project these events to the surface where such rocks are observed.

The strong band of reflections dipping from about 1.0 to 5.0 sec between V.P.s 100 and 500 on New Hampshire line 6 appears to delineate the top of the zone of abundant reflections (Figures 3, 4C) and clearly separates that zone from a more seismically transparent region above. The discordance in dips of reflections and the contrast in seismic character across this zone suggest that rocks at higher levels (i.e., rocks exposed at the surface in the Bronson Hill anticlinorium and Merrimack synclinorium) are sig-

nificantly different in terms of lithology and/or structure from those below. Surface geologic studies indicate that Silurian-Devonian and older units exposed in western New Hampshire have probably been transported westward an unknown distance as several large nappe structures. Furthermore, the Devonian synkinematic plutons such as the Mt. Clough and Cardigan bodies (see Figure 2) are concordant with regional foliation in the host rocks and are likely transported as well (e.g., Billings, 1937; Thompson et al, 1968). Gravity modeling in the region of the COCORP transect is consistent with a thin, tabular geometry for these New Hampshire series plutons (<2.5 km thick, Nielson et al, 1976). Based on the change in reflection character just discussed, we suggest that a zone of detachment along which these higher level rocks in western New Hampshire were transported lies between the zones of contrasting seismic character (Figures 3, 4C).

A feature that has figured prominently in tectonic discussions of New England is the Vermont ultramafic belt (Figure 2). Syntheses have tended to treat this zone as a Taconian "suture" (sometimes referred to as "cryptic") between the proto-North American continent and an accretionary terrane now presumably represented by pre-Silurian rocks in the Bronson Hill anticlinorium (Bird and Dewey, 1970; Osberg, 1978; Robinson and Hall, 1980). Two ultramafic (soapstone) belts are also present in the Connecticut Valley in western New Hampshire (Hitchcock, 1877, 1878). The ultramafic pods appear to be confined to Middle(?) Ordovician metamorphic rocks, and may thus be the same age as the Vermont ultramafic belt to the west (Lyons et al, 1982). In addition, some ultramafic slivers are present within the Chester dome. Because the ultramafic slivers are confined to the pre-Silurian section, and because these plus younger Silurian-Devonian units have been strongly affected by post-Taconian metamorphism and deformation, the "suture" is itself deformed, and probably transported. These geometric complexities perhaps preclude the probability of a simple reflection pattern from a Taconian suture. Although major surface structures in the region of the ultramafic belt at the latitude of the COCORP survey are nearly vertical, the reflection geometry below them strongly suggests that this attitude is either truncated at depth by east-dipping structures (the dipping reflections on Vermont line 3 and New Hampshire line 6), or merges with them. The Taconian suture therefore appears not to be a purely vertical feature at depth.

It is not clear whether COCORP data from New England bear directly on the geometries of post-Appalachian structures in the region. The youngest known structure crossed by the COCORP transect is the Grantham fault of probable Jurassic age ( $\approx 160$  Ma, Lyons and Snellenburg, 1971; Lyons, 1979). This high-angle fault, which is downthrown on its eastern side and crops out near V.P. 100 on New Hampshire line 6 (Figure 3), appears to be the northern extension of the zone of faults bounding the Mesozoic Connecticut valley graben. Although there may be as much as 1.2 mi (2 km) of throw across the fault (Thompson et al, 1968, their plate 15-1b), no obvious events on the COCORP profile can be traced to its surface location. Perhaps the steep dip of the fault zone explains why it is not seen on the seismic profile. Its

