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Reconciling deep seismic refraction and reflection data from the Grenvillian–Appalachian boundary in western New England

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ABSTRACT

The Grenvillian–Appalachian boundary is characterized by pervasive mylonitic deformation and retrograde alteration of a suite of imbricated allochthonous and parautochthonous gneisses that were thrust upon the Grenvillian continental margin during the lower Paleozoic. Seismic reflection profiling across this structural boundary zone reveals prominent dipping reflectors interpreted as overthrust basement slices (parautochthons) of the Green Mountain Anticlinorium. In contrast, a seismic refraction study of the Grenvillian–Appalachian boundary reveals a sub-horizontally layered seismic velocity model that is difficult to reconcile with the pronounced sub-vertical structures observed in the Green mountains. A suite of rock samples was collected from the Green Mountain Anticlinorium and measured at high pressures in the laboratory to determine the seismic properties of these allochthonous and parautochthonous gneisses. The laboratory-measured seismic velocities agree favorably with the modelled velocity structure across the Grenvillian–Appalachian boundary suggesting that the rock samples are reliable indicators of the rock mass as whole. Samples of the parautochthonous Grenvillian basement exposed in the Green Mountains have lower velocities, by about 0.5 km/s, than lithologically equivalent units exposed in the eastern Adirondack Highlands. Velocity reduction in the Green Mountain parautochthons can be accounted for by retrograde metamorphic alteration (hydration) of the paragneisses. Seismic anisotropies, ranging from 2 to 12%, in the mylonitized Green Mountain paragneisses may also contribute to the observation of lower seismic velocities, where the direction of ray propagation is normal to the foliation. The velocity properties of the Green Mountain paragneisses are thus insufficiently different from the mantling Appalachian allochthons to permit their resolution by the Ontario–New York–New England seismic refraction profile.

Introduction

In western New England the Grenvillian–Appalachian boundary is characterized by pervasive mylonitic deformation and retrograde alteration of a suite of imbricated allochthonous and parautochthonous gneisses that were thrust upon the Grenvillian continental margin during the lower Paleozoic (Fig. 1). Seismic studies of the Grenvillian–Appalachian boundary zone have sought to determine the deep structural relationships within the juxtaposed litho-tectonic units of the western New England Appalachians, and hence to infer the mechanisms of crustal accretion during the Taconian (Devonian) and Acadian (Ordovician) orogenies. Structural interpretations of seismic reflection data, constrained by surface geology, suggest that the Grenvillian–Appalachian boundary zone is characterized by an anastomosing system of folds and thrusts that encompass slices of Grenvillian basement interposed within the Appalachian allochthons (Ando et al., 1984). In contrast, seismic refraction data that were acquired to investigate the structural relationships across the Grenvillian–Appalachian boundary zone are difficult to reconcile with these complex imbricated basement structures (Hughes and Luetgert, 1991). Specifically, the derived model of a planar eastward-dipping velocity interface separating the Grenville province from the allochthonous and parautochthonous Appalachi-

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an units appears to be inconsistent with the exposure of parautochthonous slices of Grenvillian basement to the east of the velocity interface in the Green Mountain Anticlinorium. In this study, we seek to reconcile the discrepancy between the lithologic juxtapositions observed in the Grenvillian–Appalachian boundary zone and the planar velocity structure inferred from seismic refraction data. Of particular importance to this objective are the seismic properties of the parautochthonous gneisses of the Green Mountain Anticlinorium.

The ability of seismic techniques to resolve complex structural and lithologic discontinuities in the crust is a function of many intertwined parameters, most importantly amongst these are: (1) the physical properties (velocity and density) of the juxtaposed lithologies; (2) the principal structural grain (strike and dip) relative to the seismic profile; and (3) the spatial sampling of the seismic wavefield. Rock samples were collected from the western New England Appalachians and their physical properties were measured at pressures up to 1000 MPa in the laboratory. These measurements are used, together with lithologic and structural information, to examine the seismic properties of the allochthonous and parautochthonous gneisses. In this manner, we seek to determine the ability of in situ seismic refraction velocity measurements to resolve structural and lithologic discontinuities in the crust. We begin with a description of the geology of the western New England Appalachians and adjacent Adirondack Highlands. This geologic information

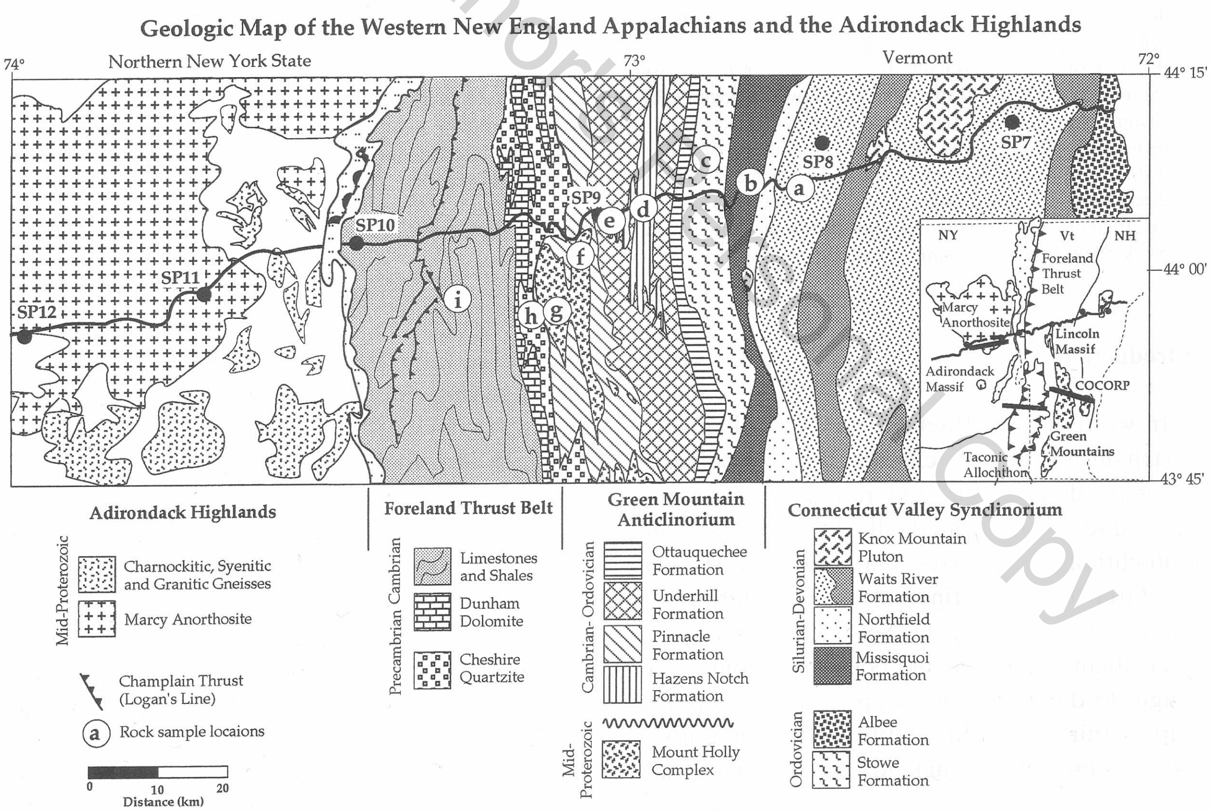

Fig. 1. Geologic map across the western New England Appalachians and the adjacent Adirondack Highlands. The Ontario–New York–New England seismic refraction/wide-angle reflection profile is shown by the bold line and shotpoints are indicated along the profile. The locations of rock samples collected from the western New England Appalachians are indicated by the letters *a–i*. Inset map shows location of seismic reflection profiles obtained by COCORP. The map has been simplified after the Vermont State geologic map compiled by Doll et al. (1961), and the New York State geologic map of Isachsen and Fisher (1970).

forms an important component in the interpretation of the rock sample measurements presented in the following sections.

