Some results of COCORP seismic reflection profiling in the Grenville-age Adirondack Mountains, New York State[1]

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COCORP deep seismic reflection profiling in the Adirondack Mountains of northern New York State has revealed a prominent zone of layered reflectors in the lower crust of the east-central Adirondacks. The strong, layered reflectors (here termed the Tahawus complex) occur between 18 and 26 km depth, beneath the sparsely reflective, granulite-grade, surface terrane, which has been uplifted from depths greater than 20 km. The Tahawus complex apparently represents layered rocks of some type in the lower crust of the Adirondacks. Possibilities include gneissic layering, cumulate igneous layering, a layered sill complex, and underthrust sedimentary strata. The Tahawus complex may be spatially coincident with a previously detected, high-conductivity zone in the lower crust, suggesting that either unusual mineralogies or interstitial electrolytes are present in the Tahawus complex. In contrast to layered reflections discovered in the lower crust of the east-central Adirondacks and southeast of the Adirondacks, cross-cutting and discontinuous reflections are recorded from the upper crust on all the COCORP Adirondack lines, including lines in both the Adirondack Highlands and Lowlands. Available three-dimensional control suggests that reflections in the upper crust of the central Adirondacks are parallel to, and hence may be related to, the folded gneisses mapped at the surface. Shallow events are also observed on a COCORP profile close to the epicenter of the 7 October 1983 magnitude 5.2 earthquake in the central Adirondacks, but their relation to the earthquake is uncertain.

Les profils de réflexion sismique de grande profondeur du programme COCORP dans les montagnes des Adirondacks du nord de l'état de New York ont fait ressortir une zone de réflecteurs stratifiés dans la croûte inférieure du centre-est des Adirondacks. Ces puissants réflecteurs stratifiés (appelés ici le complexe Tahawus) apparaissent à une profondeur de 18–26 km, sous le terrain de surface de faciès granulitique et de faible réflectivité, lequel fut soulevé d'une profondeur excédant 20 km. Le complexe Tahawus représente apparemment des roches stratifiées d'un certain type dans la croûte inférieure des Adirondacks. Le type de roche pourrait bien être un gneiss stratifié, un cumulat igné stratifié, un filon-couche complexe stratifié ou un sous-charriage de strates sédimentaires. Le complexe Tahawus peut occuper un lieu qui coïncide avec une zone de forte conductivité décelée antérieurement dans la croûte inférieure, suggérant qu'il existe dans le complexe Tahawus soit des minéralogies inhabituelles ou des électrolytes interstitiels. En contraste avec les réflexions stratifiées découvertes dans la croûte inférieure du centre-est des Adirondacks et du sud-est des Adirondacks, des réflexions entrecoupées et discontinues sont enregistrées dans la croûte supérieure sur toutes les lignes du programme COCORP dans les Adirondacks, incluant aussi bien les lignes des hautes-terres que celles des basses-terres des Adirondacks. Un contrôle tridimensionnel révèle que les réflexions dans la croûte supérieure du centre des Adirondacks sont parallèles à, et par conséquent peuvent être reliées à, des gneiss plissés cartographiés en surface. Des arrivées sismiques de faible profondeur sont également observées sur un profil COCORP près de l'épicentre du tremblement de terre du 7 octobre 1983, de magnitude 5,2 dans le centre des Adirondacks, mais leur relation avec le tremblement de terre est incertaine.

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Introduction

This paper presents some results of Consortium for Continental Reflection Profiling (COCORP) seismic surveys in the Adirondack Mountains of northern New York State, including the detection of a broad band of distinctive, high-amplitude reflections in the lower crust. These Adirondack profiles, recorded by COCORP in 1980 and 1981, are the first extensive seismic reflection surveys of the lower crust in the Precambrian Grenville Province. Initial results of these COCORP surveys appeared in Brown *et al.* (1983) and Klemperer *et al.* (1983). This paper presents the results of two additional seismic reflection profiles, including some three-dimensional control on the orientation of reflective structures in the Adirondacks, and also extends interpretations made in the earlier papers.

The Adirondack Mountains are a multiply deformed, upper-amphibolite- to granulite-facies terrane, located in northern New York State at the southern margin of the exposed late Proterozoic Grenville Province (Wynne-Edwards 1972; Wiener *et al.* 1984). The Adirondacks today form a structural and topographic dome that is onlapped on all sides by Paleozoic sediments and must be post-Devonian in age (Isachsen 1975). Neotectonic activity includes recurrent seismicity (Sbar and Sykes 1977), including a magnitude 5.2 earthquake in 1983 and perhaps also recent uplift (Isachsen 1975; Brown and Reilinger 1980).

The COCORP profiles discussed in this paper are New York lines 1, 7, 8, 10, and 11 (Figs. 1, 2). Lines 7 and 11 reveal the most prominent feature of the entire survey, a thick sequence of deep crustal reflectors called in this paper the Tahawus complex, after a nearby community (Figs. 4–6). Lines 7 and 11 lie in the predominantly meta-igneous, granulite-grade Adirondack Highlands and cross the southern part of the Marcy anorthosite massif, the largest intrusive body in the Adirondacks. Lines 8 and 10 both cross the Carthage–Colton line, a northeast-trending mylonite zone that separates the highlands from the predominantly metasedimentary, amphibolite-grade Adirondack Lowlands. Line 1 extends from the southeastern edge of the Proterozoic Adirondack dome across lower Paleozoic rocks of the Appalachian orogen. Previous reflection studies in the Adirondacks (Barton 1977; Friedman 1978), much smaller in scale, found possible reflections with two-way travel times (TWTT) as great as 5 s but demonstrated

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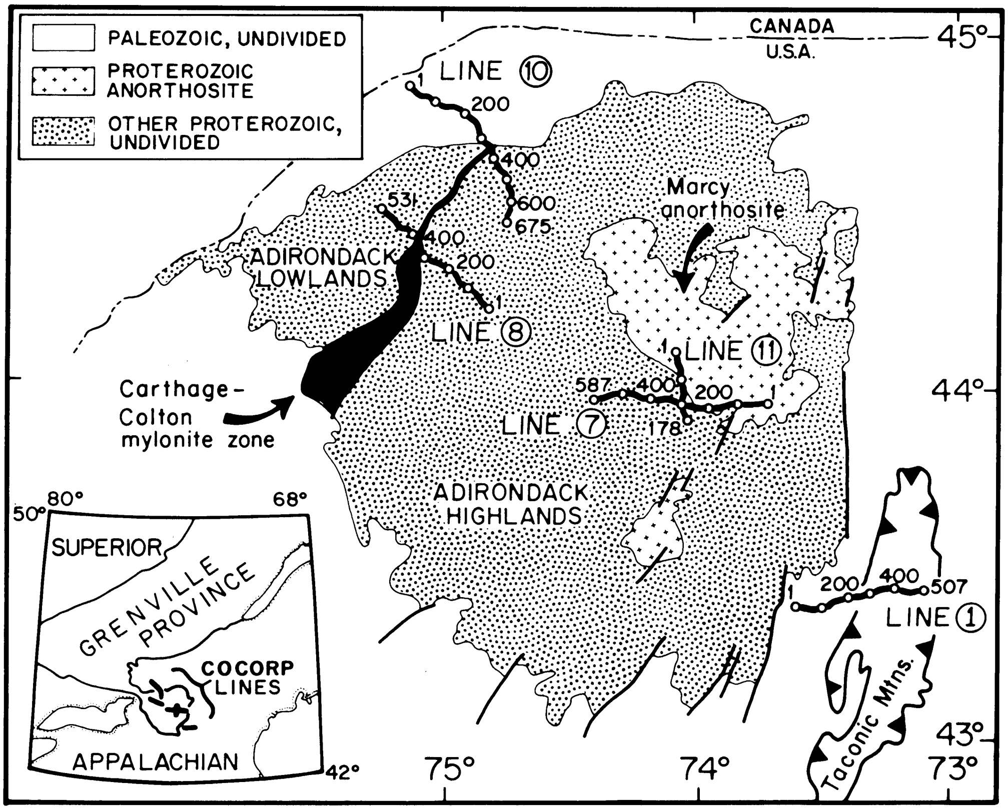

FIG. 1. Location map for COCORP New York lines 1, 7, 8, 10, and 11. Vibration point (VP) numbers are shown on each COCORP line.

lateral continuity no greater than 1 km. In contrast, the COCORP surveys reported here detect reflections from all levels in the crust, some of which may be correlated over tens of kilometres.

Data processing

The COCORP New York surveys employed recording and processing procedures (listed in Table 1) similar to those described by Schilt *et al.* (1979). For all five lines, 20 s of common-midpoint (CMP) data were collected using five vibrators and a 96-channel recording spread approximately 10 km long. Stacking fold was variable, ranging from 12 fold (line 8) to 48 fold (lines 10 and 11).

