Foreland crustal structure of the New York recess, northeastern United States

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ABSTRACT

A new structural model for the northeast part of the Central Appalachian foreland and fold-and-thrust belt is based on detailed field mapping, geophysical data, and balanced cross-section analysis. The model demonstrates that the region contains a multiply deformed, parautochthonous fold-and-thrust system of Paleozoic age. Our interpretations differ from previous ones in which the entire region north of the Newark basin was considered to be allochthonous. The new interpretation requires a substantial decrease in Paleozoic tectonic shortening northeastward from adjacent parts of the Central Appalachian foreland and illustrates the common occurrence of backthrusting within the region.

During early Paleozoic time northern New Jersey consisted of a Taconic orogenic foreland in which cover folds (F1) involved lower Paleozoic carbonate and flysch overlying Middle Proterozoic basement. F1 folds are open and upright in the foreland and more gently inclined to recumbent southeastward toward the trace of the Taconic allochthons. F1 structures were cut and transported by a fold-and-thrust system of the Alleghany orogeny. This thrust system mostly involves synthetic faults originating from a master decollement rooted in Proterozoic basement. Antithetic faults locally modify early synthetic overthrusts and S1 cleavage in lower Paleozoic cover and show out-of-sequence structural development. The synthetic parts of the regional thrust system are bounded in the northwestern foreland by blind antithetic faults interpreted from seismic-reflection data. This antithetic faulting probably represents Paleozoic reactivation of Late Proterozoic basement faults. Tectonic contraction in overlying cover occurred by wedge faulting where synthetic and antithetic components of the foreland fault system overlap. S2 cleavage in the Paleozoic cover stems from Alleghanian shortening and flattening and commonly occurs in the footwall of large overthrust sheets. Paleozoic structures in Proterozoic basement include fault blocks bounded by high-angle faults and low- to moderate-angle shear zones that locally produce overlying cover folds. Broad and open folds in basement probably reflect shear-zone displacement of subhorizontal foliation. Our cross-section interpretations require limited involvement of lower Paleozoic cover folds in the footwalls of major overthrust faults. Palinspastic restoration of F1 folds produces an arched passive-margin sequence. The tectonic contraction for the Valley and Ridge province and southeastern Pocono Plateau is about 25 km, and tectonic wedge angles are 8°–11°.

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GSA Bulletin; August 1997; v. 109; no. 8; p. 955–977; 18 figures; 2 tables.

INTRODUCTION

The objective of this chapter is to elucidate the foreland tectonics of the central part of the New York recess using data from seismic-reflection profiling and geologic mapping to construct balanced cross sections. This study focuses on data obtained during a cooperative study with the U.S. Geological Survey to revise the state geologic map of New Jersey (Drake et al., 1994). Structural interpretations based on seismic profiles are included for bordering parts of the Pocono Plateau in Pennsylvania and New York. About 120 km of Exxon Co., U.S.A., seismic-reflection data that extend to mid-crustal depths are shown along three parallel profiles. Paleozoic stratigraphic data in the region are summarized from various structural profiles and a deep hydrocarbon exploration well. A synthetic seismogram and conventional velocity survey for the well provide a stratigraphic tie to the seismic-reflection data for most of the Paleozoic cover. The Paleozoic cover sequence requires a unique set of modeling criteria for balanced cross-section analysis because of multiple deformation. Present thrust faults and related folds have been palinspastically restored for the Alleghany orogeny into a stylized foreland-fold sequence attributed to the Taconic orogeny. Gravity and magnetic data for the Valley and Ridge province were compared and utilized in preparing the structural interpretations. The basement structures that can be related to cover strains are shown, and the strain history for the cover rocks is discussed.

GEOLOGIC SETTING

The New York recess spans the junction between the central and northern Appalachian Mountains of eastern North America (Fig. 1). The bedrock north of the Mesozoic Newark rift basin includes both Proterozoic basement and Paleozoic cover. The tectonic complexity of this region systematically increases eastward from the Pocono Plateau through the Valley and Ridge and into the New Jersey Highlands (Fig. 2). The Pocono Plateau contains little structural relief and only mildly deformed Paleozoic rocks that form a gently dipping, west-facing homocline (Fisher et al., 1970; Wood and Bergin, 1970; Berg et al., 1980). The regional fold-and-thrust belt mapped farther eastward has long been recognized as a complex, polydeformed terrane variously ascribed to the Grenville (1 Ga), Taconic (450–500 Ma), and Alleghany (234–260 Ma) orogenies (Bayley et al., 1914; Lewis and Kummel, 1940; Drake, 1969; Rodgers, 1970). Those parts of the fold-and-thrust belt that include Paleozoic cover rocks contain map structures that reflect Paleozoic tectonism. Fold-and-thrust structures of Alleghanian age deform earlier structures throughout the region and involve rocks through Devonian age.