Geological framework of the Grenvillian–Appalachian boundary

The resolution of the Grenvillian–Appalachian boundary in western New England by seismic refraction and reflection techniques provides a particularly exacting challenge due its the structural complexity and narrowness (Fig. 1). From west to east across the boundary zone the following litho-tectonic units are recognized:

(1) the mid-Proterozoic gneisses of the autochthonous Grenvillian basement exposed in the Adirondack Highlands (northern New York State);

(2) a Precambrian rift-clastic sequence which lies unconformably upon the Grenvillian basement in the Champlain Lowlands;

(3) allochthonous Lower Cambrian to Lower Ordovician carbonates and clastics of the Foreland Thrust Belt (western Vermont);

(4) imbricated and metamorphosed mid-Ordovician flysch deposits interposed with parautochthonous slices of Grenvillian basement exposed in the core of the Green Mountain Anticlinorium (central Vermont); and

(5) Silurian–Devonian forearc sediments and volcanics of the Connecticut Valley Synclinorium (eastern Vermont).

Tectonic syntheses of western New England are presented by Rowley and Kidd (1980), Bradley (1983) and Stanley and Ratcliffe (1985). Herein, we concentrate on the structural framework of the Grenvillian basement exposed in the Adirondack Highlands and Green Mountain Anticlinorium.

In the Adirondack Highlands, a suite of mid-Proterozoic anorthosites, metagabbros, charnockites and syenites are exposed which typically attain hornblende-granulite facies metamorphism (Wiener et al., 1984; McLelland and Isachsen, 1986). Mantling these meta-igneous rocks to the south and east of the Adirondack Highlands, a series of paragneisses and syn-tectonic granitoids form an apron around the extremity of the Adirondack massif (Fig. 1). Typically these paragneisses are composed of hornblende-biotite-plagioclase-quartz assemblages (Chiarenzelli and McLelland, 1990). Structural fabrics within these mantling paragneisses are dominated by sub-horizontal layering related to large-scale recumbent (sub-horizontal) nappe structures (Wiener et al., 1984; McLelland and Isachsen, 1986).

The Green Mountain Anticlinorium forms a north–south structural high which lies adjacent to the eastern Adirondack Highlands (Fig. 1). In the core of the Green Mountain Anticlinorium, slices of mid-Proterozoic crystalline basement are thrust between allochthonous shelf-rise sediments (Fig. 2). These parautochthonous Grenvillian basement slices are composed of well layered, garnet-rich, biotite-plagioclase-quartz gneisses, hornblende-biotite granitic gneisses and massive quartzites of the Mount Holly Complex (Doll et al., 1961; Stanley and Ratcliffe, 1985). Field relationships, isotopic age-dating and chemical analysis indicate that the Mount Holly Complex paragneisses are one-to-one correlatives with the paragneisses and syn-tectonic granitoids exposed in the eastern Adirondack Highlands (Ratcliffe et al., 1991). Palinspastic reconstructions suggest that the Mount Holly complex was thrust eastwards from the edge of the Grenvillian continental margin during the Taconic orogeny (Stanley and Ratcliffe, 1985).

In central Vermont the core of the Green Mountain Anticlinorium is composed of two arcuate limbs which form the Lincoln massif (Fig. 1). Prominent mylonitic shear surfaces dip steeply eastward from 70° through to sub-vertical (Fig. 2). The western limb of the Lincoln massif is comparatively massive and competent, with only minor high-angle offset faulting of the recumbent anticlinal structure (DelloRusso and Stanley, 1986). The eastern limb of the Lincoln massif is characterized by pervasive mylonitic schistosity resulting from extensive imbrication along a series of anastomosing thrust surfaces within an east–west-stacked duplex structure (Fig. 2—detail). Relic Grenvillian metamorphic fabrics suggest epidote-amphibolite/garnet zone metamorphic conditions, locally attaining granulite facies conditions in the paragneisses which core the

Green Mountain Anticlinorium (DelloRusso and Stanley, 1986; Stanley, 1989).

Flanking the Green Mountains to the east, a series of distal flysch deposits are exposed that are characterized by amphibolite grade (garnet zone) metamorphism, pervasive mylonitic imbricated fabrics and retrograde alteration assemblages (Stanley and Ratcliffe, 1985; DelloRusso and Stanley, 1986).

Geophysical constraints on deep crustal structure

The Ontario–New York–New England seismic refraction/wide-angle reflection profile traverses the Adirondack massif and extends across the western New England Appalachians at an oblique angle, almost perpendicular to the north–south trend of the principal litho-tectonic units (Fig. 1). The distinct lithologic and structural characteristics of the Grenvillian and Appalachian provinces allow a seismic velocity discontinuity to be resolved that separates the Grenvillian upper crust from that of the western New England Appalachians (Hughes and Luetgert, 1991). This velocity discontinuity forms a ramp-like structure dipping eastward beneath the western New England Appalachians (Grenvillian ramp on Fig. 3a). Interpretation of the Grenvillian ramp suggests that it is a zone of detachment which separates the autochthonous Grenvillian rocks and their Precambrian "cover" sequence from the allochthonous Appalachian terranes (Hughes and Luetgert, 1991). However, surface geologic observations of pronounced dipping structures in the Green Mountain Anticlinorium are difficult to reconcile with the modeled sub-horizontal velocity interfaces in that region (Fig. 3a).