After demultiplexing and correlating the Vibroseis (TM Conoco, Inc.) data, the shot-point gathers were visually inspected and noisy traces removed ("edited"). Editing was an important stage in processing, since data quality varied considerably because of intermittent environmental noise and changing surface conditions. Because of the variability in data quality, the apparent absence of reflections on some parts of the COCORP traverse may be attributed either to locally poor data quality or to the absence of reflective structures in the crust. Figure 3*a* shows a shot-point gather (vibration point (VP) 23) recorded in quiet conditions at the east end of line 7, where the vibrators were located on anorthosite with only thin surficial cover. Figure 3*b* shows a gather (VP 310) recorded 30 km to the west of VP 23 in an area of moraine and fluvial deposits and with the recording spread in an area of substantial traffic noise (see Fig. 4 for location of source and receivers). Strong reflections extending laterally up to 5 km across the recording spread are visible on the better data set (Fig. 3*a*). The second gather (Fig. 3*b*) is noisier and has a weaker signal (compare the amplitudes of the refracted arrivals on the two shot-point gathers). Variable coupling of the source with the different near-surface lithologies may have caused some of the variations in signal strength. It is uncertain whether reflections are absent on the second gather or merely obscured by the traffic noise superimposed on a weaker signal. After editing, the seismic traces were equalized in amplitude to further mitigate the adverse effects of variable data quality. Amplitude equalization reduces the weighting of a noise-dominated seismic trace in inverse proportion to the amplitude of its noise.

Elevation corrections ("statics") were next applied to the data, and the traces were sorted into common-depth-point gathers. Refraction statics (time corrections to allow for differences in the near-surface weathering layer, calculated from the refracted waves from each vibration point) were also applied to line 7, but no significant differences were observed between the final stack sections prepared with and without this technique.

Information about surface velocities was obtained from refracted arrivals recorded on the shot-point gathers (e.g., Fig. 3) as part of the COCORP survey. These refraction data indicate surface velocities in the Adirondacks ranging from 5.5 km/s for metasediments and granitic gneisses to 6.4 km/s in gabbroic gneiss and anorthosite. Subsurface velocity analysis was carried out using velocity coherence spectra and constant-velocity stack sections prepared with stacking velocities ranging from 5.5 km/s to infinity. Although crustal velocities are unlikely to exceed 8 km/s even locally, processing with higher velocities is necessary to search for steeply dipping structures, since imaging steep dips requires abnormally high velocities (e.g., Waters 1981). Steep reflections were not detected on stacked sections processed to enhance reflections with dips from 30 to 90°, but some shot-point gathers (discussed below, Fig. 9) contain arrivals that may be reflections from steeply dipping structures. However, these putative reflections are not

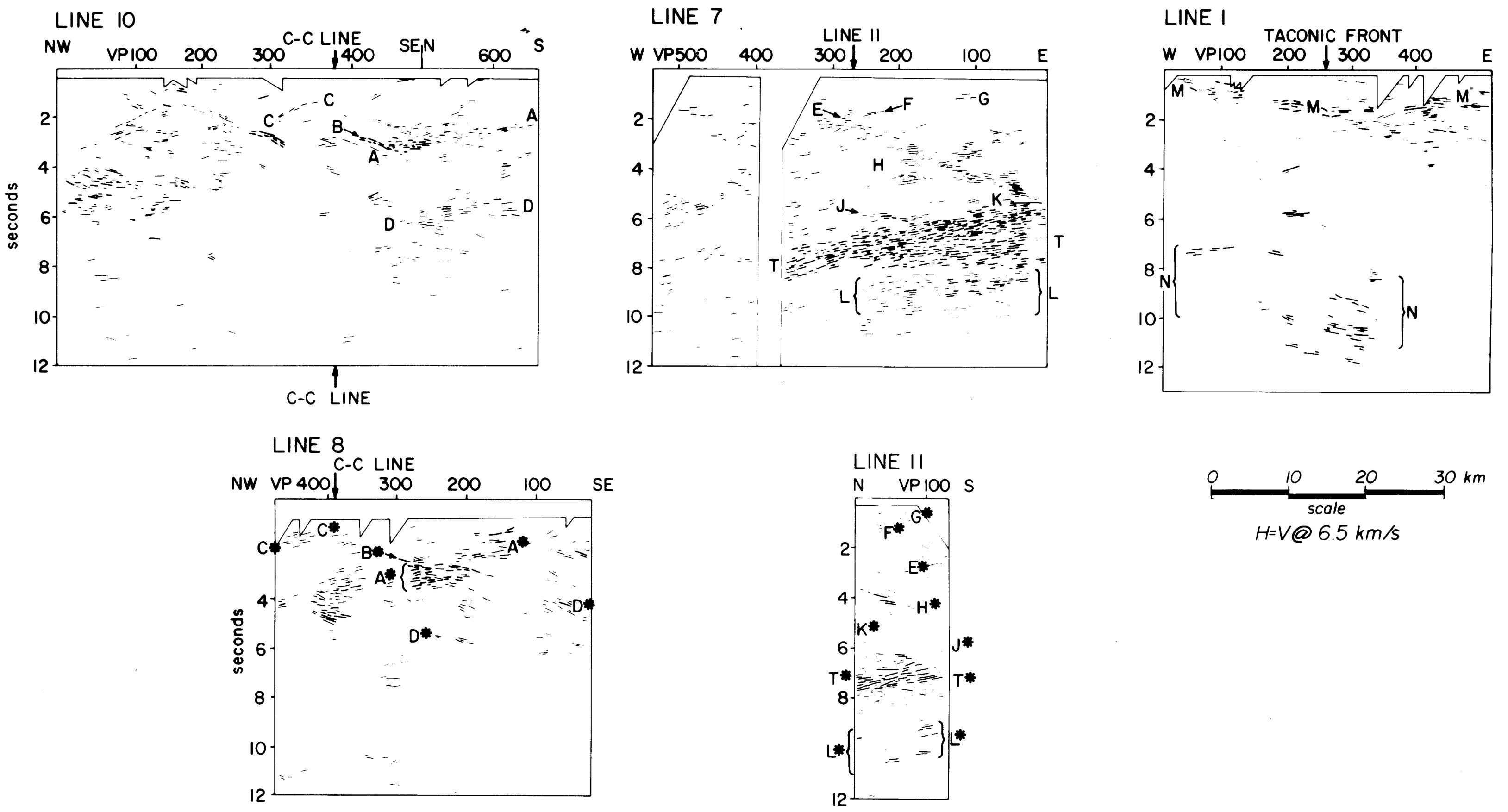

FIG. 2. Line drawings of the seismic sections for COCORP New York lines 1, 7, 8, 10, and 11. Numbers along top of sections are VP numbers, which key to those in Figs. 1 and 4. Vertical scale is seconds of two-way travel time (TWTT). For approximate depth, multiply TWTT by 3.25 km/s (half the average crustal velocity). Lettered reflections are discussed in the text. Possible correlations between lines 7 and 11 and between lines 8 and 10 are indicated by using the same letter followed by an asterisk. C–C line = Carthage–Colton line.

TABLE 1. COCORP northeast traverse: data acquisition parameters

CONTRACTOR	Crew 6834 of Petty-Ray Geophysical, a division of Geosource, Inc.
SOURCE	Vibroseis (TM Conoco, Inc.), nominal 5 vibrators
	Upsweep 8−40 Hz (lines 10 and 11, 8−32 Hz)
	Sweep length 22 s (lines 10 and 11, 32 s)
	Source spacing 201 m (line 8, 402 m; lines 10 and 11, 101 m)
	Source array length 175 m (5 vibrators) or 160 m (4 vibrators)
	Sweeps per vibration point 16 (lines 10 and 11, 8 sweeps)
RECEIVER	96 channels; station spacing 101 m
	Geophone array length 94 m (24 elements)
	Nominal distance: near station 503 m (line 1, 302 m)
	far station 10 058 m (line 1, variable)
RECORDING	Recording system MDS-10 (Geosource, Inc.)
	Correlated record length 20 s
	Digitizing interval 4 ms (lines 10 and 11, 8 ms)
	Nominal fold: lines 1 and 7, 2400%
	line 8, 1200%
	lines 10 and 11, 4800%
DIRECTION	Line 1: W to E; VP's 35−91, vibrate through spread
	VP's 93−173, split spread, pull 88 stations,
	push 8 stations
	VP's 175−505, vibrate through spread, pull 96 stations
	Line 7: E to W; VP's 1−487, push
	Line 8: SW to NE; VP's 1−430, push
	Line 10: NW to SE; VP's 1−412, push
	VP's 444−673, pull
	Line 11: N to S; VP's 1−78, push
PROCESSING	Megaseis (TM Seiscom Delta) system operated by the Department of Geological Sciences, Cornell University. Demultiplex, correlate, amplitude balancing, edit, common-midpoint (CMP) gather, elevation statics, velocity analysis, normal-moveout (NMO) correction, mute, stack, filter, automatic gain control (AGC), display

laterally extensive across individual shot-point gathers, nor can they be confidently traced across many consecutive shot-point gathers. Stacking normally enhances reflection strength, but any reflections in this data set from steeply dipping structures may be too incoherent to survive the stacking process.