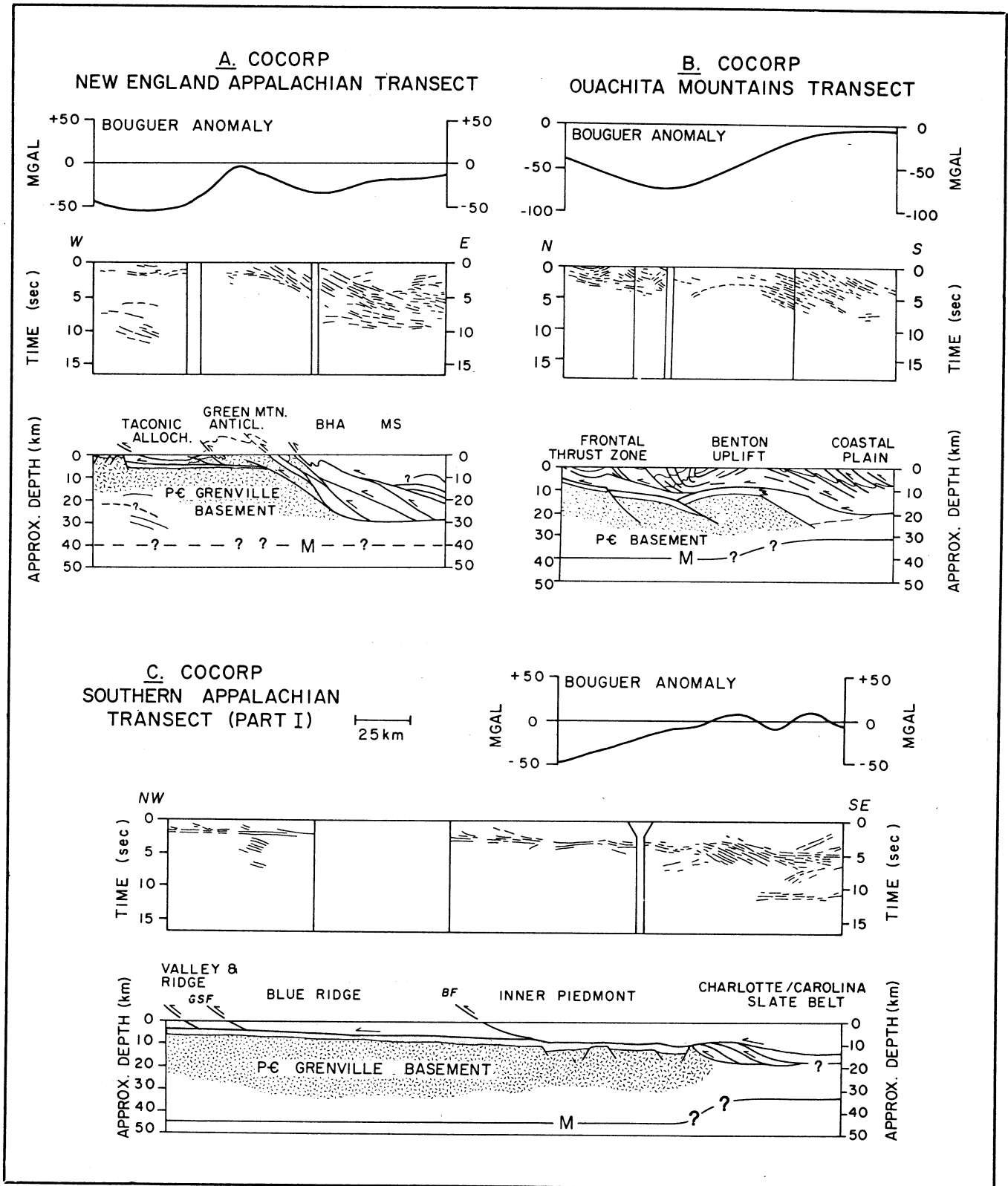
relationship to the deeper reflections is thus difficult to determine.