Seismic velocity measurements of the Grenvillian basement are remarkable consistent despite considerable compositional variability within the meta-igneous lithologies of the Adirondack Highlands (Hughes and Luetgert, 1992). In the eastern

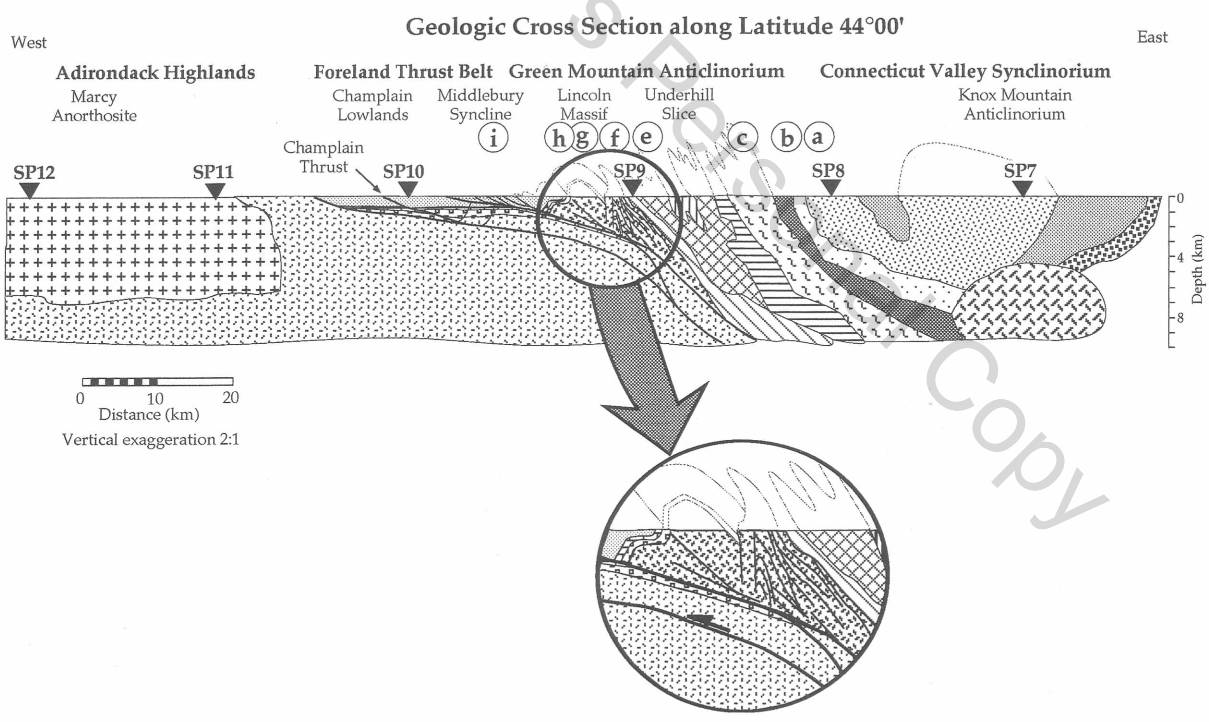

Fig. 2. Geologic cross section along the Ontario–New York–New England seismic refraction/wide-angle reflection profile where it traverses the western New England Appalachians and the adjacent Adirondack Highlands. The seismic expression of the steeply dipping imbricated structures at the edge of the Grenvillian crust is examined by means of seismic refraction velocities (shotpoints indicated) and rock sample velocities (a–i). For key to lithologies see Fig. 1. The cross section is simplified after Doll et al. (1961) and Stanley (1989).

Adirondack Highlands, where anorthosites, metagabbros and granitic gneisses are exposed, seismic velocities lie in the range 6.4–6.6 km/s and are nowhere as low as 6.0 km/s (Fig. 3a). Lateral velocity variations in the Grenvillian basement do not appear to be significant given the 25–35 km shotpoint spacing and 800 m receiver spacing of the seismic refraction data (Hughes and Luetgert, 1992). Correlation of the Grenvillian basement gneisses with those exposed in the core of the Green Mountain Anticlinorium (see previous section) suggests that high velocities (6.5–6.6 km/s) would be expected in the region of the Green Mountain parautochthons. The seismic velocities of 5.95–6.05 km/s modeled beneath the Green Mountain Anticlinorium (Hughes and Luetgert, 1991) are inconsistent with the characterization of Grenvillian basement with seismic velocities of 6.5–6.6 km/s.

The thickness of the Grenvillian basement slices at depth beneath the Green Mountain Anticlinorium is an important factor in contributing to the resolution of the velocity structure of the Grenvillian–Appalachian boundary zone. Estimates of the deep geometry of the Green Mountain Anticlinorium are most readily obtained from structural cross sections constrained by surface geology (Stanley and Ratcliffe, 1985; Stanley, 1989). The Grenvillian basement extends at shallow depth beneath the Foreland Thrust Belt and crops out in a broad antiformal structure in the Lincoln massif (Fig. 2). Extrapolations of the surface geology indicate that the Green Mountain parautochthons extend, in the form of tapering basement slices, to a depth of 5–6 km where they become contiguous with the eastward extension of the Grenvillian basement beneath the western New England Appalachians (Fig. 2—inset). Note

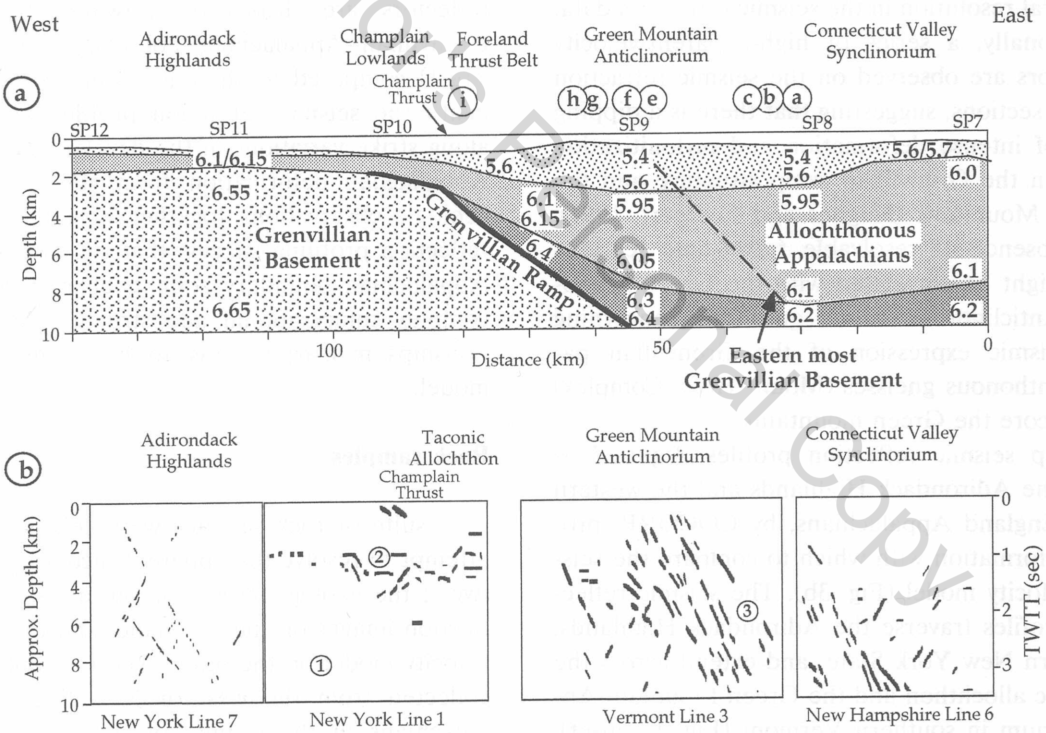

Fig. 3. Comparison between a seismic refraction velocity model (a) and deep seismic reflection sections (b) acquired across the Grenvillian–Appalachian boundary in western New England. The seismic velocity model shows a steeply dipping ramp structure (Grenvillian ramp) dividing the western New England Appalachians from the Adirondack Highlands (Hughes and Luetgert, 1991). Note the absence of velocity features that might be correlated with the parautochthonous Grenvillian rocks of the Green Mountains. The seismic reflection profiles (b) acquired across the Green Mountains and the Taconic Allochthon in southern Vermont (Brown et al., 1983; Ando et al., 1984) display prominent dipping reflections characteristic of mylonitized and imbricated structures at the edge of the Grenvillian craton. The models are aligned with respect to the Champlain thrust (Logan's line).

that the Grenvillian parautochthons (Mount Holly Complex) form a 20-km-wide basement block that should be readily resolvable, given the high seismic velocities (6.5–6.6 km/s) of the lithologically associated units in the Adirondack Highlands.