The stacked sections in Figs. 5 and 6 were created using stacking velocities between 5.5 and 6.4 km/s at the surface, increasing to about 7.3 km/s at 12 s TWTT. These velocities were chosen to give visually the most continuous and strongest reflections on the final stacks. Stack sections prepared with somewhat different velocities show the same reflections with slight degradation of quality, and it is difficult to obtain accurate velocity estimates for these crustal sections, particularly in the deeper parts, since the normal-moveout corrections from which velocities are estimated are small because of the high velocities and great depth of the target reflectors (e.g., Waters 1981). Velocity coherence spectra also give velocity estimates that become less precise with increasing depth and for higher velocities. The presence of noise (Fig. 3) hinders trace to trace correlation of reflections and also increases the uncertainty in velocity measurements. In any case, velocities obtained from these COCORP reflection data, or from any other seismic technique, cannot directly constrain the lithology of reflecting layers at depth in the Adirondacks, because of the uncertainty in estimating the velocities and because different rock types show overlapping ranges of velocities. Rocks with velocities between 6.5 and 7.5 km/s in the pressure range 5 to 10 kbar (500−1000 MPa), for example, include such diverse lithologies as mafic to intermediate igneous rocks, amphibolites, marbles, and many gneisses, schists, and serpentinites (Christenson 1982).

After velocity analysis was completed, final stacks were prepared; these are summarized by the line drawings in Fig. 2. These line drawings emphasize the main features of the survey, with heavier lines representing stronger and more coherent reflections. The reflections are lettered to emphasize possible three-dimensional correlations between lines 7 and 11 and between lines 8 and 10. Thus the lettering scheme of Fig. 2 does not coincide with that of Brown *et al.* (1983, their Fig. 2) who lacked the now-available three-dimensional seismic control that is discussed in this paper. Because of the three-dimensional complexity of the highly deformed Adirondacks, the stacks include seismic energy reflected back to the recording array from many directions. Cross-lines determine the direction from which energy is arriving and are therefore important in locating reflector positions. Line 11, a cross-line to line 7, constrains the three-dimensional geometry of the Tahawus complex, the important deep crustal structure also seen on line 7 (Fig. 8). Cross-lines are not yet available for lines 1, 8, and 10, but these lines were recorded perpendicular to the strike of surface structure to minimize possible sideswipe. The possible correlation of events between lines 8 and 10 also offers three-dimensional control. Even when reflections come from within the plane of the section they are systematically mislocated in the stacking process, but this can be corrected by migration (e.g., Waters 1981). Hand migrations for all the lines were used to estimate the true dips of reflections; for a computer migration of the deep reflections on line 7, see Klemperer *et al.* (1983).

COCORP data: description and interpretation

Central Adirondacks

The most striking feature seen on lines 7 and 11 is the

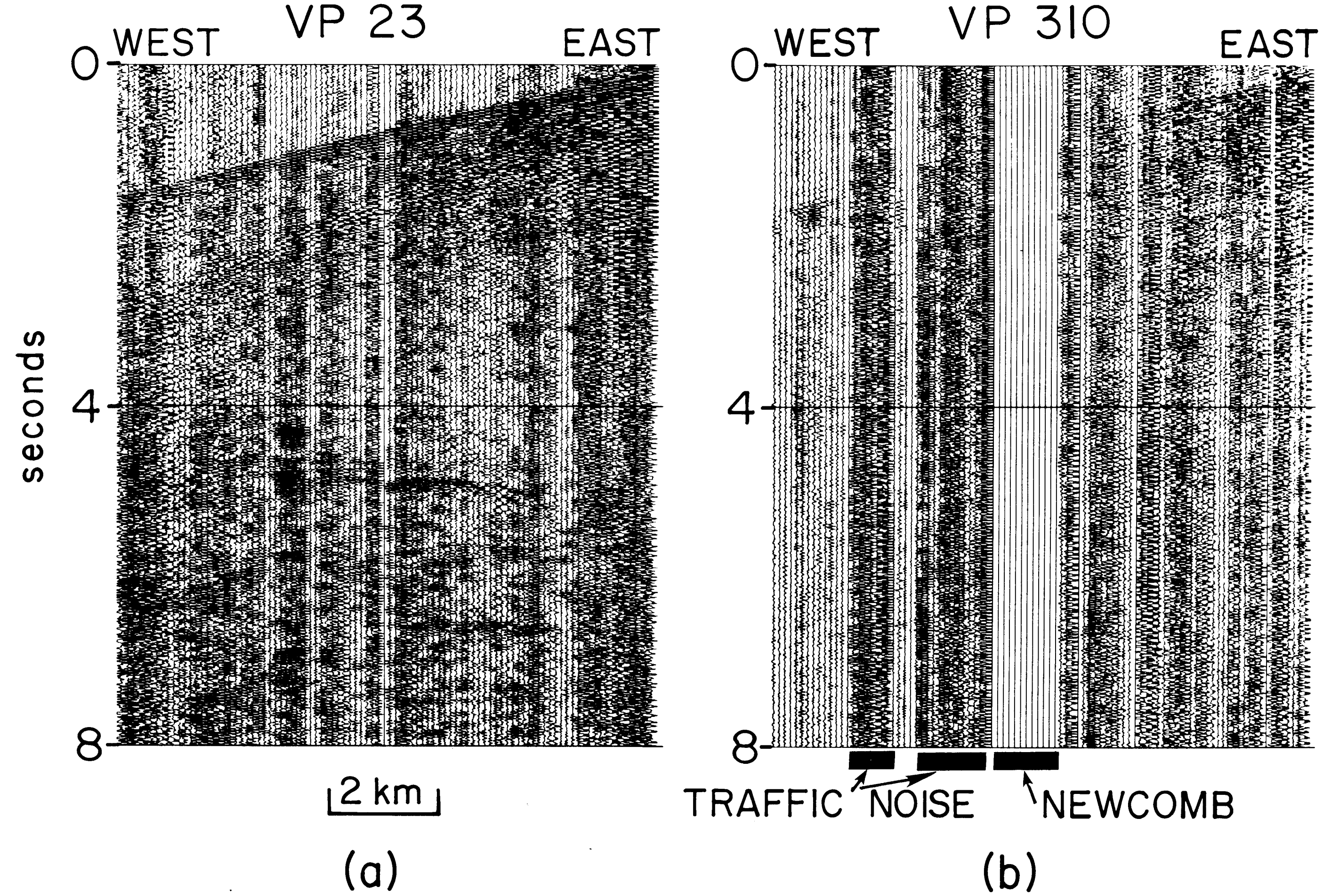

FIG. 3. Correlated shot-point gathers (96 traces, 8 s of total 20 s recorded), illustrating variable data quality along line 7. (*a*) VP 23, at the east end of line 7, shows a strong refracted arrival and many reflections from the Tahawus complex from 5 to 8 s TWTT. (*b*) VP 310, close to Newcomb on the western part on line 7, shows a weaker refracted arrival, some traffic noise, and no discernible reflections. (*a*) and (*b*) are displayed relative to the same constant amplitude, with automatic gain control applied.

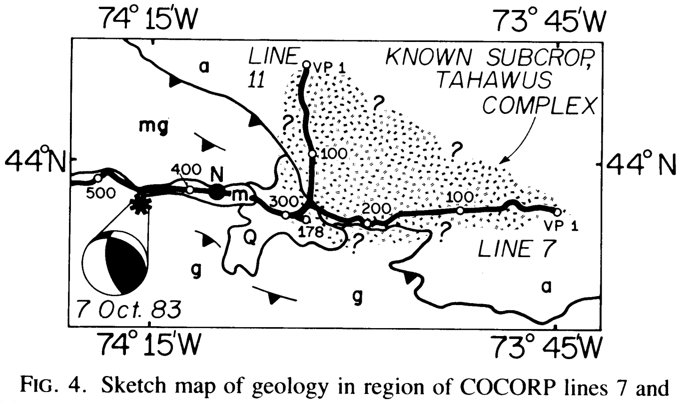

FIG. 4. Sketch map of geology in region of COCORP lines 7 and 11. Hachured region represents presently estimated subcrop of the Tahawus complex (a minimum estimate). Earthquake focal mechanism and epicenter from L. Seeber (personal communication, 1983). Geology simplified from Isachsen and Fisher (1970). Abbreviations: a = anorthosite, including some gabbro; g = granitic gneiss; mg = mixed metasediments and granitic gneiss; m = marble; Q = extensive Quaternary deposits; N = town of Newcomb; triangles indicate dip of contacts and foliation.