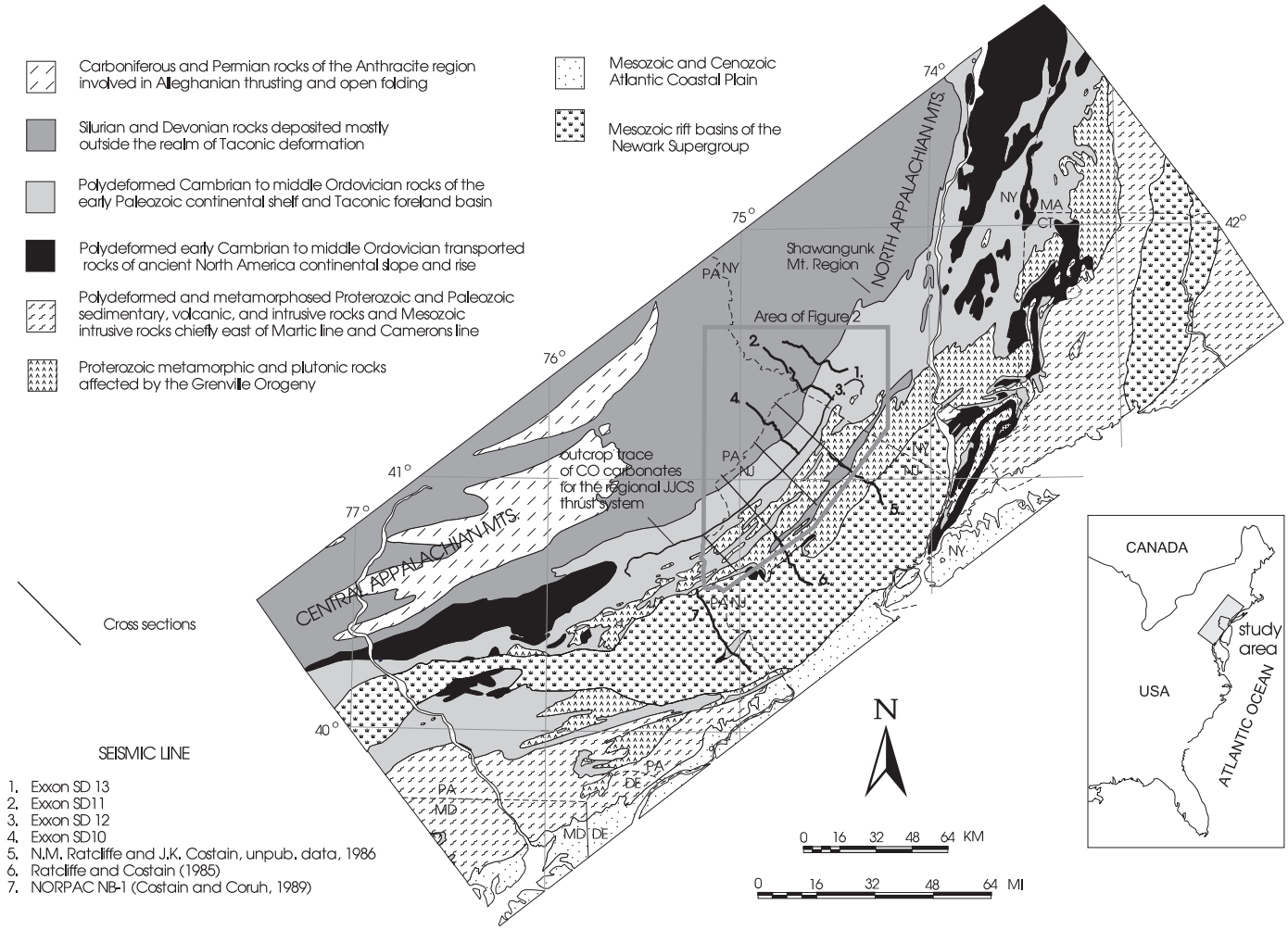

Figure 1. Generalized bedrock geology of the New York recess showing the locations of the study area, regional cross sections, and nearby seismic reflection data. Modified from Williams (1978). The distribution of Cambrian–Ordovician (CO) rocks at the Jenny Jump–Crooked Swamp (JJCS) thrust belt serves to approximate the fault length when calculating a length-displacement scaling ratio.

The basement massifs of the Reading Prong mostly contain Grenville age gneiss, marble, and granitoid rocks (Drake, 1984). Later diabase dikes probably intruded basement during Late Proterozoic rifting along the eastern Laurentian margin (Ratcliffe, 1981; Rankin et al., 1989; Drake et al., 1994). Cambrian–Ordovician cover rocks underlie most intermontane valleys in the New Jersey Highlands and the entire Kittatinny Valley. The Cambrian–Ordovician cover extends northwestward from the Kittatinny Valley beneath middle Paleozoic rocks of Kittatinny Mountain and the Pocono Plateau (Fig. 2). Lower and middle Paleozoic rocks also crop out in the Green Pond syncline in the New Jersey Highlands and adjacent parts of New York (Fig. 2). Some isolated fault slices of Silurian conglomerate also crop out along the trace of the Ramapo fault on the northwest border of the Newark basin (Drake et al., 1994).

The Green Pond syncline is a block-faulted and downwarped basin containing stratigraphic and structural evidence indicating at least three phases of Paleozoic compressive deformation in the region (Herman and Mitchell, 1991). The first phase was a broad uplift during the Taconic orogeny resulting in widespread removal of Cambrian–Ordovician rocks in the central part of the syncline. The second phase involved regional faulting, kink folding, and cleavage development along a northeast trend in cover rocks through Devonian age. The third phase resulted in north-south shortening strain that correlates with cross-cleavage development and oblique fault slip along the northwest margin of the syncline (Herman, 1987). The second and third phases are attributed to the Alleghany orogeny because they involve rocks of Middle Devonian age and because the progressive clockwise rotation of the recorded finite-strain azimuths correlates with those reported for the Allegheny Plateau in Pennsylvania and New York (Mitchell and Forsythe, 1988; Geiser and Engelder, 1983). Most of the mapped faults were probably active during the Alleghany orogeny, on the basis of their involvement of rocks of Devonian age, but they may have originated in basement earlier and may have been subsequently reactivated later during Mesozoic rifting (Lewis and Kummel, 1940; Ratcliffe, 1980). Mallizi and Gates (1989) suggested that the syncline represents a positive flower structure formed by late Paleozoic dextral transpression with later sinistral strike-slip reactivation.