A further discrepancy lies in the modeled location of the Grenvillian ramp structure between shotpoints 9 and 10 beneath the Foreland Thrust Belt (Hughes and Luetgert, 1991). The Grenvillian ramp structure delineates a seismic velocity boundary that is located 25 km west of the easternmost exposure of Grenvillian basement in the Green Mountains (Fig. 3a). Thus, there is a 25-km-thick "wedge" of Grenvillian basement enclosed between the modelled Grenvillian ramp structure and the easternmost exposure of Grenvillian basement. The shotpoint spacing is 25–35 km across the Grenvillian–Appalachian boundary zone, so that the modelled location of the Grenvillian ramp is unlikely to result from a lack of lateral resolution in the seismic refraction data. Additionally, a series of high-apparent-velocity reflectors are observed on the seismic refraction record sections, suggesting that there is a dipping zone of intense deformation and mylonitization between the Grenvillian ramp structure and the Green Mountains (Hughes and Luetgert, 1991). The absence of resolvable travel-time features that might be correlated with the Green Mountain Anticlinorium raises questions concerning the seismic expression of the Grenvillian parautochthonous gneisses (Mount Holly Complex) which core the Green mountains.

Deep seismic reflection profiles acquired across the Adirondack Highlands and the western New England Appalachians, by COCORP, provide information with which to compare the seismic velocity model (Fig. 3b). The seismic reflection profiles traverse the Adirondack Highlands, northern New York State, and extend across the Taconic allochthon and the Green Mountain Anticlinorium in southern Vermont (Fig. 1—inset). The geology is remarkably similar along strike, so that comparisons may be drawn between the refraction model and the seismic reflection section. However, it should be noted that the Foreland Thrust Belt (Taconic allochthon) is significantly broader in the vicinity of the reflection profile, than in the location of the refraction profile where it is at its narrowest and structurally most complex (Fig. 1).

Interpretation of the seismic reflection profiles suggests that the Grenvillian basement extends eastwards beneath a planar décollement which underlies the Taconic allochthon (see 2 in Fig. 3b). Beneath the Green Mountain Anticlinorium a series of prominent sub-parallel dipping reflectors were imaged extending to approximately 5–6 s beneath the Connecticut Valley Synclinorium (See 3 in Fig. 3b). These eastward-dipping reflectors splay out into a zone of anastomosing reflections in the mid-lower crust (Brown et al., 1983; Ando et al., 1984). The dipping seismic reflectors beneath the Green Mountain Anticlinorium are inferred to be highly deformed thrust-imbricated basement slivers interposed with mylonitic shear zones (Ando et al., 1984; Phinney and Roy-Chowdhury, 1989; Thigpen, 1989). These dipping reflectors are displaced eastwards from the Grenvillian–Appalachian boundary (Champlain Trust) compared to their location observed beneath the seismic refraction profile because of along strike variations in the development of the Appalachian deformation front (Fig. 3). Thus, geologic observations together with the seismic reflection profiling suggest that the Grenvillian–Appalachian boundary zone is characterized by complex compositional and structural interrelationships, in sharp contrast to the seismic velocity model.

Rock samples

A suite of rock samples were collected in an attempt to resolve the apparent inconsistency between the geologic cross section and seismic reflection images on the one hand, and the seismic velocity model on the other. These samples were collected from the western New England Appalachians in the vicinity of the Ontario–New York–New England seismic refraction profile where it traverses central Vermont (Fig. 1). The rock samples were carefully selected, in the field, to ensure that representative samples of the principal lithologies were obtained (Table 1). Three mutually perpendicular cores were cut from these samples parallel and normal to the principal foliation (cleavage plane) and the structural lineation respectively. Seismic velocities were measured on each core at increasing pressures up to 1000 MPa (Table 2). The samples display a characteristic rapid velocity increase up to pressures of 200–300 MPa associated with closing of microcracks and pore spaces. At pressures in excess of 200–300 MPa the seismic velocity increases linearly with pressure with mean velocities in the range 6.0–6.5 km/s (Fig. 4a). In contrast, rock samples collected from the Adirondack Highlands are characterized by mean velocities in the range 6.2–7.2 km/s as shown by Figure 4b (Birch, 1960; Manghnani et al., 1974; Christensen and Fountain, 1975). The seismic velocities of the Adirondack samples are approximately 0.5 km/s faster than those measured for samples collected from the western New England Appalachians.

Comparisons of the rock sample velocities with the seismic refraction model shows a scatter about the in situ velocity measurements, but in general, a broad agreement is attained between the two measurements (Fig. 5). The favorable correlation between the laboratory measurements and the seismic velocity model indicates that the rock samples are likely to be reliable indicators of the rock mass as a whole. This is because the seismic wavefield data effectively averages all the lithologic variations observed along the seismic refraction profile, thus non-representative samples would be easily identified by their mismatch with the seismic velocity model. Noticeably, the paragneisses which core the Green Mountain Anticli-