Tahawus complex, a thick zone of distinctive, high-amplitude reflectors (Figs. 4–6, event package T in Fig. 2), which contrasts with the sparsely reflective upper crust in this region. At the east end of line 7, reflections from the Tahawus complex lie between 5.3 and 8 s TWTT, corresponding to about 18–26 km depth. Within this band, reflections dip and converge to the northwest, ranging from a 10–15° dip at the top to subhorizontal at the base (all dips are two-dimensionally migrated). These reflections form a wedge thinning to the northwest. The northwest-dipping reflections in the lower crust contrast with the COCORP data for the upper crust beneath line 7 that show as many east-dipping as west-dipping events. Underlying the Tahawus complex is a transition zone between 8 and 8.3 s TWTT with fewer reflections. Beneath 8.3 s TWTT more numerous, predominantly west-dipping or flat reflections appear again (L on line 7), which are similar to the reflections from the Tahawus complex. It is possible that T and L represent similar or related structures.

On shot-point gathers (Fig. 3) and on stack sections (Fig. 5) individual reflections within the Tahawus complex can be followed for no more than about 5 km. The resolution of the COCORP seismic data within the Tahawus complex is about 750 m horizontally (Fresnel zone radius) and about 75 m vertically (one quarter wavelength) (Neidell and Poggiagliolmi 1977). Thus, seismic events extending more than about 750 m laterally should represent reflectors, whereas shorter events may be diffractions from point objects. Also, reflecting boundaries separated by less than about 75 m vertically are not separately imaged in this experiment. The convergence and

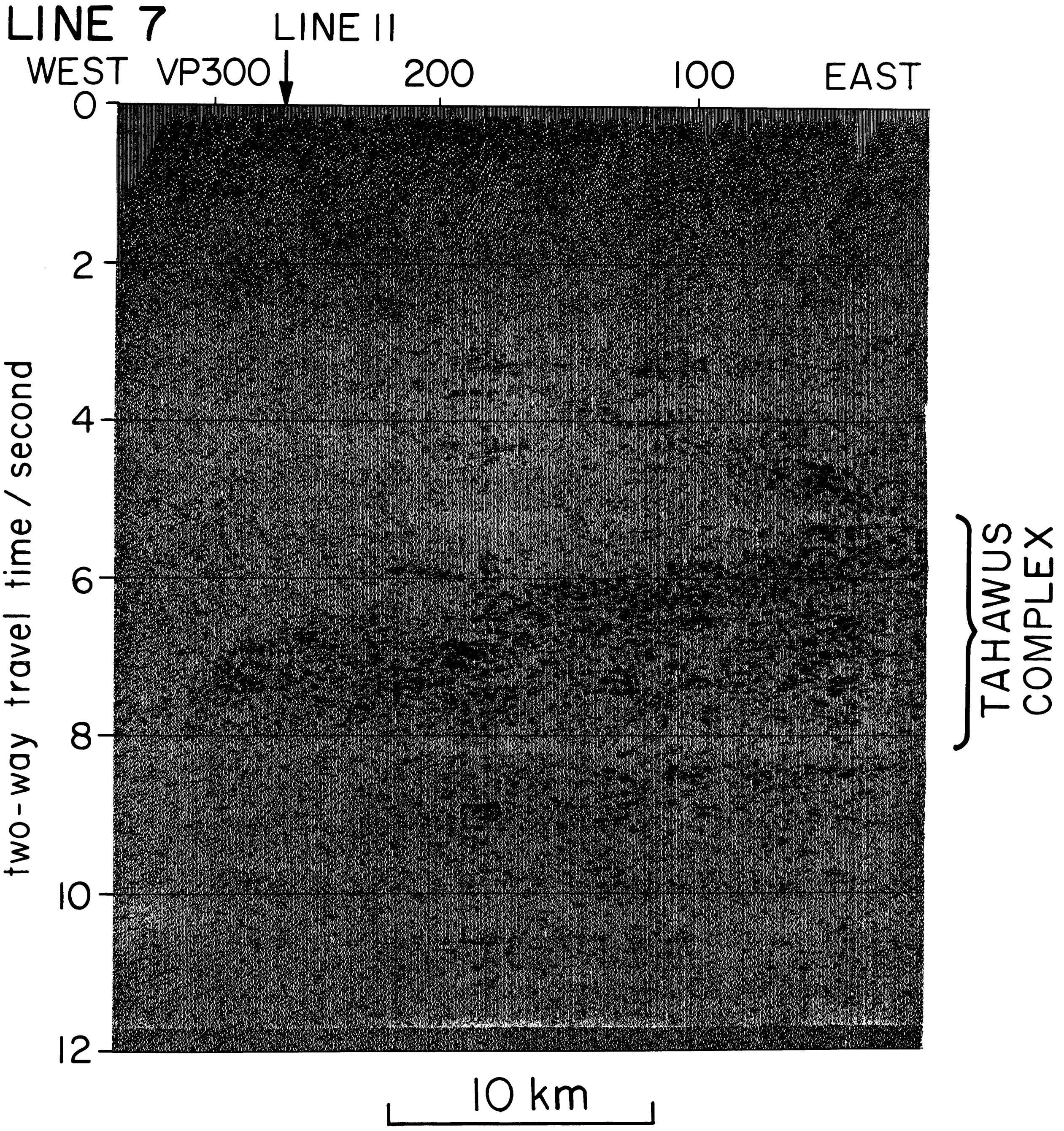

FIG. 5. Line 7: unmigrated stacked section, VP's 1−380, top 12 s only. No vertical exaggeration assuming an average velocity of 6.5 km/s. Note very prominent reflections between 5 and 8 s (the Tahawus complex). For data processing sequence, see Table 1.

truncation of reflecting segments in Fig. 5 imply layer thickness reductions to less than about 75 m or equivalent layer travel-time changes caused by velocity increases. The absence of long (>5 km) reflections suggests that the reflective layering is complex on a scale of 5 km or less, rather than being continuous and uniform.

To the east, the reflections continue to the end of line 7. To the west, the Tahawus complex appears to die out into a diffuse zone in which the reflections are neither as prominent nor as numerous as farther to the east (Fig. 2). The disappearance of the Tahawus complex towards the west may be real or may be due to the effects of changing near-surface geology and (or) changing recording conditions. Traffic noise is considerably worse for VP's 295−587 along New York State Route 28N through Newcomb (Fig. 3*b*) than for VP's 1−295 along Essex County Road 2B (Fig. 3*a*). Moraines in Newcomb Valley west of about VP 270 may be up to about 30 m thick, whereas east of VP 270 the surficial cover is neither so thick nor so extensive (Balk 1932). Additional processing of line 7, including application of refraction statics and automatic residual statics, did not succeed in imaging a continuation of the Tahawus complex west of Newcomb. For these reasons, and also because of the short extent of line 11, the full lateral extent of the Tahawus complex cannot be determined from this data set.

Line 11 (Fig. 6), north of and perpendicular to line 7, shows reflections that appear to correlate well with those on line 7 (Fig. 8*a*). The two lines do not quite cross in the subsurface, and so reflections cannot be correlated wiggle for wiggle. How-

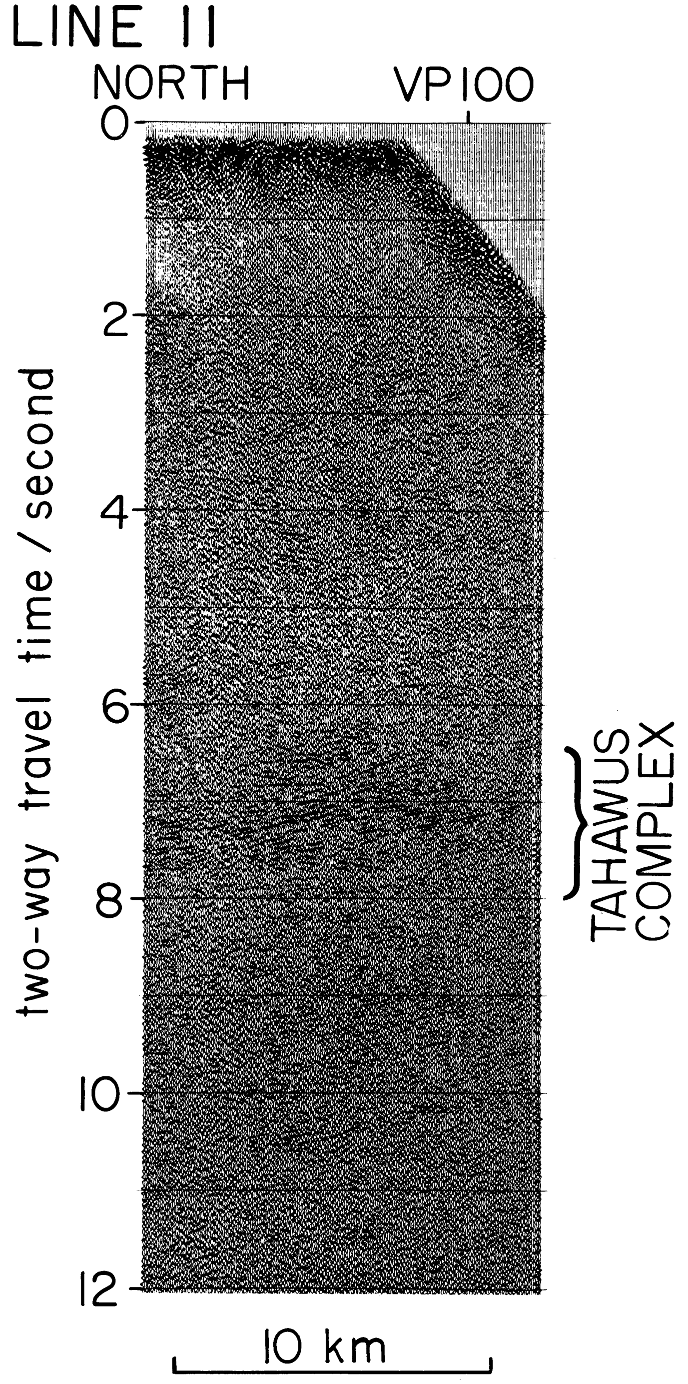

FIG. 6. Line 11: unmigrated stacked section of the whole line, top 12 s of data only. For data processing sequence, see Table 1.