#### IMPLICATIONS FOR EVOLUTION OF APPALACHIAN SYSTEM AND OTHER MOUNTAIN BELTS

One of the most striking aspects of the COCORP Appalachian data both in New England and in the southeast is the presence of east-dipping reflections beneath transported rocks (see Figure 6A and C). It is our opinion that the steepening of dips of reflections eastward beneath internal parts of the Appalachians represents a fundamental signature of the crust which may, in part, be preserved from the initial (late Proterozoic) rifting of the proto-Atlantic ocean. Specifically, these east-dipping events have been interpreted as regions of thrust faulting involving off-shelf or pre-shelf (rift-related) metasediments and basement located within the ancient zone of transition from continental to rift stage or oceanic crust. In addition, it has been suggested that far-traveled, complexly deformed allochthons presently at higher structural levels in the crust have ridden over this (largely preserved) transition zone. Some of the relationships which collectively contribute to this interpretation have been discussed at length by Cook et al (1979, 1981), Cook and Oliver (1981), Ando et al (1983), and Brown et al (1983).

We note the spatial correlation of these east-dipping reflections, in the southern and northern areas, with the Bouguer gravity gradient or gravity high that exists over the Inner Piedmont-Charlotte belt and the Green Mountain anticlinorium, respectively (Figures 1, 6A, 6C). Extensive modeling of the gravity has led to suggestions that, although complicated by near-surface contrasts, the Bouguer gradient, in part, represents a change at depth from less dense on the west to more dense on the east, perhaps related to changes in Moho depth and/or absolute densities of deep crustal materials (Bean, 1953; Diment, 1968; Haworth, 1978; Kumarapeli et al, 1981, for the northern Appalachians; Cook and Oliver, 1981; Thomas 1983, for the southern Appalachians). Other seismic modeling (e.g., Leet, 1941; Long, 1979; Taylor and Toksöz, 1979, 1982; Peseckis and Sykes, in press) tends to support the notion that deep lateral velocity contrasts in the crust and/or upper mantle are present beneath transported rocks of the Appalachians. Because the gravity gradient bifurcates northward near the Connecticut-Massachusetts border (see Haworth et al, 1980), simple interpretations of the Green Mountain-Sutton Mountain gravity high as representing a buried, ancient continental edge transition are problematic. Nevertheless, the existing data, taken together, indicate this is a zone of major geologic and geophysical contrasts which are comparable to those observed at transitions across modern passive continental margins to oceans (Buffler et al, 1981; Grow and Sheridan, 1981).

Synthesis of available geologic and geophysical data suggests to us that the observed contrasts in density as delineated by gravity, contrasts in velocity as delineated by refraction or earthquake studies, and the seismic reflection character, can be related to a tectonically buried transition beneath the southern (Cook and Oliver, 1981) and northern (Ando et al, 1983) Appalachians. We particularly



**Figure 6—Crustal models for COCORP transects discussed in text. (A) COCORP New England transect; BHA = Bronson Hill anticlinorium; MS = Merrimack synclinorium; (B) COCORP Ouachita Mountains transect; (C) COCORP southern Appalachian transect part I; GSF = Great Smoky fault; BF = Brevard fault. Each has simplified line drawing of seismic data and Bouguer gravity profile in addition to crustal interpretation. Note spatial relationship of hinterland-dipping reflections and Bouguer gravity gradients or highs. Configuration of Moho in each case inferred from seismic refraction, P-wave delay studies and/or surface wave studies. Note that proposed early continent to ocean transitions are many kilometers from modern continent to ocean transition along Atlantic and Gulf Coast margins (see Figure 1).**

regard the lateral change in reflection character, and its spatial correlation with the Bouguer gravity gradient as a fundamental feature that persists along strike despite significant changes in surface geology between north and south. Indeed, the westward divergence of surface exposures of some allochthonous Grenville basement massifs (e.g., Berkshire Highlands, Ratcliffe and Harwood, 1975; Housatonic and Hudson Highlands, Hall, 1980; Reading Prong, Drake, 1970) from the locus of the gravity gradient (as noted by Isachsen, 1964), may be a measure of the magnitude of transport from their places of initial detachment.