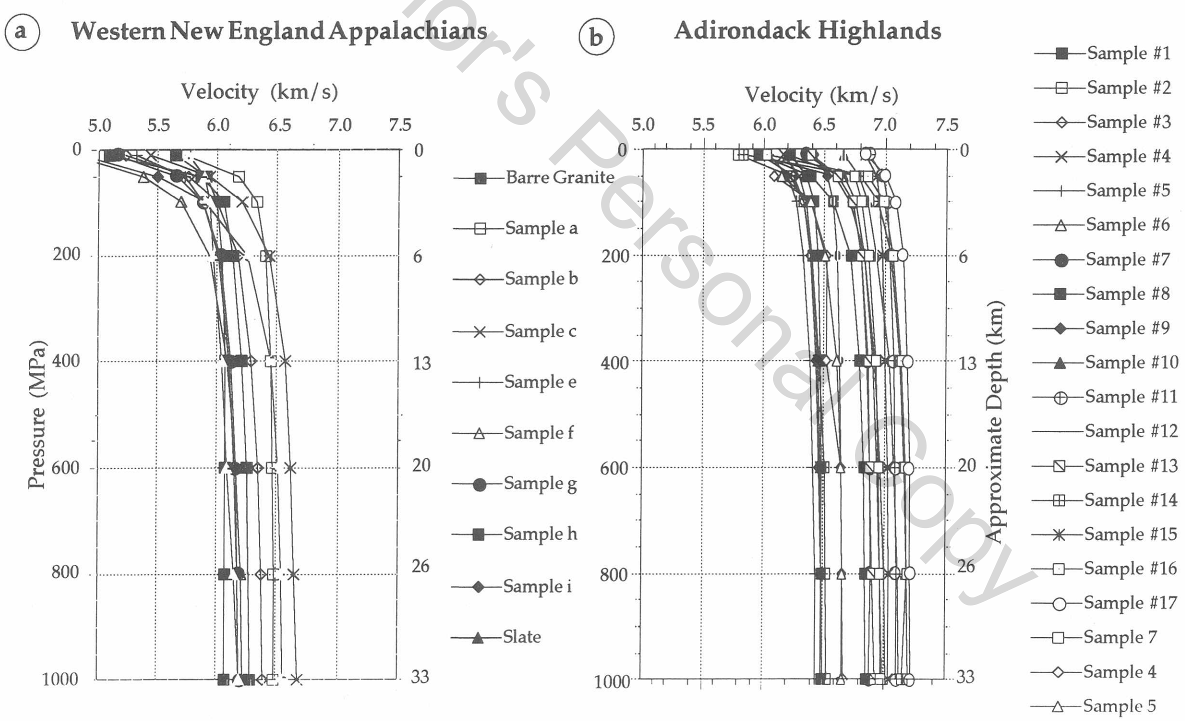

Fig. 4. Comparison of mean laboratory velocity measurements for rock samples collected from the western New England Appalachians (a) and from the Adirondack Highlands (b). Note that the Adirondack rock samples have an average compressional wave velocity that is 0.5 km/s faster than that of samples collected from the western New England Appalachians. Appalachian rock samples (a) were collected from localities shown in Fig. 1, and additional Appalachian rock samples are from Birch (1960). Adirondack rock samples (b) denoted by samples #1–14 are from Manghnani et al. (1974) and samples 4, 5, 7 are from Christensen and Fountain (1975). See Table 1 for location and composition of these rock samples. Laboratory data have been corrected for temperature using a geotherm of 15°C/km (Blackwell, 1971) and an average thermal coefficient of 2.0×10^{-4} km/s °C^{-1} (Christensen, 1979; Kern and Richter, 1981).

TABLE 1

Location and composition of rock samples used in this study

Sample*	Locality	Rock type
Sample a	Barre, VT	Phyllitic schist
Sample b	Roxbury, Vt	Phyllite
Sample c	East Warren, Vt	Phyllitic schist
Sample e	Lincoln Gap, Vt	Mica shist
Sample f	South Lincoln, Vt	Granitic schist
Sample g	South Lincoln, Vt	Granitic gneiss
Sample h	East Middleburry, Vt	Quartizite
Sample i	Middlebury, Vt	Shaley limestone
Barre Granite [3]	Barre, VT	Granite
Adirondack #1 [2]	Lake Placid, NY	Anorthosite
Adirondack #2 [2]	Tupper Lake, NY	Garnet-biotite-qtz-fldsp gneiss
Adirondack #3 [2]	Colton, NY	Migmatitic biotite-qtz-fldsp gneiss
Adirondack #4 [2]	Tupper Lake, NY	Ferrohypersthene granulite
Adirondack #5 [2]	Tupper Lake, NY	Charnockite
Adirondack #6 [2]	Willsboro, NY	Gabbroic anorthosite
Adirondack #7 [2]	Long Pond, NY	Gabbroic anorthosite
Adirondack #8 [2]	Saranac Lake, NY	Quartz mangerite
Adirondack #9 [2]	Saranac Lake, NY	Mangerite
Adirondack #10 [2]	Tupper Lake, NY	Microcline granulite
Adirondack #11 [2]	Everton, NY	Gabbroic granulite
Adirondack #12 [2]	Willsboro, NY	Two-pyroxene-plagioclase granulite
Adirondack #13 [2]	Lake Placid, NY	Metasedimentary granulite
Adirondack #14 [2]	Everton, NY	Hornblende-proxene granulite
Adirondack #15 [2]	Everton, NY	Gabbroic granulite
Adirondack #16 [2]	Elizabethtown, NY	Almadine-CPX-oligoclase granulite
Adirondack #17 [2]	Willsboro, NY	Almandine-pryoxenite gneiss
Sample 4 [1]	Saranac Lake, NY	Charnockitic gneiss
Sample 5 [1]	Saranac Lake, NY	Charnockitic gneiss
Sample 7 [1]	Saranac Lake, NY	Charnockite

* Suffixes refer to the following references: (1) Christensen and Fountain, 1975; (2) Manghnani et al., 1974; and (3) Birch, 1960.

TABLE 2

Laboratory measurements of seismic velocity at elevated pressures for rock samples collected from the western New England Appalachians

Core *	Density (g/cm^3)	Velocity (km/s)							
		10 MPa	50 MPa	100 MPa	200 MPa	400 MPa	600 MPa	800 MPa	1000 MPa
Sample a, phyllitic schist									
A	2.741	5.501	5.954	6.123	6.217	6.285	6.324	6.352	6.374
B	2.728	6.086	6.449	6.583	6.662	6.723	6.758	6.784	6.803
C	2.739	5.574	6.131	6.308	6.397	6.466	6.506	6.534	6.557
Anisotropy		9.6	7.7	7.0	6.7	6.5	6.4	6.4	6.3
Mean	2.736	5.720	6.178	6.338	6.425	6.491	6.530	6.557	6.578
Sample b, phyllite									
A	2.705	4.731	5.146	5.466	5.677	5.843	5.941	6.011	6.066
B	2.719	5.560	5.948	6.158	6.343	6.476	6.540	6.586	6.621
C	2.720	5.765	6.200	6.404	6.554	6.662	6.722	6.765	6.799
Anisotropy		21	13.5	11.2	10.5	9.7	9.1	8.7	8.4
Mean	2.715	5.232	5.765	6.009	6.192	6.327	6.401	6.454	6.459

TABLE 2 (continued)