ever, lines 7 and 11 come within 2 km of one another, and correlations may be made based on similarity of reflection character and travel time. Reflections or groups of reflections on line 11 that are correlated with events on line 7 are denoted by asterisks in Fig. 2. Zone T* on line 11 correlates with the Tahawus complex and, as on line 7, shows unusually high-amplitude reflections by comparison with reflections from the upper crust (Fig. 7). In a later section we discuss various hypotheses to explain the Tahawus complex, including the possibilities of a buried metasedimentary wedge or a layered plutonic complex.

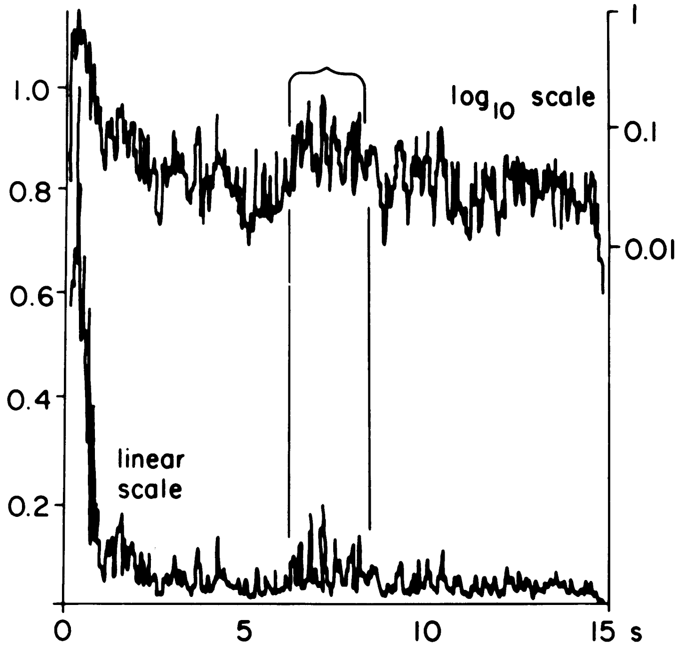

FIG. 7. Amplitude decay curve for VP's 46–52 on line 11, showing high amplitudes at 6–8 s from the Tahawus complex reflections. The Tahawus complex produces stronger reflections than any structures in the crust above it.

Shallow reflections on lines 7 and 11 are not as coherent as the Tahawus complex reflections, but the surface geology allows a better constrained interpretation of the upper crustal reflections. Line 11 and the eastern part of line 7 (to about VP 250, Fig. 4) cross the Marcy anorthosite, which is inferred from gravity measurements to be about 3–4 km thick over most of its area (Simmons 1964). Near-horizontal reflection segments G and G* at 0.5–1.0 s TWTT (about 1.6–3.2 km) may represent compositional layering within the Marcy anorthosite or possibly its base. Fold axes and foliation immediately south of line 11 have trends from 110 to 130° (Isachsen and Fisher 1970). The suggested correlations of F* on line 11 with F on line 7 and of E* with E (Figs. 2, 8) imply reflectors striking roughly west-northwest–east-southeast, parallel to mapped fold axes and foliations (Fig. 4). Hence we interpret E–E* and F–F* as reflections from lithologic contrasts within folded gneisses extending beneath the Marcy anorthosite. Correlations H–H*, K–K*, and J–J*, chosen on the basis of similarity of reflection character and travel time on lines 7 and 11, also imply reflectors striking roughly west-northwest–east-southeast, suggesting that nappes related to those mapped at the surface may extend vertically from the surface to 6 s TWTT (about 18 km).

In contrast to the west-northwest–east-southeast structural trend of reflectors E, F, H, K, and J, the Tahawus complex reflectors strike northeast–southwest (Fig. 8*b*). This change in strike of reflectors at about 6 s TWTT (Fig. 8*b*) (caused, perhaps, by a structural break), in addition to the change in reflection character (Fig. 8*a*) (which possibly represents a change in rock fabric or lithology), further suggests that the Tahawus complex is different from the reflectors in the upper crust.

COCORP data and the 7 October 1983 earthquake

West of Newcomb (Fig. 4), COCORP line 7 serendipitously passes less than 3 km north of the epicenter of the 7 October 1983 magnitude 5.2 earthquake. Although there are fewer re-

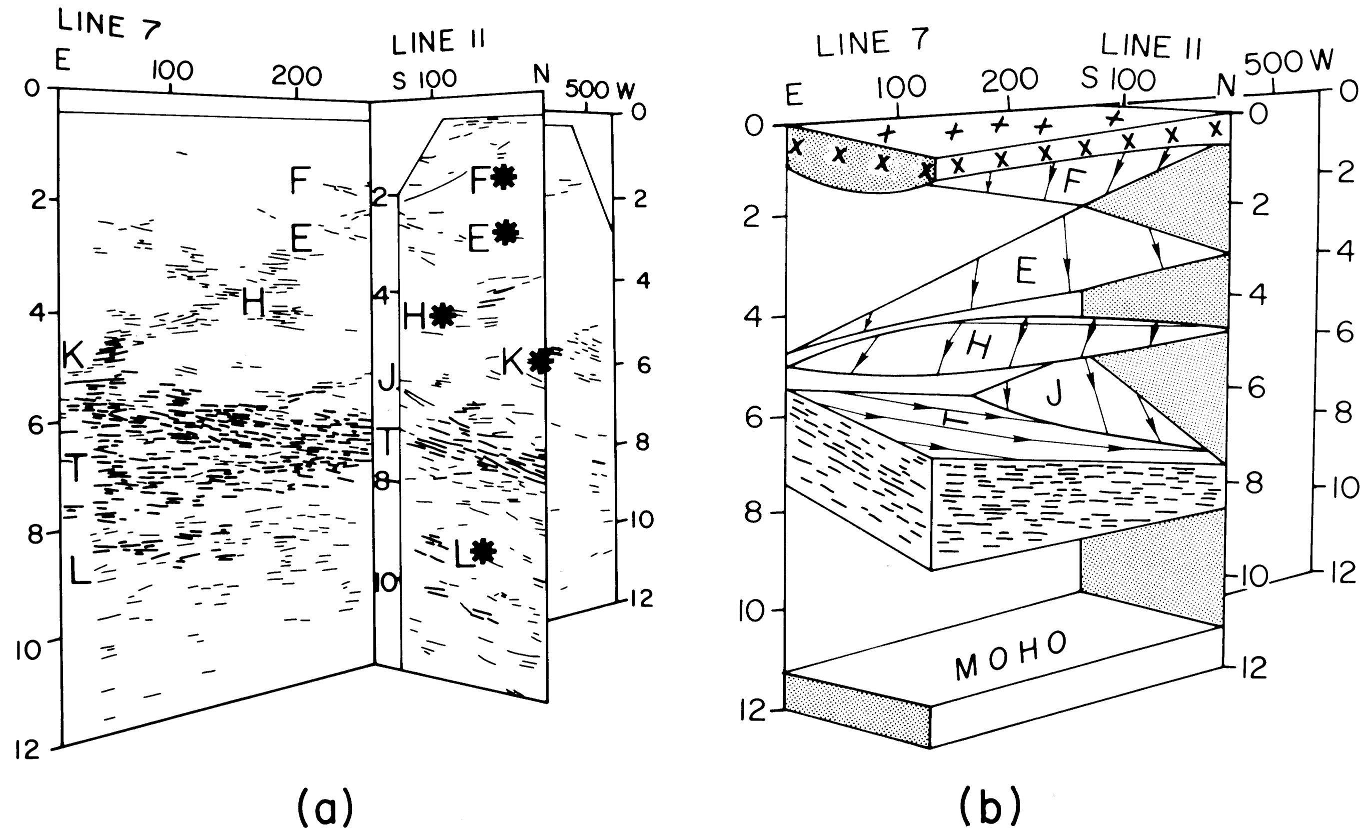

FIG. 8. (*a*) Lines 7 and 11: three-dimensional fence diagram of line drawings from Fig. 2 to show the correlations between the reflections on lines 7 and 11. Fence diagram is viewed from the northeast. Note particularly the northwest-dipping Tahawus complex. Vertical scale is two-way travel time in seconds. (*b*) Lines 7 and 11: three-dimensional cartoon of possible structures represented by reflections on lines 7 and 11 (see Fig. 2) based on Fig. 9*a*. Arrowheads show dip directions of reflectors. The Tahawus complex is represented as a solid wedge of reflectors. Moho depth from refraction studies. Surface geology in this area is anorthosite (cross pattern).

flections visible on the stack section in this area than to the east (Fig. 2), probably because of poorer data quality (Fig. 3), coherent energy is present on at least some shot-point gathers. Modelling by ray tracing suggests that one of these seismic events could correspond to a fault associated with the 7 October 1983 earthquake, though in the absence of three-dimensional data any interpretation must be speculative. This earthquake was a thrust, with aftershock hypocenters delineating a zone, striking 345 ± 10° and dipping 60 ± 10°W at a depth of 7–8.5 km, that is inferred to correspond to the main rupture zone (Seeber *et al.* 1984).