From Cambrian through Late Ordovician time, the Appalachian basin gradually deepened as it evolved from a carbonate platform at a passive margin to a foreland basin in a convergent margin. The total thickness of Cambrian and Lower Ordovician carbonate rocks is less here than for adjacent areas in the Appalachians, reflecting a depositional setting of comparatively

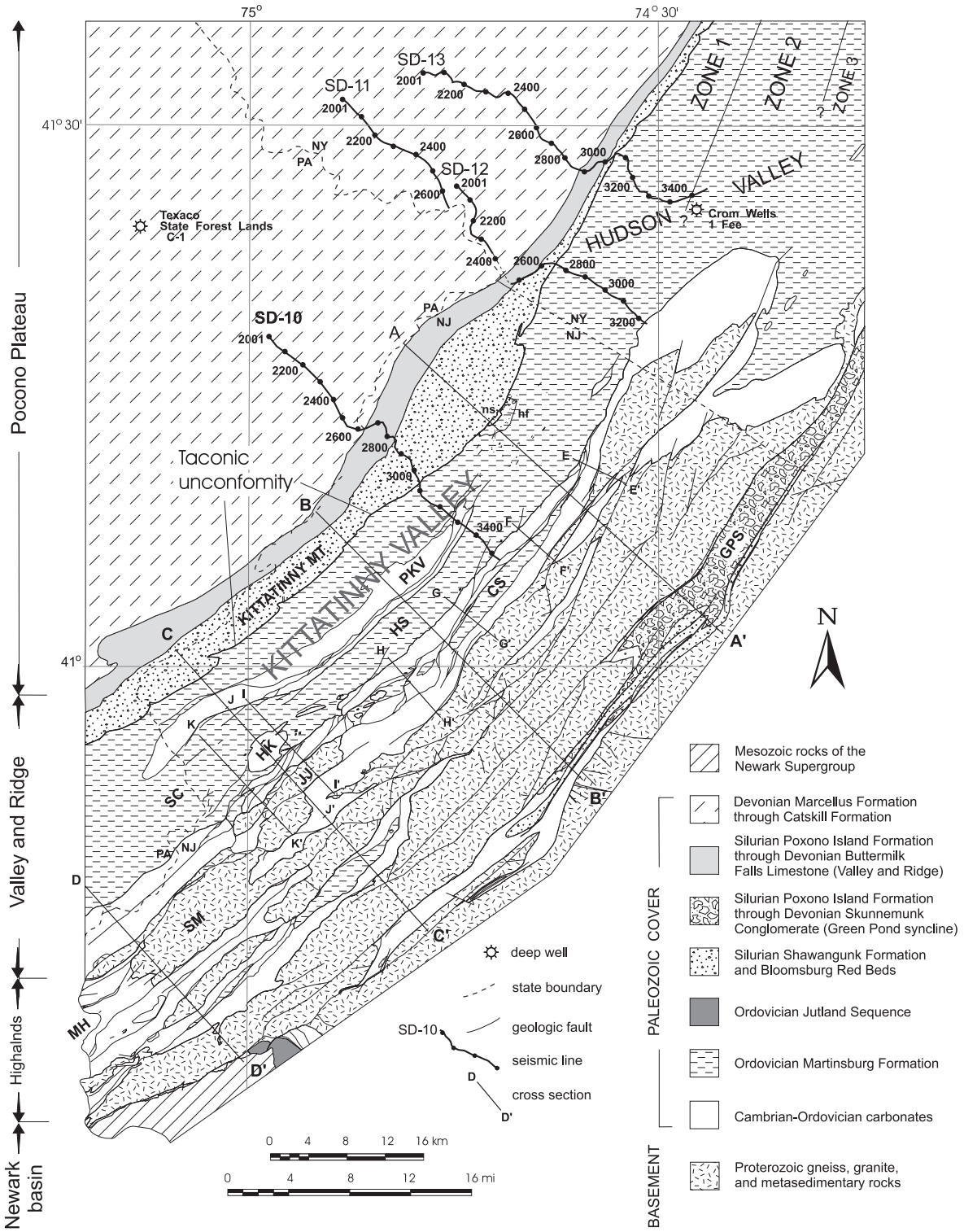

Figure 2. Generalized bedrock geology of northern New Jersey and adjacent area showing the locations of cross sections, seismic reflection lines, and deep petroleum-exploration wells. The geology is modified from Drake et al. (1994). Tectonic zones in the Hudson Valley are adapted from Epstein and Lyttle (1987). MH—Morgan Hill, SM—Scotts Mountain, GPS—Green Pond syncline, SC—Stone Church syncline, HK—Hope klippe, HS—Halsey syncline, PKV—Paulins Kill Valley, CS—Crooked Swamp syncline, ns—nepheline syenite, hf—Martinsburg Formation hornfels.

higher structural relief during early Paleozoic time (Rankin et al., 1989). Tectonic uplift and differential erosion of the carbonate shelf by the end of the Early Ordovician produced the Beekmantown unconformity, and were probably related to westward migration of a peripheral bulge stemming from an east-dipping subduction zone of the Taconic orogeny (Jacobi, 1981; Shanmugam and Lash, 1982; Bradley and Kidd, 1991). Resubmergence of the shelf during Middle Ordovician time marked the onset of rapid basin subsidence and deeper neritic-flysch sedimentation followed by progradational influx of terrigenous clastic sediments that extended into Late Ordovician time (Hobson, 1963; Drake, 1969; Epstein and Epstein, 1969).