Core *	Density (g/cm^3)	Velocity (km/s) 10 MPa	50 MPa	100 MPa	200 MPa	400 MPa	600 MPa	800 MPa	1000 MPa
Sample c, phyllitic schist									
A	2.587	5.031	5.649	5.994	6.287	6.476	6.565	6.627	6.675
B	2.862	5.643	6.125	6.383	6.588	6.715	6.776	6.819	6.853
C	2.859	5.632	6.042	6.280	6.496	6.640	6.703	6.745	6.777
Anisotropy		10.8	7.7	6.1	4.6	3.6	3.1	2.8	2.6
Mean	2.769	5.435	5.939	6.219	6.457	6.611	6.681	6.730	6.769
Sample e, mica schist									
A	2.677	4.909	5.453	5.645	5.793	5.936	6.021	6.082	6.130
B	2.706	5.590	5.921	6.068	6.183	6.277	6.331	6.369	6.399
C	2.675	5.471	5.812	5.970	6.103	6.214	6.278	6.324	6.360
Anisotropy		12.1	7.9	7.0	5.6	5.4	4.9	4.5	4.2
Mean	2.686	5.323	5.729	5.894	6.026	6.142	6.210	6.258	6.296
Sample f, granitic gneiss									
A	2.670	4.635	5.248	5.586	5.873	6.063	6.154	6.219	6.269
B	2.666	4.653	5.378	5.734	5.992	6.165	6.260	6.328	6.381
C	2.682	4.927	5.515	5.809	6.025	6.166	6.240	6.294	6.335
Anisotropy		5.9	4.8	3.8	2.5	1.7	1.7	1.7	1.7
Mean	2.673	4.738	5.381	5.710	5.963	6.131	6.218	6.280	6.328
Sample g, granitic gneiss									
A	2.752	4.636	5.299	5.604	5.806	5.937	6.009	6.061	6.102
B	2.727	5.381	5.847	6.048	6.181	6.277	6.332	6.371	6.401
C	2.741	5.456	5.845	6.030	6.165	6.261	6.314	6.352	6.381
Anisotropy		15.2	9.4	7.3	6.1	5.4	5.1	4.9	4.7
Mean	2.740	5.158	5.664	5.894	6.051	6.159	6.218	6.261	6.295
Sample h, quartzite									
A	2.639	5.575	5.938	6.043	6.105	6.161	6.194	6.217	6.236
B	2.641	5.640	5.842	5.923	5.973	6.011	6.033	6.049	6.061
C	2.642	5.729	5.965	6.048	6.105	6.155	6.185	6.206	6.222
Anisotropy		2.7	2.1	2.1	2.1	2.4	2.6	2.7	2.8
Mean	2.641	5.648	5.915	6.004	6.061	6.109	6.137	6.157	6.173
Sample i, shaley limestone									
A	2.693	5.116	5.668	6.024	6.345	6.525	6.583	6.619	6.647
B	2.690	4.637	5.308	5.768	6.216	6.484	6.562	6.605	6.636
C	2.685	4.907	5.544	5.922	6.259	6.471	6.559	6.618	6.665
Anisotropy		4.5	6.3	4.2	2.0	0.6	0.4	0.2	0.4
Mean	2.689	4.887	5.507	5.905	6.273	6.493	6.568	6.614	6.649

* Core A is taken normal to the gneissic foliation (slow direction), core B is taken parallel to the lineation and the foliation (fast direction) and core C is taken parallel to the foliation and perpendicular to the lineation. See Fig. 1 for locations of samples.

$$\text{Anisotropy} = \frac{V_{\text{pmax}} - V_{\text{pmin}}}{V_{\text{pmax}}} \times 100\%$$

norium (samples f and g) have lower velocities compared to the amphibolitic gneisses, schists and phyllites (samples b and c) which mantle the Green Mountains to the east (Fig. 5). The association of low seismic velocities (5.9 ± 0.1 km/s) with the paragneisses of the Green Mountain

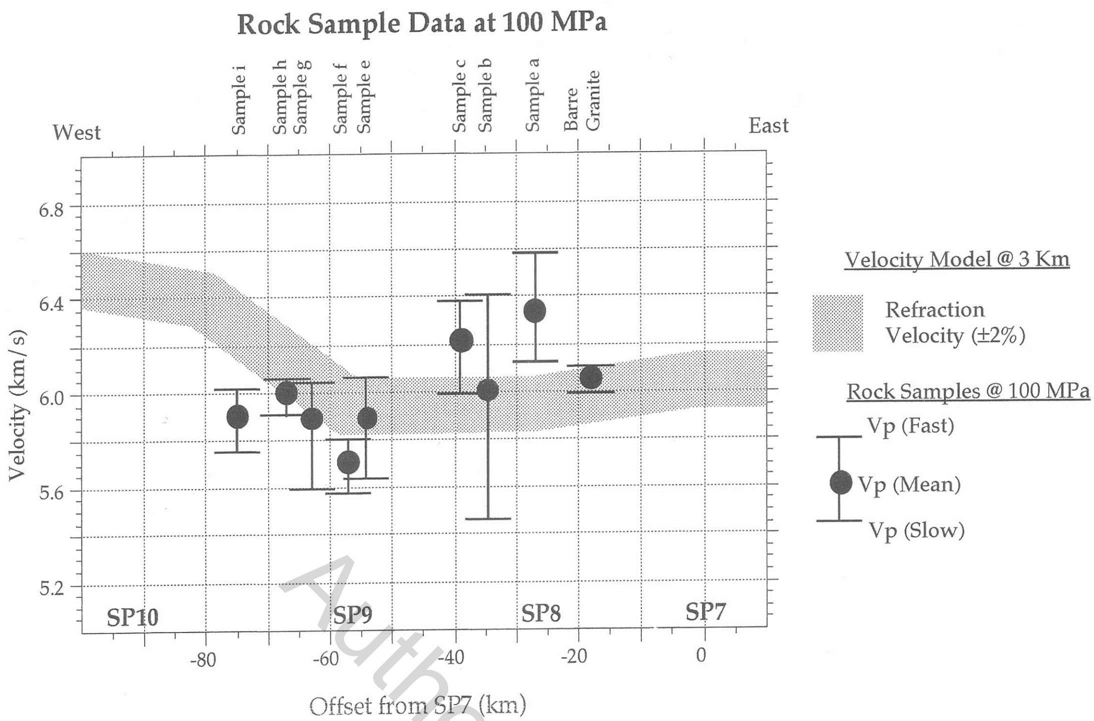

Fig. 5. Rock samples collected from the western New England Appalachians and measured for seismic velocity at 100 MPa in the high-pressure laboratory. Sample velocities were measured parallel (slow direction) and normal (fast direction) to the principal foliation to enable comparison with the seismic velocity model. The graph shows that the laboratory velocities agree favorably with the seismic refraction velocities at 3 km ($\sim$ 100 MPa). Note that samples from the core of the Green Mountain Anticlinorium (*f* and *g*) have a lower velocity than the mantling amphibolitic gneisses (*b* and *c*). Sample localities and shotpoints are shown in Fig. 1.

Anticlinorium is in contrast to that observed within the Adirondack Highlands where velocities in excess of 6.5 km/s predominate.

Discussion

Structurally complex regions, such as the Green Mountain Anticlinorium, are extremely difficult to image with regional seismic refraction techniques. Seismic velocities obtained from refraction profiling are frequently attributed to an aggregate of the lithological and structural variations along the seismic profile whose bulk properties tend to increase with depth resulting in a sub-horizontally stratified Earth model (Mooney, 1989). On first inspection such an interpretation for the velocity structure of the Green Mountain Anticlinorium appears to be satisfactory in the absence of resolvable seismic velocity evidence for complex interlayered structural fabrics associated with the obducted allochthons and parautochthons (Fig. 3a). However, both structural geology and seismic reflection profiling in the Green Mountain Anticlinorium suggest that such an interpretation is grossly simplistic and inappropriate to these highly deformed paragneisses (Fig. 3b). Some additional factors must be affecting our ability to resolve the seismic velocity expression of the Green Mountain Anticlinorium.