Two of the better shot-point gathers, VP 427 and VP 421, are shown in Fig. 9. Two relatively prominent events, X and Y, can be traced on these and adjacent shot-point gathers. Ray tracing has been used to identify possible sources for these two events. Event X is visible on shot-point gathers recorded from VP's 397–433. X may be modelled as either a diffractor (Xa, Fig. 10*a*) or as a reflector (Xb, Fig. 10*b*) to within 0.1 s using simple constant velocity models. Although ray paths and synthetics are shown only for VP 427, the models were checked against all the data. Both the modelled reflector and diffractor are at 5–6 km depth, shallower than the 7 October 1983 hypocenter, and thus cannot be directly related to the recent shock.

Event Y, subparallel to the refracted arrival, is visible on shot-point gathers recorded from VP's 419–439. Y is delayed by approximately 0.4 s from the refracted arrival on the shot-point gathers shown in Fig. 9. The 0.4 s delay time and the high amplitude of Y suggest that Y represents the arrival of a new phase rather than a continuing reverberation of the refracted wave. One possibility is that Y is a reflection from a steeply dipping structure, as modelled in Fig. 10*a*. Reflector Ya (Fig. 10*a*) dips 60° to the west from VP 405, passing through the 7 October 1983 hypocentral zone of Seeber *et al.* (1984) at about 8 km depth. If the 7 October 1983 fault plane extends from the hypocenter to within 2 km of the surface, then event Y could be a reflection from that fault plane. However, the limited data set and the lack of three-dimensional control allow the data to be fitted with reflections from planes dipping from about 50 to 70°W, so that, even if Y is a reflection, it may not be from the earthquake fault plane. Events similar to Y are not frequent on line 7, but are found near VP's 88, 105, and 193. These features could be related to the high-angle fracture zones that cross line 7 at VP's 70, 80, and 175 (Isachsen and Fisher 1970). However, events Y may not be reflections. One alternative possibility is that Y represents a multiple refraction, as schematically shown in Fig. 10*b*. Such refractions are fairly common on seismic profiles. Quaternary deposits beneath VP's 419–433 are probably no more than about 30 m thick (Balk 1932), too thin to produce the observed travel-time delay for event Y, but a multiple refraction might also be generated within a weathered basement layer. Another alternative cause for Y is a phase conversion from shear or surface waves to *P* waves. Unfortunately, the available two-dimensional data set does not distinguish between these possibilities.

Even if both X and Y are unrelated to the 7 October 1983 earthquake, it is of interest that coherent events are recog-

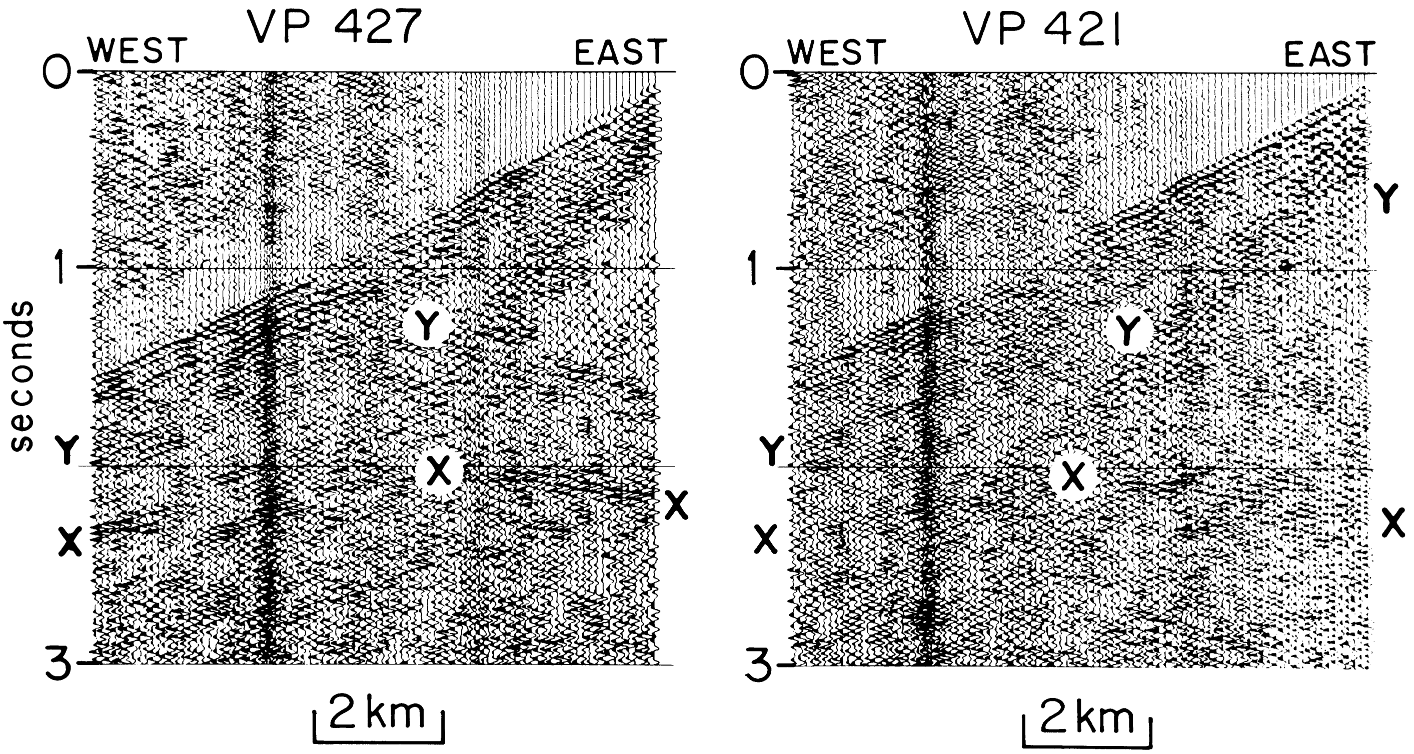

FIG. 9. Correlated shot-point gathers recorded at VP's 421 and 427. Events X and Y are discussed in the text. Traces are positioned proportional to their distance from the source. Automatic gain control applied.

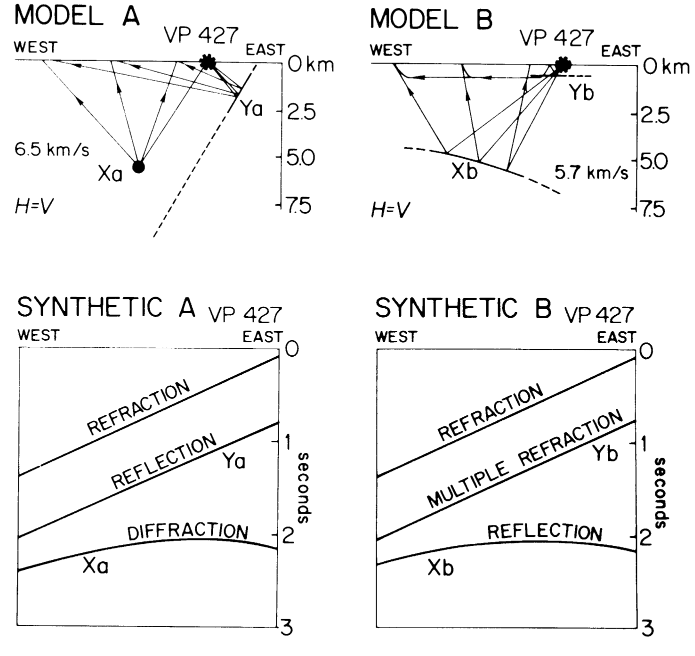

FIG. 10. Model structures and synthetic seismograms for events X and Y in Fig. 9.

nizable in the shallow section. The COCORP data were collected using field parameters suitable for a whole-crustal survey. The success, albeit limited, of this COCORP survey in detecting shallow structures suggests that a different seismic experiment aimed specifically at shallow, steeply dipping structures, such as the presumed earthquake fault plane, could be quite successful.