An alternative explanation suggested for the east-dipping events observed in the south is that they are the expression at depth of a crustal-penetrating "suture" (central Piedmont suture of Hatcher and Zietz, 1980) or "root zone" (Iverson and Smithson, 1982). The Appalachian Bouguer gravity gradient has also been interpreted to represent the tectonic juncture of two different crustal blocks with contrasting densities (e.g., Hatcher and Zietz, 1980; Thomas, 1983). At present, the seismic reflection data alone do not directly provide sufficient information to distinguish between models for the lithologies represented by the east-dipping reflections, or the nature of the crustal boundary they delineate. Perhaps the same is true for New England. Although we regard the previously discussed lateral contrasts in the deeper crust as fundamental, we do not necessarily interpret them as representing lithosphere-penetrating boundaries of the sort suggested for the southern (Hatcher and Zietz, 1980; Iverson and Smithson, 1982; Thomas 1983) and northern (Taylor and Toksöz, 1979, 1982) Appalachians.

Central to this discussion is that in the north, some east-dipping reflections can be projected from within a zone of exposed Grenville basement and high-grade metasediments east of the Green Mountains to deeper levels beneath New Hampshire. This strongly suggests that similar rock types may extend to considerable depths in the crust, and perhaps by analogy strengthens the interpretation of Cook et al (1979) for the east-dipping reflections beneath the Inner Piedmont-Charlotte belt. Furthermore, because the Green Mountain anticlinorium in general appears to carry the shelf to off-shelf sedimentary facies transition, ramping of the Grenville basement in the massif probably occurred near the carbonate bank edge defined by Rodgers (1968) or the rifted continental margin. Thus, in our view, the seismic reflection signature at depth beneath eastern Vermont and western New Hampshire could represent a former declivity in the Grenville basement inherited from earlier rifting, which subsequently acted as a ramp for convergent deformation during Appalachian orogenesis. Presumably the steep dips of surface structures east of the Green Mountains (within the Taconic "root" or "suture" zone) were acquired as a result of ramping of thrust sheets at this position. It might further be suggested that other surface geologic complexities in New England, such as the late stages of backfolding east of the basement massifs recognized by Rosenfeld (1968), Thompson et al (1968), and Robinson and Hall (1980), may have developed as a response to nappe structures riding over this ramp at depth. A similar suggestion has been

made by Cook (1983) for the relationship between the east-dipping zone of reflections at depth and steep dips of surface exposures of the Kings Mountain belt in the southern Appalachians.

Data from other areas surveyed by COCORP allow interpretations similar to those just discussed. Recently acquired COCORP seismic reflection profiles from the Ouachita Mountains of Arkansas (Figure 1) have revealed a pattern of reflections which displays a general similarity to the Appalachian transects (Figure 6). Specifically, south-dipping reflections beneath the southern flank of the Benton uplift (Figure 6B) occur beneath a steep Bouguer gravity gradient, much like the relationship in the Appalachians. These reflections have been interpreted by Nelson et al (1982, their Figure 3A, sequence E) as imbricated off-shelf metasediments initially deposited along the early Paleozoic continental margin. While not constrained by surface or drill-hole data, modeling of the gravity signature along the Benton uplift in conjunction with refraction and reflection seismic data (Lillie et al, 1983) suggests that the interpretation of a buried continent to ocean transition is a reasonable alternative to placing a "suture" zone beneath the uplift (see Figure 6B for model). The steep gravity gradient, from low values on the north to higher values on the south, has been regarded as a fundamental geophysical feature of the Ouachita-Marathon orogenic system along which major antiformal features such as the Benton-Broken Bow, Devils River, and Waco uplifts now lie (Nicholas and Rozendal, 1975).