The amount of pre-Silurian erosion of the Cambrian–Ordovician shelf sequence varies widely. In the Kittatinny Valley of New Jersey, the southwest side of the Hudson Valley of New York, and southwest New Jersey Highlands, as much as 91 m of upper Beekmantown strata were locally removed during development of the Beekmantown unconformity (Lewis and Kummel, 1940; Offield, 1967; Markewicz and Dalton, 1977). However, Middle Ordovician Trenton Limestone and subjacent localized clastic rocks rest atop the Beekmantown unconformity with only slight angular discordance (Lewis and Kummel, 1940; Offield, 1967; Markewicz and Dalton, 1977; Monteverde and Herman, 1989). Beekmantown rocks also show localized paleokarstification (Markewicz and Dalton, 1977; Monteverde et al., 1989). Silurian conglomerate locally rests directly on top basement in the central part of the Green Pond syncline (Figs. 2 and 3), where Cambrian–Ordovician carbonate rocks were completely removed in parts of the New Jersey Highlands (Finks, 1968). Basal Silurian conglomerate mostly overlies Lower Cambrian dolomite elsewhere in the syncline. However, tectonized shales mapped as Martinsburg Formation locally occur along a major fault along the syncline's western boundary (Kummel and Weller, 1902; Barnett, 1976), which may indicate localized deposition of Middle Ordovician flysch directly on basement rocks (Herman and Mitchell, 1991). Erosion of the Cambrian–Ordovician carbonates in parts of the central New Jersey Highlands therefore continued during deposition of Trenton rocks elsewhere, and erosion of the carbonate shelf extended from pre-Trenton emergence to at least the time of deposition of the Martinsburg Formation.

A regional uplift during Late Ordovician time resulted in the Taconic unconformity that separates underlying flysch from superjacent Silurian molasse in the Valley and Ridge (Rodgers, 1970). The map trace of this unconformity across the New York recess is shown in Figure 1. The angular discordance along the Taconic unconformity in New Jersey is at most a few degrees, but is generally at a much larger angle in Pennsylvania and New York (Epstein and Epstein, 1969; Epstein and Lyttle, 1987).