Grenville basement beneath the Taconics

New York line 1 crosses Paleozoic sediments overlying basement that is regarded as continuous with that exposed in the Adirondacks, a presumption based on the proximity of the Adirondacks to the west. The top of the Precambrian is not evident on New York line 1, but should be below reflections M (Fig. 2), which are interpreted to represent the lower Paleozoic shelf and miogeoclinal sedimentary sequence lying structurally beneath the Taconic klippen (Ando *et al.* 1984).

On line 1 the crust can be divided into upper and lower regions, based on seismic character (Fig. 2). Above 6 s TWTT (18 km) the grain of the section within the basement is mainly west dipping, though some opposing dips also appear, and scattered single-cycle reflections predominate over many-cycled events and closely spaced packages of events. Beneath 6 s TWTT, reflections N (Figs. 2, 11) appear to be significantly more numerous, more laterally coherent, more tightly grouped, and of higher amplitude than intrabasement events above 6 s TWTT. Events N have easterly apparent dips of 10–20°, in contrast to the general west dips seen above 6 s TWTT. It is noteworthy that on line 1, as on line 7, the lower crust apparently has more coherent reflectors than the upper crust. Based on the change on line 1 in seismic character and in reflection dip from the upper to the lower crust, it is possible that the lithology or structural style and the prevalent structural vergence undergo a change at about 18 km depth on line 1, just as on line 7. Since line 1 is offset more than 50 km south of line 7 (Fig. 1), it is speculative to suggest that reflections N (Fig. 11) might be a continuation of the Tahawus reflections T (Fig. 5). The deep reflections on line 1 may well represent structures formed during the Grenville Orogeny when, on the evidence of exposures in the Adirondacks to the east, the crust below line 1 suffered major folding. The deep reflections could alternatively correspond to pre-Grenville structures or even to Taconic structures developed within the Precambrian basement, though

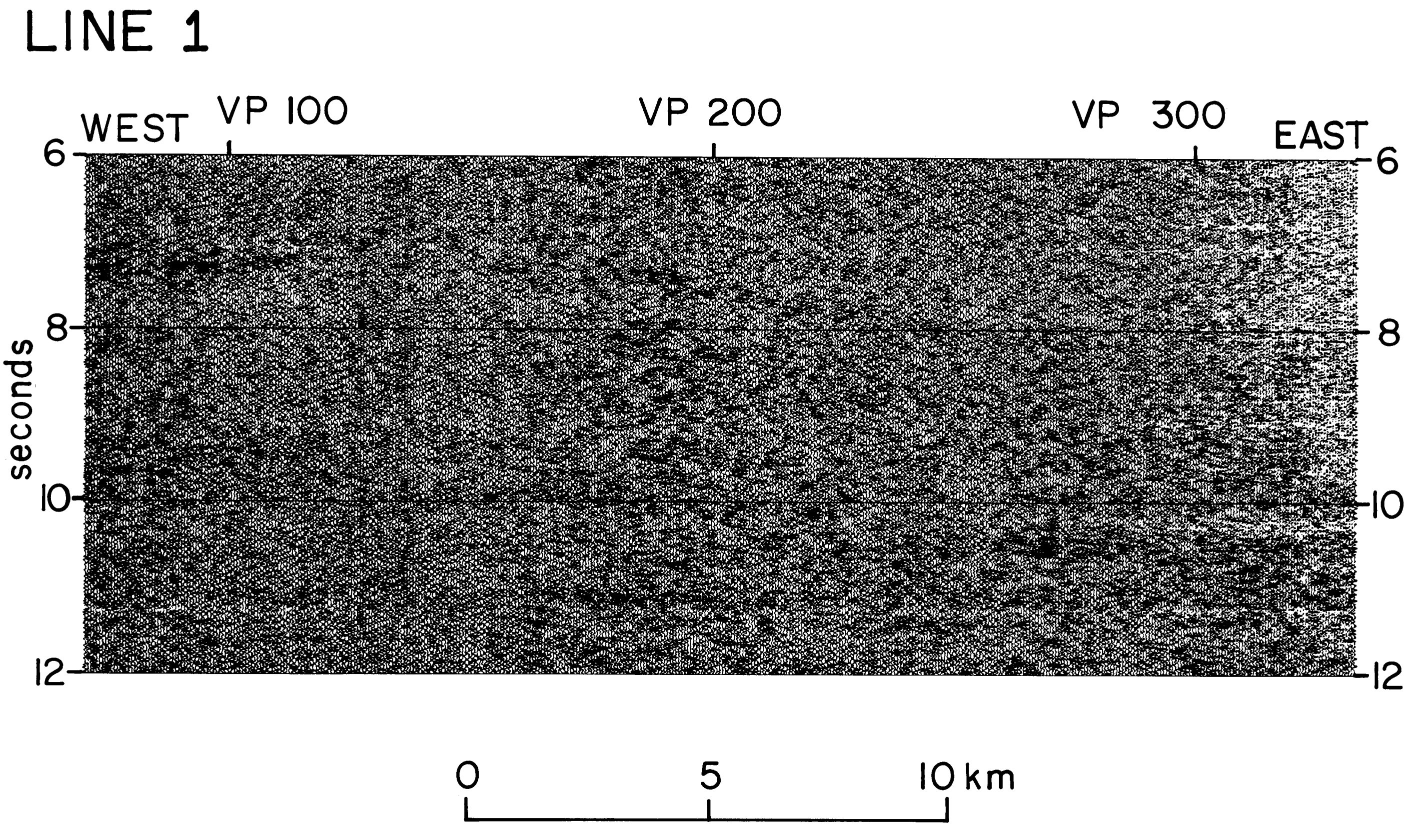

FIG. 11. Line 1: VP's 70 to 335, 6 to 12 s TWTT, of the unmigrated stack section. No vertical exaggeration at 6.5 km/s. Note the prominent deep-crustal layering. For data processing sequence, see Table 1.

the Taconic Orogen in New York State is generally regarded as being thin skinned in nature (e.g., Robinson and Hall 1980), and the deep reflections on line 1 lie west of the western margin of the Taconic allochthons mapped at the surface (Fig. 2).

Below 12 s on line 1 events are less numerous; many-cycled packages are not present, and all dips are near horizontal. These reflections, which continue to at least 13 s TWTT, are the deepest events seen on the New York lines. Refraction results (Katz 1955) and earthquake travel-time residual studies (Taylor and Toksoz 1979) yield velocity–depth structures that indicate that Mohorovičić (Moho) reflections should arrive at 10.5–12 s TWTT. Thus, if they are not multiples or sideswipes, the deepest reflections on line 1 could be intramantle events. There is no sharp lower bound to the crustal reflections on any of the COCORP Adirondack seismic lines, but in general all reflections die out near the expected Moho depth, as is the tendency in many seismic reflection studies of the continental crust.

Northwest Adirondacks

Lines 8 and 10 trend northwest–southeast and run from the Adirondack Lowlands, across the Carthage–Colton mylonite zone, and into the Adirondack Highlands. The top 4 s TWTT on each line contains a number of reflections that represent major structures in the upper crust, but there are few reflections from the lower crust. It is uncertain whether substantial reflectors are absent from the lower crust in the northwest Adirondacks or whether reflectors are not imaged because of a lack of penetration of the seismic signal. It should be kept in mind that there is considerable lateral variation in apparent data quality; note, for example, the vertical strips on line 8 beneath VP's 100 and 320, which are devoid of reflections. Whether such zones are due to local degradation of signal quality, as is perhaps implied by the vertical character of these reflection-free zones, or whether such zones are truly indicative of crust that lacks structures of a resolvable scale is a continuing issue in crustal seismology.

Lines 8 and 10 are about 30 km apart and run roughly perpendicular to geologic strike. Because of the separation of the lines, geologic variation along strike, and variable data quality, correlations between the reflections on lines 8 and 10 are far more tentative than the correlations linking lines 7 and 11. A possible correlation suggested in Fig. 2 is based on the geometry of the reflections and on surface geology. In Fig. 2, reflection events are lettered to correspond to this suggested correlation, and line 10 is aligned above line 8 along the Carthage–Colton line, so that points vertically above one another are along geologic strike. The most prominent events on both lines, A on line 10 and A* on line 8, lie at 2–4 s TWTT just east of the surface outcrop of the Carthage–Colton line. Southeast-dipping events B (B*), above A (A*), and scattered events D (D*), underlying A (A*), are present in similar positions on both lines. Events C and C* both dip northwest away from the Carthage–Colton line. The above correlation would imply that the northeast-trending Precambrian structures exposed in the northwest Adirondacks extend to at least 6 s TWTT (about 18 km depth) in the area beneath lines 8 and 10. Correlations across a distance of 30 km appear reasonable, since, if A is a continuous structure, it extends over 20 km along lines 8 and 10 and so might also be continuous 30 km between lines 8 and 10. However, in view of the structural complexity of the region, it is also possible that no detailed correlation is appropriate.