In view of the implications presented in the preceding discussion, an interesting alternative regarding the nature of some of the dipping reflections becomes apparent. Comparison of deep seismic reflection and other geologic and/or geophysical patterns from intracontinental rifts and passive continental margins (presumably resulting from continental rifting) suggest that certain large-scale geometries may be fundamental signatures of rifts. In particular, basinward-dipping reflections are pervasive on COCORP profiles from areas known or inferred to have been involved in intracontinental rifting (Lillie et al, 1983, personal communication). More specifically, extensive marine seismic reflection profiling along passive continental margins has revealed prominent sequences of oceanward-dipping, subacoustical basement reflectors (e.g., Hinz, 1981; Mutter et al, 1982). These reflectors in general occur within the zone of transition between continental and oceanic crust as well displayed by examples from the Baltimore Canyon Trough of the eastern United States (see Grow, 1980, his Figure 56), and have been interpreted as synrift layered volcanic or other stratigraphy (Grow, 1980; Hinz, 1981; Mutter et al, 1982). The implication that these seaward-dipping sequences and the transition zone they lie above may be preserved (or partially preserved) during subsequent episodes of convergent mountain building, is indeed intriguing.

Because one observes very different surface geology above similar geophysical transitions in the Appalachian and Ouachita orogenes, it seems viable to entertain the possibility that these transitions, rather than being sutures, represent hereditary features above which intra-crustal detachment has taken place. Our observations of

crustal reflection geometry from orogenes where such work has been carried out suggest to us that declivities in continental basement, created during an initial rifting and thinning phase, may affect the geometry of subsequent convergent deformation by acting as large thrust ramps. Implicit in the foregoing is the suggestion that these ramps may also exert some control on the locus and style of the involvement of continental basement in deformation. Although basement involvement was not necessarily invoked, such an interpretation has been made by Price (1981, his Figure 5b) for formation of the Purcell anticlinorium in the Canadian Cordillera. Using palinspastic restorations, the evolution of this large hinterland structure can be linked via shallow detachments to the foreland thrust and foldbelt far to the east.