Composition

The Grenvillian basement lithologies exposed in the Green Mountain Anticlinorium are characterized by lower velocities than lithologically associated units in the Adirondack Highlands. Laboratory-measured seismic velocities obtained from a range of samples collected across the Green Mountains and the Adirondacks show a marked velocity contrast, with lower velocities in the Appalachians than in the Adirondacks (Fig. 4). A first-order comparison is possible between Adirondack and Green Mountain basement samples which have similar mineralogies. In these complementary laboratory measurements, samples obtained from the Green Mountains have a seismic velocity about 0.5 km/s lower than those measured for samples from the Adirondack Highlands (Fig. 6). The Adirondack samples are composed of biotite-quartz-feldspar assemblages with minor garnet and pyroxene components (Manghnani et al., 1974), and the Green Mountain samples (Mount Holly complex) are composed of garnet-biotite-plagioclase-quartz assemblages.

The Green Mountains suffered extensive retrograde metamorphism during the Taconian and Acadian orogenies. As a result, all lithologies exposed in the Green Mountains are hydrated (1–2% H_2O is typical), pervasively refoliated, and commonly display abundant chlorite-muscovite-epidote as retrograde minerals (DelloRusso and Stanley, 1986). From this petrological analysis it is clear that the mineralogical composition of the Green Mountain paragneisses has been substantially altered compared to their associated lithologies in the Adirondacks, which remain relatively unscathed by lower Paleozoic re-metamorphism. The retrograde mineralogies observed in

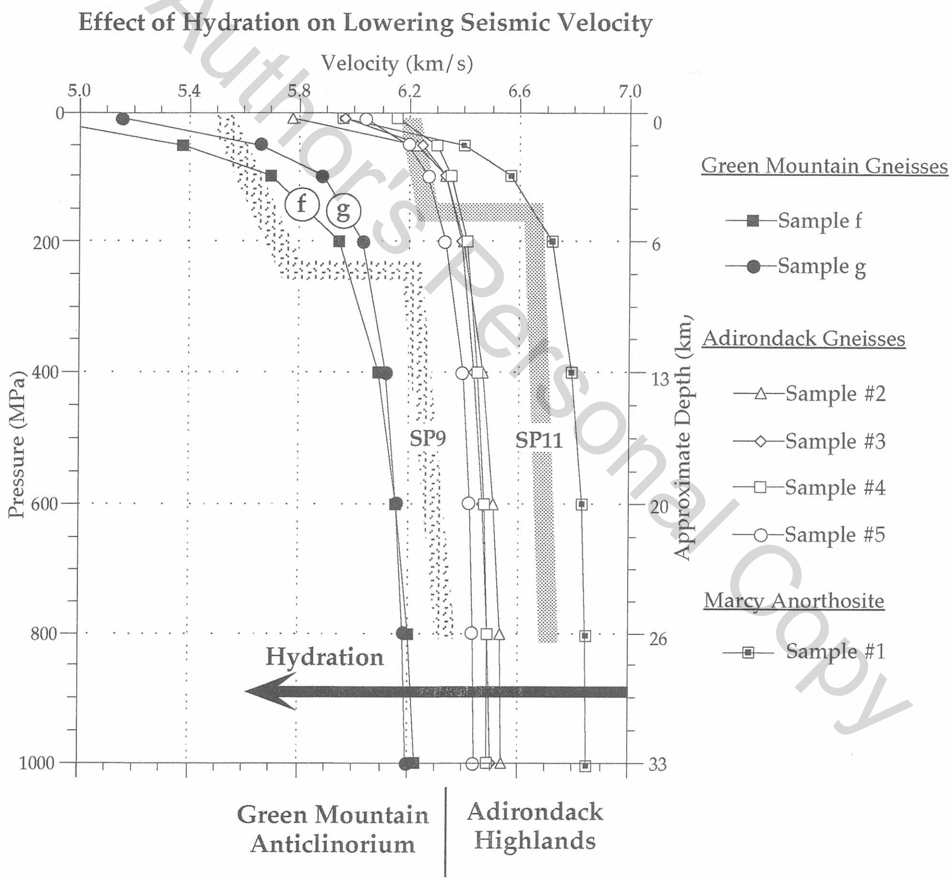

Fig. 6. Comparison of laboratory measurements of seismic velocity for samples of mid-Proterozoic gneisses from the Adirondack Highlands (Manghnani et al., 1974) and from the Green Mountain Anticlinorium (Mount Holly Complex—samples *f* and *g*). The samples have similar bulk compositions (garnet biotite-plagioclase-quartz gneisses), but seismic velocities are significantly lower in the Green Mountains than in the Adirondack Highlands. We conclude that retrograde alteration (hydration) of the paragneisses from the Green Mountain Anticlinorium has an important effect in lowering the measured seismic velocities. One-dimensional velocity–depth functions for the Green Mountains (*SP9*) and the Adirondack Highlands (*SP11*) are shown. A sample of Marcy Anorthosite is shown for reference.

the Green Mountains result in a lowering of the seismic velocity of the Mount Holly Complex (Fig. 6). Thus, a primary reason for the absence of a resolvable velocity anomaly associated with the Green Mountain Anticlinorium is the re-metamorphism and hydration of the Grenvillian basement parautochthons.

Structure and anisotropy

The structural relationships of the juxtaposed litho-tectonic units in the Grenvillian–Appalachian boundary zone have an important affect upon the determination of seismic velocity. The samples collected from western New England are