Although lines 8 and 10 show numerous reflections, the relation of these reflections to the surface geology is unclear. On either side of the Carthage–Colton zone northeast-trending folds are mapped, on all scales up to 50 km wavelength (Isachsen and Fisher 1970). These structures should produce both northwest- and southeast-dipping reflections. Such reflections need not correlate with mapped faults and fold axes, but might be expected to represent layering within the fold and thrust nappes. Both COCORP lines show complex reflection patterns with apparent dips to the northwest and southeast, which might represent parts of these folds.

Both lines 8 and 10 cross the Carthage–Colton line, at VP 390 and VP 380, respectively. Detailed mapping of the Carthage–Colton zone in the vicinity of lines 8 and 10 suggests that it is an eastward-directed fold-thrust nappe, dipping 25–45°NE (Geraghty *et al.* 1981). Such a structure would be represented by events with dips of 23–35° on the line drawings, which are taken from unmigrated seismic sections. Reflections C and C* could extrapolate to the surface outcrop of the Carthage–Colton line if they steepen towards the surface. Alternatively, C and C* may represent layering beneath the mylonite zone. The lack of prominent reflections associated with the Carthage–Colton zone is consistent with it not being a major crustal discontinuity (Wiener *et al.* 1984), though structures formed early in the Grenville Orogeny might be too strongly deformed by subsequent events to survive as prominent seismically reflective structures.

Interpretations of the Tahawus complex

Several interpretations of the Tahawus complex detected by COCORP lines 7 and 11 have already been given by Brown *et al.* (1983) and are discussed here in more detail. Possible interpretations include layered cumulates, basaltic intrusions, gneissosity, and metasedimentary layering. The lithologic layering might also be deformed, perhaps by recumbent isoclinal folding, stacked thrusts, or metamorphic foliation. The emplacement of the Tahawus complex (whether by igneous intrusion, underthrusting, or other means) may have been related to uplift and exposure of the granulite terrane. In the following sections we discuss these possibilities and their relation to the COCORP seismic data and to previous electromagnetic experiments in the Adirondacks.

Electromagnetic studies and the Tahawus complex

Correlation of COCORP data with controlled-source electromagnetic data (Connerney *et al.* 1980) suggests that the Tahawus complex is at least partially coincident with a high-conductivity zone detected beneath the central Adirondacks. As described by Connerney *et al.* (1980), this layer of high conductivity lies below 20.5–25 km and is 6–12 km thick. This layer has a conductivity of 0.04–0.08 S/m, two orders of magnitude higher than material immediately above and below it. Using velocities derived from the COCORP data, the highly conductive zone corresponds to reflections below 6.0–7.2 s TWTT, continues for at least 1.6 s TWTT, and possibly to 10.5–11.0 s TWTT. The electromagnetic data suggest that the top of the conductive layer is either horizontal or dips gently, no more than 15° in any direction (B. Thompson, personal communication, 1983). Thus, at least the lower part and possibly all of the Tahawus reflections (T on line 7), perhaps together with the underlying flat reflections (L on line 7), apparently lie within the source region for the conductivity anomaly. The magnitude of the conductivity anomaly is an important constraint for models of the lower crust in northern New York State and requires that the lower crust, including the Tahawus complex, contains either conductive minerals or electrolyte-filled cavities. However, if electrolytes or conductive minerals are pervasive in the lower crust of the Adirondacks, then the observed spatial correlation of the Tahawus complex with the conductivity anomaly could be fortuitous rather than genetic.

Igneous layering?

One mechanism for the uplift of granulite terranes to the surface from a depth of 20 km or more, as seen in the Adirondacks, is igneous underplating, or large-scale igneous intrusion into the crust from the mantle. If the Tahawus complex (and perhaps also the deep layering on line 1) represents igneous intrusions, it could have contributed 8 km of uplift in this area. If the reflections L have the same origin, a total of 16–18 km of uplift is possible.

Igneous layering could be cumulate layering or a complex of sills interfingering with country rock. A layered intrusion might be of any age or it could be genetically associated with the Marcy anorthosite, the largest intrusive body outcropping in the Adirondacks. Some models of anorthosite formation postulate large quantities of associated mafic or ultramafic differentiates (Isachsen 1968). The volume of the Tahawus sequence (4000 km^3 imaged thus far, a minimum estimate), considered as parent cumulates to the surface anorthosites, could be consistent with the volume of anorthosite in the Adirondacks (10 000 – 20 000 km^3 from surface exposure and gravity data). The presently available seismic data show some spatial correlation between the Marcy anorthosite and the Tahawus reflections, but the thickest part of the Tahawus complex is beneath the extreme southeast edge of the Marcy massif, and future profiling may show the reflectors to extend well beyond the surface anorthosite exposures.

The electromagnetic data of Connerney *et al.* (1980) would be satisfied if a cumulate body contained sufficient metal oxides or sulphides (Parkhomenko 1982). Whether a layered intrusion would produce the strong reflections of the Tahawus complex is unknown. The seismic response from a layered mafic intrusion has been modelled by Wong *et al.* (1982) as a series of subparallel reflections. However, to our knowledge there exist no published seismic profiles showing reflections from layered cumulates, while COCORP data from southern Oklahoma do not show reflections from layered gabbros exposed at the surface there (Brewer *et al.* 1983). Whether the Tahawus complex could represent a layered igneous intrusion is thus unresolved.

A sill complex might reasonably have been intruded into the lower crust of the Adirondacks, perhaps during Atlantic rifting in the mid-Mesozoic, since minor dikes of this age are exposed in the eastern Adirondacks (Isachsen and Fisher 1970), or at some other time. Basaltic intrusions would not have high conductivity unless serpentinized, but if fluids are present in the lower crust then the Tahawus complex could represent multiple sills.

Gneissic layering?

The Tahawus reflectors might be due to gneissic layering. Drilling and reflection results in Arizona have shown that highly metamorphosed and plastically deformed granites and Precambrian quartzo-feldspathic gneisses can produce prominent subhorizontal seismic layering of this type (Reif and

Robinson 1982). If gneissic layering is the cause of the Tahawus reflections, it is necessary to explain why the seismic layering of the Tahawus complex is restricted to the lower crust, since layered gneisses (themselves formed in the lower crust) are seen in surface outcrop in the Adirondacks but the upper crust is not highly reflective. Possibly the lower crust has deformed differently, perhaps by subhorizontal ductile flow, than the upper crust, which is multiply folded.

Metasedimentary and metavolcanic layering?

Another possible cause for the seismic layering is relict sedimentary stratification. In this case the individual reflections of the Tahawus complex would represent original lithologic variation modified by tectonism and metamorphism associated with emplacement during the Grenville Orogeny. Mechanisms must exist to bury sediments deep in the crust, since metasedimentary terranes, such as are seen at the surface in the Adirondacks, are known to have equilibrated at pressures of 7 kbar (700 MPa) or more. There is clear evidence from Phanerozoic orogens that sediments on continental margins can be buried to substantial depths by overthrusting of large crustal sheets (Cook *et al.* 1979). That sediments may still be seismically reflective even after deep burial and consequent metamorphism is suggested by other COCORP seismic surveys, which have detected reflections beneath Appalachian allochthons at depths of 5–25 km (Cook *et al.* 1979; Ando *et al.* 1984). A major overthrust in the Adirondacks would explain the uplift of granulite-facies rocks to the surface. Further, the rocks now seen at the surface would be allochthonous with respect to the present lower crust, thus offering an explanation for the suggested difference between the structural trends of the southwest-striking Tahawus complex and the overlying reflections, which strike west-northwest.

A metasedimentary–metavolcanic sequence could be sufficiently conductive to explain the Adirondack anomaly if it contained rocks such as graphitic schists (Camfield and Gough 1977), or sodium- and iron-rich amphiboles (Parkhomenko 1982) that are typical of high-pressure metamorphism (Miyashiro 1973), or detrital hematite and magnetite. Mafic volcanics, if serpentinized, can also be sufficiently conductive to explain the Adirondack anomaly (Stesky and Brace 1973). The high-conductivity anomaly beneath the Appalachians has been attributed to Paleozoic sediments thrust below the crystalline Appalachians (Greenhouse and Bailey 1981), whereas the Southern Cape Conductive Belt has been attributed to underthrust serpentinized basalts (De Beer *et al.* 1982). Thrusting in the Adirondacks might similarly permit hydrated mineralogies or free electrolytes to exist beneath the surface granulites.

At present it is not possible to distinguish whether the Tahawus complex represents metasediments thrust beneath the Adirondack Highlands or igneous intrusions into the lower crust. Either possibility could account for the seismic character of the Tahawus reflections and could help explain the uplift of the exposed granulite-grade terrane. Further profiling could help to distinguish between these possibilities, by tracing the complete subcrop of the Tahawus complex, to clarify the relationship between the Tahawus complex and the Adirondack conductivity anomaly and to elucidate the structural configuration of the Tahawus complex. If the overall form of the Tahawus complex proves to be a wedge elongate along strike this would point towards an origin as an underthrust block, whereas a domal structure, for example, might be more easily attributed to igneous activity.

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