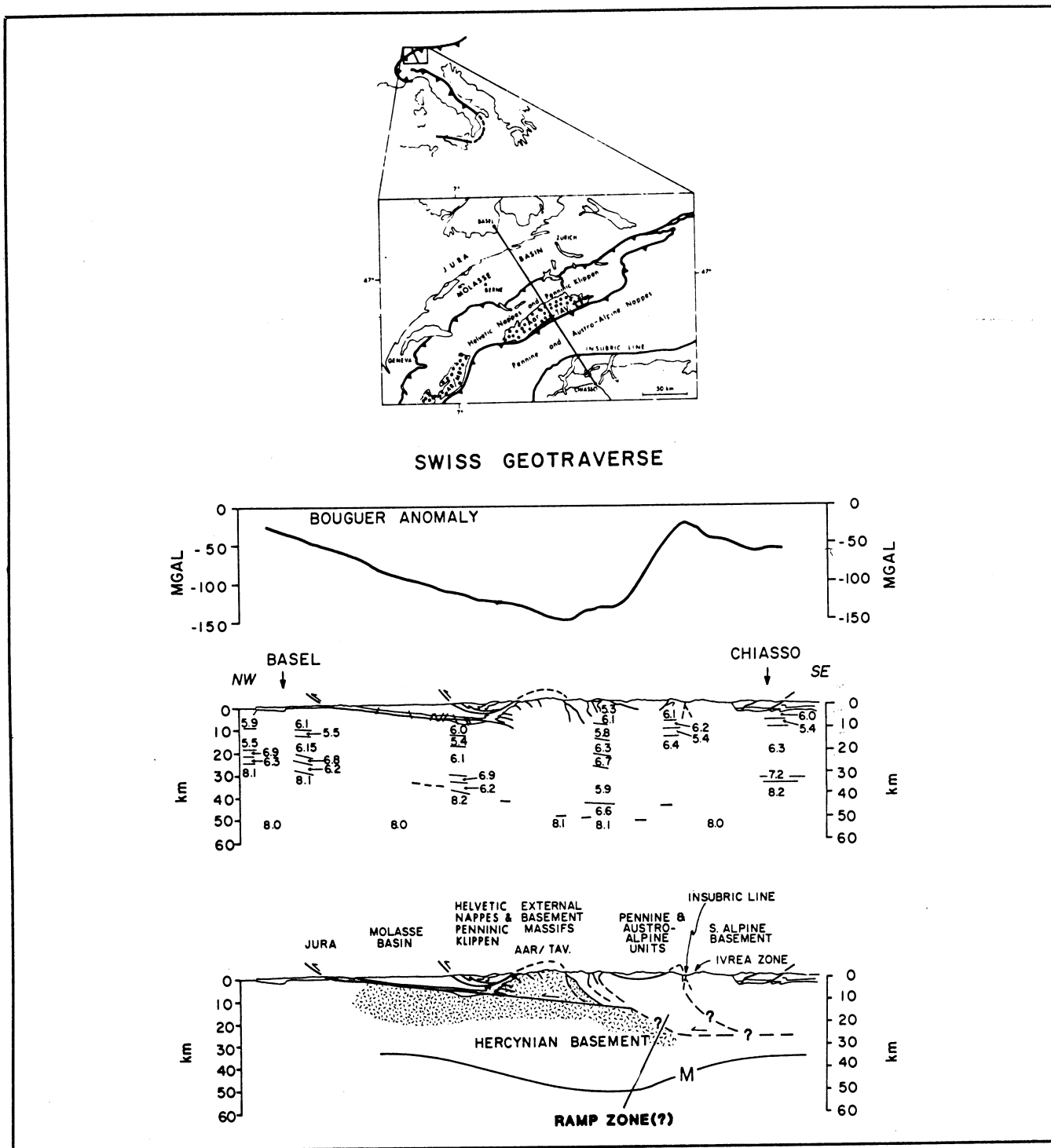
Inferentially, it can be pointed out that other mountain belts in the world might be shown to possess very similar crustal signatures if the necessary data were to be collected. In other orogenes for instance, the types of Bouguer gravity gradients discussed previously are not uncommon. A few examples include the Timor trough-Australian margin (Chamalaun et al, 1976), the Mauritanide belt of Senegal (Briden et al, 1981), the Canadian Cordillera (Woollard and Joesting, 1964), and the Alps (Klingelé and Olivier, 1980). In each of these areas it can be shown or inferred that a passive continental margin existed prior to the convergent deformation which produced the orogene. Such gravity patterns have also been noted in Precambrian orogenic belts where geologic and geophysical observations indicate to some that "suturing" of different crustal blocks has taken place (e.g., Gibb and Thomas, 1976; Fountain and Salisbury, 1981). Fountain and Salisbury (1981) have recently cited examples of terranes where lower crustal rocks are interpreted to be exposed at the surface adjacent to suture zones. A pronounced paired Bouguer gravity low and high is suggested to obtain from a low-density root in the underthrust plate, and the presence of high-density lower crustal rocks near the surface in the upper plate, respectively (Fountain and Salisbury, 1981, their Figure 2). An alternative to this is that the Bouguer gradient may largely represent the locus of thinning of continental crust of the lower (underthrust) plate. Rocks of the upper plate seen at the surface would certainly contribute to the gravity signature, but given the suggestions made for the Appalachian and Ouachita mountain belts, it is tempting to speculate that if one were able to remove near-surface density contrasts in all the orogenes exhibiting these paired anomalies, a "residual" gradient relating to a continent to ocean transition (such as that suggested for eastern Timor by Chamalaun et al, 1976) might remain. All of the aforementioned mountain belts (and others) are candidates for deep crustal reflection profiling.

In this regard it is interesting that a geologically well-studied mountain belt like the Alps bears many similarities to the New England Appalachians (compare Figures 2, 3, 7). It has been noted, for example, that features such as the external basement massifs of the Alps (Aar-Tavetsch and Aiguilles Rouges-Mont Blanc) and high grade metasedimentary nappes (Pennine zone) have likenesses in New England (Green Mountain and Berkshire massifs, Bron-

son Hill anticlinorium-Merrimack synclinorium, respectively, Thompson et al, 1968; Robinson and Hall, 1980). Detailed refraction studies for the Alps (see Figure 7) indicate considerable complexities such as lateral velocity contrasts and crustal low-velocity zones (Mueller et al, 1980; Perrier and Vialon, 1980; Rybach et al, 1980). Recent interpretations that basement massifs like the Aar and Tavetsch (Hsü, 1979) or the Belledonne and Pelvoux (Beach, 1981) are detached along intracrustal fault zones, indicate it may be possible that they were initially ramped in a fashion much like that suggested for the Green Mountains.