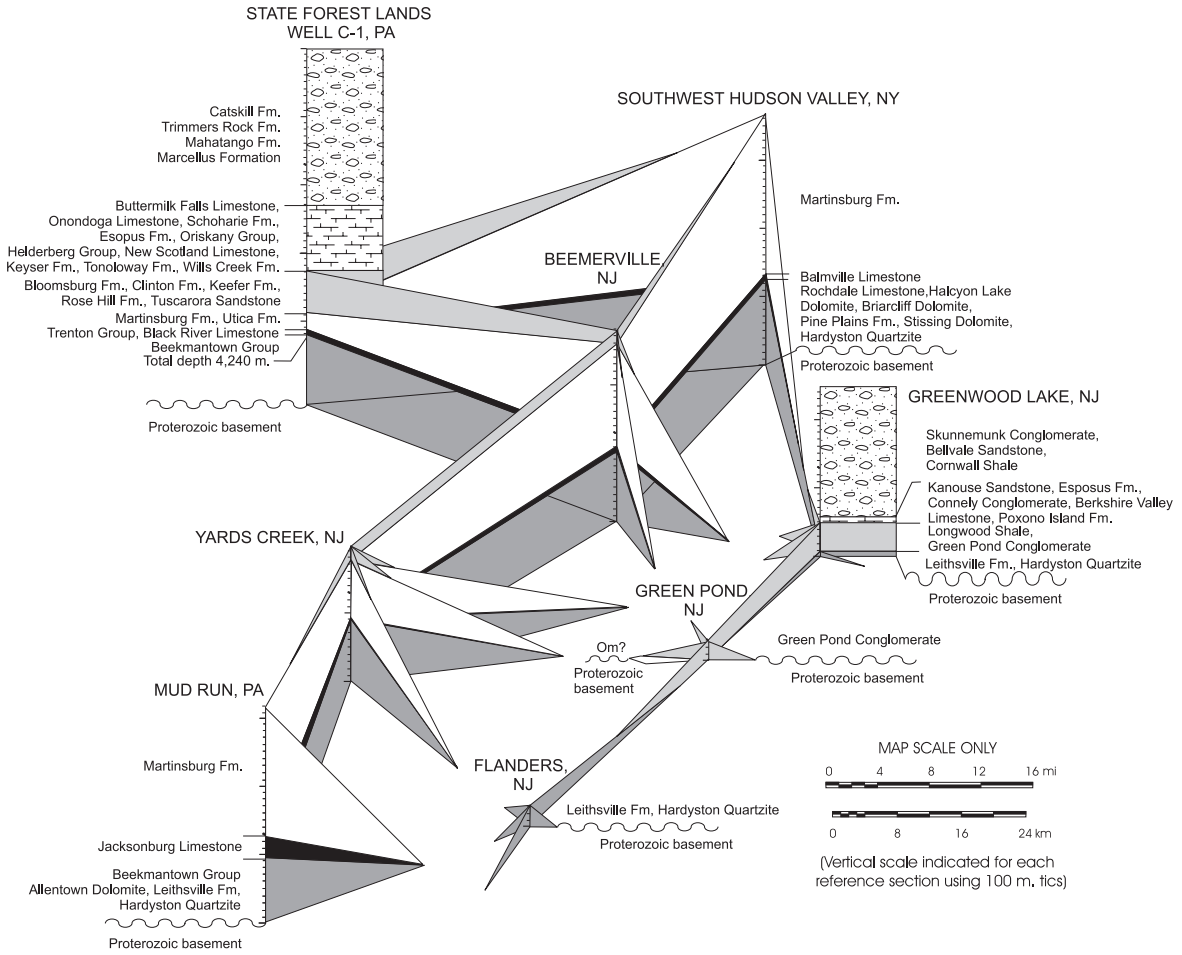

Figure 3. Fence-panel diagram summarizing the distribution and thicknesses of the Paleozoic rocks in the study area. Thicknesses are shown above the basement-cover contact. Data were compiled from Sherwood (1964), Davis et al. (1967), Offield (1967), Sevon et al. (1989), Sanders (1983), Herman and Monteverde (1989), and Herman and Mitchell (1991).

As summarized by Epstein and Epstein (1969), the foreland region began receiving abundant clastic sediments during Early Silurian time in a marginal marine environment from rising Taconic sourcelands to the southeast. A gradual return to prolonged, shallow-marine conditions by lowermost Devonian time is marked by marine shelf–orthoquartzite deposits. Approximately midway into the Early Devonian, a major regressive event culminated with post-Oriskany emergence, followed by a return to deep neritic conditions, and eventual geosynclinal flysch sedimentation during Middle Devonian time. Subsequent deposits of Middle and Upper Devonian molasse resemble the Middle Ordovician through Upper Silurian flysch to molasse sequence.

Compelling evidence points to an early phase of cover folding and faulting throughout the New Jersey Valley and Ridge and highlands during the Taconic orogeny. This includes the aforementioned pre-Silurian erosion of the lower Paleozoic shelf sequence, stratigraphic pinchouts of Middle Ordovician sediments in the region (Hobson, 1963; Monteverde and Herman, 1989), and reconstruction of pre-Silurian cover folds and related structures in southern New York (Offield, 1967; Epstein and Lyttle, 1987). A sequence of three tectonic zones aligned parallel to regional strike was proposed by Epstein and Lyttle (1987) for the Hudson Valley of New York on the basis of styles of faulting and folding within Ordovician parautochthonous flysch. The southwestern parts of these zones are shown in Figure 2. The zones are southwestward continuations of similar zones mapped in the Albany, New York, region that show faulting, folding, and cleavage in Ordovician flysch strengthening southeastward toward and parallel to the foreland trace of the regional Taconic allochthon (Bosworth and Vollmer, 1981). The line between broad open folding (zone 1) and tight folding and thrust faulting to the southeast (zone 2) extends southwestward from the Shawangunk Mountain region to Middletown, New York (Fig. 2). Zone 3 contains overturned folds, thrust faults, and melanges. It parallels the previous line starting about 6 km to the southeast of zone 1.

PALEOZOIC CLEAVAGE IN COVER ROCKS

Abundant information about the kinematics and penetrative strains in the regional fold-and-thrust system is gained from studies of rock cleavage within Paleozoic cover, especially in the Martinsburg Formation (Broughton, 1946; Maxwell, 1962; Drake, 1967a, 1967b; Drake et al., 1969, 1985; Groshong, 1976; Epstein and Epstein, 1969; Epstein, 1973; Beutner, 1978; Beutner and Diegel, 1985; Drake and Lyttle, 1985; Herman and Monteverde, 1989; Herman et al., 1994). All varieties of cleavage are grouped here for display purposes into an early regional set (S1) and later localized sets (S2), which overprint bedding (S0) and S1 with structural discordance. S1 includes spaced solution cleavage in Cambrian–Ordovician carbonate rocks, slaty cleavage in the Martinsburg Formation (Broughton, 1946; Drake, 1967a, 1967b, 1969; Drake et al., 1969, 1985; Drake and Lyttle, 1985), and any spaced cleavage in middle Paleozoic rocks of the Valley and Ridge province. S1 is best developed (spacing of a few millimeters or less) in slates, shales, and argillaceous limestone in the Kittatinny Valley, where it commonly obscures bedding and is the dominant parting surface in outcrop. Cleavage is also well developed in siltstone, sandstone, conglomerate, and crystalline limestone in the Kittatinny Valley and highlands region, but is more widely spaced (less than 1 cm to a few centimeters). Dolomite is more sparsely cleaved, but generally shows well-developed solution cleavage with spacing of less than 1 cm to a few centimeters near reverse faults, within fault horses, and in the hinge areas of tight bedding folds. S1 is poorly developed in some middle Paleozoic clastic rocks and in hornfels of the Martinsburg Formation near the Beemerville Intrusive Complex (Drake and Monteverde, 1992). S1 spaced cleavage is also diffuse and gently dipping in the Martinsburg Formation along the base of Kittatinny Mountain from the development of cleavage pressure shadows in interbedded and folded rocks of different competencies (Epstein and Epstein, 1969).