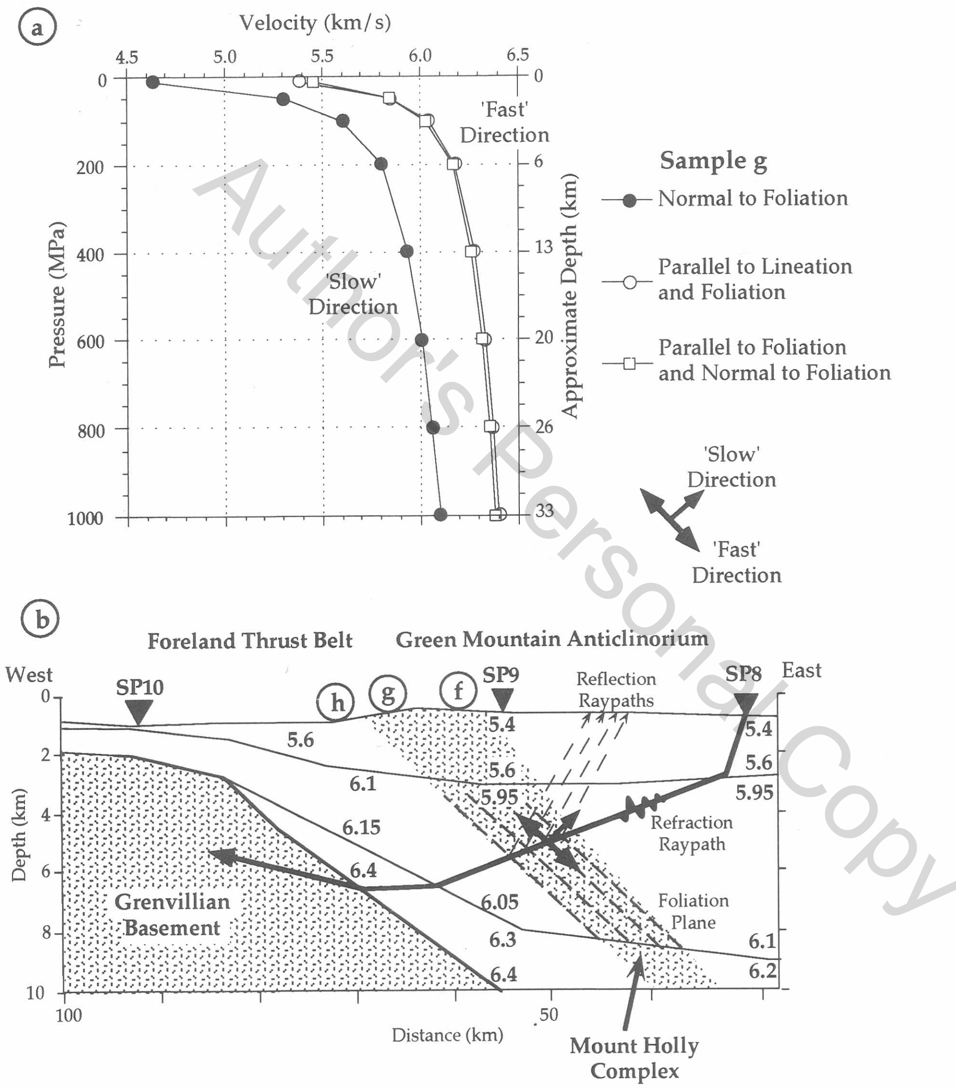

Fig. 7. The mylonitized gneisses of the Green Mountain Anticlinorium are characterized by 5% seismic anisotropy (a). Seismic refraction ray paths propagate approximately normal to the steeply dipping gneissic foliation (b). Consequently, the "slow" velocity of the Mount Holly Complex gneisses is measured by the seismic refraction profile. The bulk velocity of the Mount Holly Complex is insufficiently different from the mantling amphibolitic gneisses of the Green Mountain Anticlinorium to permit resolution of the imbricated basement structures by the seismic refraction profile. The observation of clear back-scattered energy (reflected raypaths) is inhibited by the finely imbricated structures within the Green Mountain Anticlinorium.

characterized by variable degrees of seismic anisotropy, from 2% in the massive granitic lithologies to as much as 12% in the phyllites and schists (Table 2). Brocher and Christensen (1990) showed that seismic velocity measurements vary as a function of dip relative to the azimuth of the seismic profile. For velocity measurements normal to the plane of the seismic profile, the maximum velocity is attained when the transmitted seismic energy is parallel to the foliation and the velocity decreases, as a sine of the dip angle, to a minimum when the foliation is normal to the transmitted energy. This observation is related to the preferential alignment of highly anisotropic minerals, such as micas and amphiboles in pervasively foliated gneisses (Fountain and Christensen, 1989; Brocher and Christensen, 1990).

From west to east across the Grenvillian–Appalachian boundary, the structural dip of the "Adirondack" gneisses increases from sub-horizontal in the recumbent nappes of the Adirondack Highlands to sub-vertical in the core of the Green Mountain Anticlinorium (McLelland and Isachsen, 1986; Stanley, 1989). Both the seismic refraction profile (Hughes and Luetgert, 1991) and the reflection profiles (Ando et al., 1984) acquired across the Grenvillian–Appalachian boundary support the existence of steeply dipping fabrics (mylonitized paragneisses) beneath and along the flanks of the Green Mountain Anticlinorium in southern Vermont (Fig. 3). Thus, transmitted seismic energy which traverses the Green Mountain Anticlinorium propagates through a series of sub-vertical lithologic units which lie normal to the direction of propagation. Consequently, the minimum laboratory velocity (i.e., normal to the foliation) should be most representative of the in situ seismic velocity measured along the Ontario–New York–New England seismic refraction profile (Fig. 7a). In this manner, lower seismic velocities would be expected across the Green Mountains than across the Adirondack Highlands for lithologically equivalent basement units (Fig. 7b). Seismic anisotropy in the basement paragneisses beneath the Green Mountains may play a contributing role in lowering the velocities observed by the seismic refraction profile.

Spatial sampling

A variety of geometrical factors also contribute to the ability of regional seismic refraction/ wide-angle reflection studies to resolve regions of prominent structural fabric. Observation of the Green Mountains with seismic refraction data will be very difficult unless the bulk velocity of the paragneisses is quite different from the surrounding crust, or unless the geometry of the seismic reflectors is such as to provide clear back scattered reflected arrivals. In the Green Mountains the bulk velocity of the mylonitized paragneisses is insufficiently different from the mantling schists and phyllites to permit its delineation with seismic refraction measurements as shown by Figure 5.

The observation of steeply dipping seismic reflectors with wide-angle seismic data necessitates an optimum source–receiver configuration relative to the lamination geometry. The relatively sparse shotpoint geometry of the Ontario–New York–New England seismic refraction profile does not permit back-scattered reflected energy to be readily observed from the sub-vertical imbricated structures of the Green Mountains (Fig. 7b). Although Hughes and Luetgert (1991) were able to identify high-apparent-velocity reflections in the vicinity of the Grenvillian ramp, these reflections were insufficiently continuous and poorly separated in time from the first arrivals to facilitate incorporation into 2-D ray trace modeling. Vertical incidence seismic profiling across the Green Mountains, have a much better chance of observing reflections because reflected energy path lengths are shorter, other interfering arrivals are fewer and the geometry is more favorable for observation of back scattered energy.

Conclusions

The mid-Proterozoic parautochthonous rocks that form the core of the Green Mountain Anticlinorium were obducted from the edge of the Grenvillian continental shelf during the later stages of the Taconian orogeny (Stanley and Ratcliffe, 1985). Although comparable rock types (quartzites, felsic gneisses and garnet-rich, biotite-plagioclase-quartz gneisses) are exposed in the eastern Adirondack Highlands and the Green Mountain Anticlinorium their physical properties are sufficiently different to inhibit their correlation with seismic refraction measurements. Retrograde alteration (hydration) and pervasive mylonitic deformation of the paragneisses that core the Green Mountain Anticlinorium play an important role in affecting the resolution of velocity anomalies associated with the Grenvillian parautochthonous basement. Specifically, the velocity properties of the Green Mountain paragneisses renders them insufficiently different form the mantling schists and phyllites to permit the imbricated Grenvillian basement structures to be distinguished by seismic refraction techniques alone. Seismic reflection studies on the other hand permit the resolution of steeply dipping reflections beneath the Green Mountain Anticlinorium, but are unable to assign velocities and thus lithologic inferences are hindered.

The application of high-pressure laboratory measurements to the interpretation of regional seismic refraction data suggests that caution should be exercised in assigning seismic velocities in regions of high structural dip where the anisotropic properties of the deformed and mylonitized rocks are likely to be of paramount importance (Fountain and Christensen, 1989; Brocher and Christensen, 1990). Inferences of structural relationships from seismic refraction studies must be viewed with respect to the metamorphic, structural and anisotropic properties of the lithologies traversed by the seismic profile.

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