Recent balanced cross sections across the Alps southwest of the Swiss geotraverse suggest the possibility of about 37 mi (60 km) of offset between hanging wall and footwall cutoffs of the Aiguilles Rouges basement massif (Boyer and Elliott, 1982, their Figure 8-0-2). This cross section assumes that shortening within the basement is accomplished above a shallowly dipping detachment which passes beneath the Aiguilles Rouges and Mont Blanc massifs, and which is tied to shortening in the Jura foldbelt to the northwest. If geometries and magnitudes of shortening similar to those described by Boyer and Elliott (1982) can be extended to the cross section along the Swiss geotraverse (Figure 7), an interesting speculation arises. Perhaps the Aar and Tavetsch basement massifs presently lie above a shallow detachment zone that extends south of the surface exposures of the massifs. If the suggestions made in this paper prove to be valid, one might reasonably speculate that a reflection profile across the Alps would reveal a zone of southward-dipping reflections beneath the Pennine zone north of the Insubric line (Figure 7). This zone, in our view, would represent the sort of inherited continental margin structure proposed earlier and would constitute a major ramp structure at depth. The classic Alpine "root zones," where nappes turn steeply downward in the crust (e.g., see Burchfiel and Livingston, 1967; Milnes, 1974; Büchi and Trümpy, 1976; Milnes and Pfiffner, 1980), and zones of backfolding or retrocharriage (e.g., Argand, 1911; Rosenfeld, 1978; Roeder, 1979; 1980) south of the external basement massifs, might then have developed as a geometric consequence of thrust sheets riding over the ramp.

In the same context, but more speculatively, such features as the gravity gradient north of the Insubric line might in part be caused by deep contrasts. Although the pronounced gravity high over the Ivrea zone south of the Insubric line (see Figure 7B) has been attributed to the presence of these probable lower crustal rocks at the surface (Kaminski and Menzel, 1968; Berckhemer, 1969; Fountain, 1976), perhaps some part of the gravity signature is also due to lateral density changes in the deeper crust, or suggested southward shallowing of the Moho (e.g., see Rybach et al, 1980, their Figure 6; also Figure 7, this paper). Indeed, if transitional continental margin crustal structure of the European plate is preserved beneath the Alps, and if the Ivrea zone represents upturned lower crust of the southern Alps (e.g., Giese, 1968), the spatial location of the Ivrea zone above the proposed ramp in Figure 7B would not be random coincidence. It has been established for some years that



**Figure 7—(A)** Location map (modified from Roeder, 1980; Rybach et al, 1980) and cross sections for Swiss Alpine geotraverse seismic refraction study. Stipple pattern = external basement massifs: AR/MB = Aiguilles Rouges/Mont Blanc; Aar and Tav = Aar and Tavetsch. External basement massifs occupy structural positions similar to Green Mountain and Berkshire Highlands massifs in New England (Figure 2). **(B)** Swiss geotraverse from Rybach et al (1980). Gravity profile from Klingelé and Olivier (1980); numbers on geotraverse panel are refraction velocities in kilometers/second. Bottom panel is speculative tectonic crustal cross section modified from Büchi and Trümpy (1976), Mueller et al (1980), and Rybach et al (1980). Cross hatch pattern = Hercynian basement (mostly pre-Triassic); fine stipple pattern = sedimentary cover of folded Jura province lying beneath Molasse basin and transported Helvetic nappes. Detachment beneath Aar/Gotthard external basement massifs from Mueller et al (1980) and Hsü (1979); low-angle geometry of detachment inferred from balanced cross section of Boyer and Elliott (1982, their Figure 8-0-2). Queried ramp structure at depth north of Insubric line is based on crustal comparisons with COCORP deep reflection profiles which suggest that a reflection profile over internides of Alps might reveal steepening of seismic dips at depth beneath Pennine zone. Note interpreted shallowing of Moho beneath Alps (Mueller et al, 1980, their Figure 7; Rybach et al, 1980, their Figure 6).