S2 includes all mapped secondary spaced cleavages. S2 displays variable spacing; it locally crenulates S1, or forms more widely spaced subparallel planes that may offset S1 surfaces with visible shear slip and associated drag folds (Fig. 8 of Broughton, 1946; Fig. 25 of Drake, 1969). S2 commonly occurs in the footwall region of large overthrust sheets (Fig. 4) and shows both normal slip on northwest-dipping S2 and reverse slip on southeast-dipping S2 (Broughton, 1946; Herman and Monteverde, 1989). Only one slip lineation is recorded for these types of S2. In some locations, particularly near faults with complex movements, multiple sets of systematic cleavage planes reflect complex fault movements and reactivation histories. S3 cleavage is not regional in extent and is beyond the scope of this study.

The age of penetrative cleavage within the Paleozoic cover sequence has been the subject of considerable debate. Field evidence indicates that most cleavages in the foreland stem from the Alleghany orogeny (Epstein and Epstein, 1969; Ratcliffe, 1981; Herman and Monteverde, 1989; Wintsch and Kunk, 1992). However, Ratcliffe (1981) found evidence for pre-Alleghanian tectonic foliation in Martinsburg Formation xenoliths from a Late Ordovician diatreme (Zartman et al., 1967; Ratcliffe, 1981) of the Beemerville carbonatite-alkalic rock complex in the western Kittatinny Valley (Fig. 2). Epstein and Lyttle (1987) also noted that cleavage in Ordovician rocks in parts of the Shawangunk Mountain region of New York (Fig. 1) is locally truncated by overlying Silurian rocks. Drake and Lyttle (1980) proposed that spaced cleavage in Paleozoic cover may migrate in time progressively toward the foreland, and thereby stems from both Taconic and Alleghany orogenies.

SEISMIC-REFLECTION AND DRILLING DATA

Four seismic-reflection profiles were collected by Exxon Co., U.S.A., in and near northern New Jersey in 1987 (Figs. 1 and 2). The profiles extend southeastward from the Pocono Plateau across Kittatinny Mountain into the Appalachian Great Valley. The Exxon data are introduced below as 5 s two-way traveltime (TWT) profile records with full display, migrated data (Fig. 5). Exxon profiles SD-11 and SD-12 were shot separately with about 3 km of overlapping coverage and 2 km of strike separation (Fig. 2). They are shown together here by edge matching shot point (SP) 2620 for SD-11 with SP 2001 for SD-12 (Fig. 5). The profiles were shot with a Vibroseis source using a 4 s, 4 vibration sweep of 12–72 Hz and a 9 s record length. A split-spread field layout was used with 120 recording channels, resulting in a maximum of 60 fold, common depth point data records. Geophone spacing was 24.4 m with a recording configuration of 1609.8-170.7, shot point, 170.7-1609.8 m. Other field parameters include a recording filter of 8–90 Hz with the compressional wave recorded as negative values. The profile data were processed by Exxon to a regional reference frame utilizing modern techniques of migration and coherency filtering. The processing sequence included use of refraction statics to reduce long-period statics problems, prestack deconvolution, surface-consistent reflection statics to eliminate short-period (<1 spread length) statics problems, and application of a time-variant filter to reduce coherent noise outside the signal bandwidth. The seismic profiles are shown here with approximately equal horizontal and vertical scales using an average velocity of about 4.6 km/s. The line drawings were hand traced from 1:24 000 horizontal-scale unmigrated records. All profile records were digitally scanned and recompiled at a reduced scale.

Proterozoic basement rocks are grouped into a single unit for interpretation of seismic profiles. However, the Paleozoic cover is subdivided into five lithologic groups based on lithologic contrasts reported at the Texaco State Forest Lands C-1 (SFL C-1) deep well in Pike County, Pennsylvania