transported rocks of the Helvetic-Ultrahelvetic belt probably once lay along a "passive" continental margin (Trümpy, 1975). Thus, the attempt at comparison seems viable to us. The extent to which deep structure of this continental margin is preserved beneath the Alps certainly remains to be tested.

The implication that continental margin transition zones may be preserved at depth beneath transported rocks in orogenic belts raises an interesting question. In areas where detachments involving the continental basement can be documented at the surface, what is the style of deformation at depth? The possible preservation of continent to ocean transitions suggests that, during convergent deformation, lower levels of the crust may not have deformed significantly and may have behaved relatively rigidly rather than in a distributive ductile manner. Where detachments did take place, they may have occurred along discrete zones of finite thickness. Processes such as these, which can at present only be inferred from crustal reflection profiling, receive needed documentation from detailed geologic studies. In parts of the Caledonian mountain system where erosion levels are deep enough (e.g., the Norwegian Caledonides) (Bartley, 1981; Hodges, 1981), the effects of Caledonian ductile basement deformation can be seen to die out structurally downward and appear to be confined to higher levels, implying that thermal structure of the crust there may have had less influence on the locus of ductile deformation than other mechanisms, such as the availability of water (Bartley, 1982). In addition, some basement thrusts develop at a late stage during convergence, and appear to have geometries (e.g., ramp upward in the direction of upper plate transport) very similar to those in foreland thrust belts (Hodges et al, 1982). These field observations imply that considerable continental underthrusting has taken place in the Caledonides, and that the style of deformation in the continental basement appears to be markedly different from the style traditionally postulated within such basement in collisional settings. The extent to which this style pervades other convergent mountain belts needs to be investigated.

### CONCLUSIONS

Deep seismic reflection profiling has produced important information from beneath high-grade metamorphic and plutonic rocks in the New England Appalachians, and has revealed a gross crustal geometry at depth which is similar to the COCORP traverses of the southern Appalachian and Ouachita Mountains. Some of these reflections in New England can be projected toward the surface into a terrane of probable thrust-imbricated Precambrian basement and garnet-grade metasedimentary cover, allowing the suggestion that similar rocks may extend to considerable depths in the crust beneath New Hampshire. Geologic and geophysical data from the Appalachian-Ouachita system indicate the possibility of a preserved zone of transition from continental to rift stage or oceanic crust tectonically buried beneath transported rocks of the mountain belt. Major differences in surface geology along strike might be explained by the erosion level and by dif-

fering amounts of transport of allochthonous units. This interpretation postulates significant zones of intracrustal detachment and is a major alternative to suggestions of lithosphere-penetrating suture zones beneath certain terrane boundaries in the Appalachians.

Whether continental margin transition zones lie preserved beneath deformed mountain belts has important implications for what we know about the behavior of the crust at all levels during convergent mountain building. Testing various aspects of this question could potentially impact concepts of the development of large-scale structural geometries, continental accretion, emplacement of metamorphic rock suites, and igneous geochemistry. For example, do high-grade metamorphic rocks currently at the surface of the earth in orogenic belts indicate anything about properties of the lower crust and upper mantle presently beneath them? During past episodes of continental accretion, how much material volume can we actually prove was added to the continents through time? And how much does the interpretation of igneous rock chemistry depend on assumptions of the lithology of the continental crust through which the melts pass? Although existing data do not provide a unique interpretation, deep seismic reflection profiles from other convergent mountain systems should collectively contribute to a solution.

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