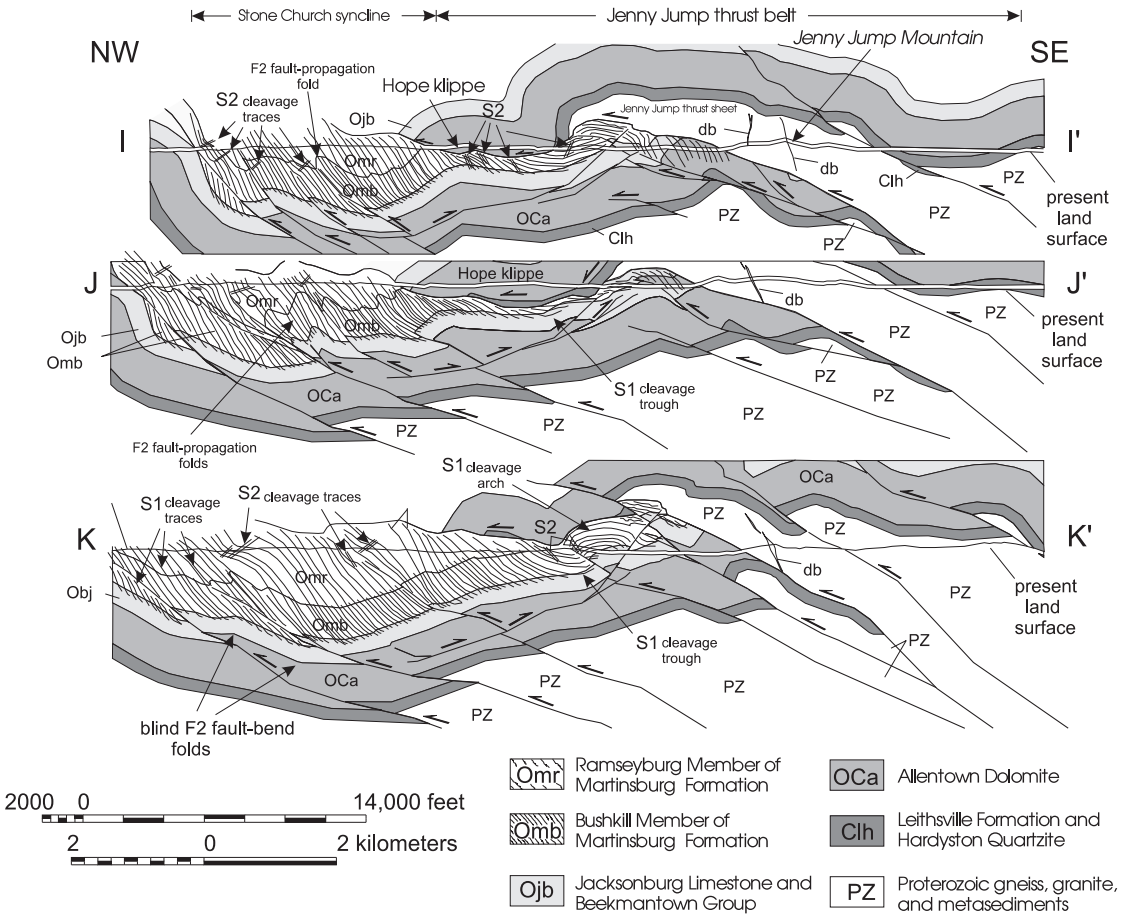

Figure 4. Cross sections of the Jenny Jump thrust belt and Stone Church syncline in the southwest Kittatinny Valley showing structural details associated with emplacement of the Hope klippe. The broad and open Stone Church syncline and "blind" cover antiform beneath Jenny Jump Mountain are interpreted as F1 folds. F1 folds are assumed to include S1 cleavage. All faults and associated bedding (S0) and F2 folds in cover are interpreted as d2 structures along with S2 cleavages. The locations of the profiles and the Hope klippe are shown in Figures 2 and 11A. J–J′ is palinspastically restored in Figure 15 as part of regional cross section C–C′.

(Figs. 2 and 6; Table 1), and reflection configurations observed in the seismic profiles. The lithologic groups and seismic reflectors used here (Table 1) are similar to those used in other seismic reflection studies in the central and southern Appalachians (Beardsley and Cable, 1983; Christensen and Szymanski, 1991; Wilson and Shumacher, 1994).

SFL C-1 was drilled by Texaco, Inc., in 1971 to a total depth of 4240 m. It is located about 25 km southwest along strike from the northwest end of Exxon profile SD-11 (Fig. 2). A stratigraphic log and borehole geophysical data for SFL C-1 provide a subsurface stratigraphic tie to Exxon profile SD-11 to about 1.7 s TWT in the western part of the study area (Fig. 6). Sevon et al. (1989) noted that the names of all units below the Oriskany Group stem from a drilling log and may not be correctly applied. A synthetic seismogram based on the borehole geophysics shows good correlation with both the geologic log and reflection events from the western end of profile SD-11 (Fig. 6). The synthetic seismogram was generated by Exxon from a borehole-compensated sonic log for an areal datum elevation of 487.68 m, and was adjusted for depths below the first check shot at a depth of 152.2 m below the local datum. The synthetic seismogram shows the response from a rarefaction-unit impulse of 20 Hz and a cycle breadth of 31.83 ms. A constant lithologic density of 2.0 g/cm^3 was used for modeling the signal responses.

Bedrock Lithic Groups and Seismic Stratigraphy

Table 1 summarizes the lithologic and seismic-reflection characteristics for the foreland interval of the New York recess. A pair of seismic reflections directly beneath the base of stratigraphic unit D are the strongest and most continuous ones beneath the Pocono Plateau (Figs. 6–9). The lithic group boundary is placed at the top of the upper reflection H in the seismic profiles. This horizon has a reflection coefficient of about 0.17, stemming from the lithologic boundary between the Devonian Buttermilk Falls Limestone (about 98 m thick) with the superjacent Marcellus Formation (about 366 m of shale). Although other coherent signals occur above this reference horizon, all subsequent formations are combined for regional structural analysis. The base of stratigraphic unit SD correlates to a semicontinuous reflection horizon (SB in Figs. 7–9) approximately 10 reflection cycles below reflection H in profile SD-11 (Fig. 6). However, a single reflection cannot be traced confidently eastward beyond SP 2500 in profile SD-11. Therefore, the lower boundary was extrapolated into profile SD-12 by using the same number of reflectors below reflector H. Farther eastward in SD-12 this boundary interval separates parallel-layered reflectors overlying sets of complex-layered reflectors (cl in Fig. 8) below SP 2200. Stratigraphic unit S contains simple-layered reflections in parallel alignment beneath the Pocono Plateau in New

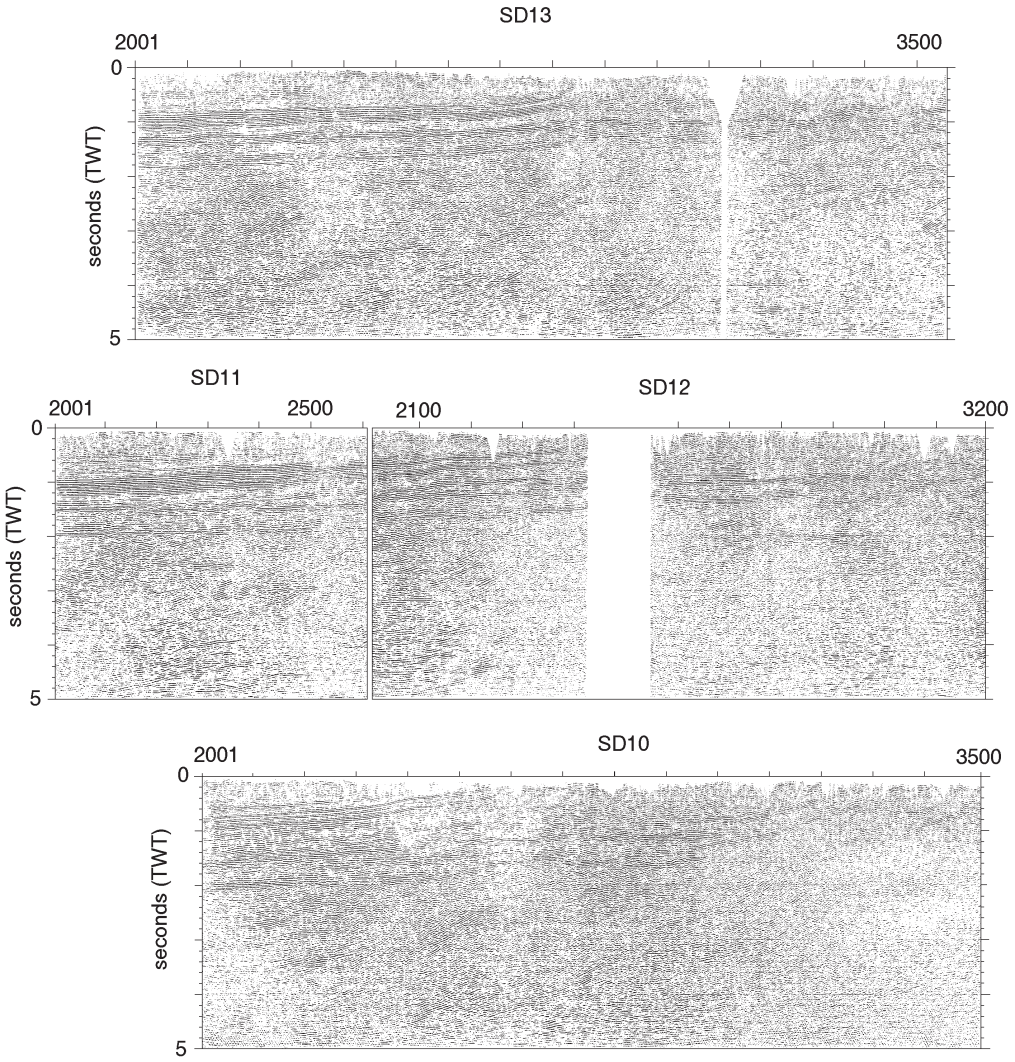

Figure 5. Exxon seismic-reflection profiles SD-10, SD-11, SD-12, and SD-13. Profiles show maximum 64 fold common depth point migrated data on the central foreland of the New York recess in New Jersey, Pennsylvania, and New York. The shot point locations are shown in Figure 2. TWT—two-way traveltime.

York (Figs. 7–9). The unit's lower boundary (OS in Figs. 6 and 8, Table 1) is placed among four coherent reflections at the west end of SD-11, based on data for SFL C-1 (Fig. 6). This boundary coincides with the regional Taconic unconformity. Its reflection configuration varies elsewhere and displays oblique layering, truncated reflectors, and stratigraphic pinchouts (tr in Figs. 8 and 10). The position of this boundary in profile SD-10 and the southeast parts of all profiles is uncertain, especially where the reflection configuration is chaotic above 0.8 s TWT. The lower group boundary is generally diffuse due to the apparent thickening of the underlying lithologic group and local structural complications. Its placement is primarily based on selection of a time interval comparable to other parts of the seismic profiles. Stratigraphic unit O shows considerable variations in thickness in the study area. The unit's lower boundary is reflection horizon T (Figs. 7–9; Table 1). This horizon is also unclear, but generally separates an upper time interval displaying complex- to simple-layered reflections from the lower, simple-layered reflections. The location of T is aided by using a constant time interval above the better defined B reflector (Table 1). A pronounced thickening of this group is seen toward the southeast and southwest in the composite set of geologic profiles (Fig. 10). Stratigraphic unit CO is mostly dolomite, but is regionally capped by Middle Ordovician limestone that typically grades upward from crystalline wackestone into superjacent black shale of the overlying flysch sequence. This gradation probably accounts for the diffuse reflection horizon T. Thick-bedded chert sequences commonly occur directly below the Middle Ordovician Jacksonburg Limestone in the Kittatinny Valley of New Jersey, and thick-bedded sequences of dolomitic shale are common in lower parts of the unit. The group is floored by Hardyston Quartzite of minor thickness, and generally displays a simple-layered reflection configuration. The lower part of the group commonly displays coherent, continuous reflections, whereas the upper part commonly displays discontinuous reflections and localized complexities. The unit apparently thins toward the northeast (Fig. 10), but is generally interpreted to be of constant thickness (about 350 ms TWT) within a single profile, except where disrupted by faulting.

Structural Interpretation of Exxon Seismic Profiles

Each seismic-reflection profile shown here displays both the migrated, full display records, and conventional line drawings of the unmigrated data. The migrated data preferentially elucidate cover structures, whereas the line drawings clarify basement structures. The line drawings of profiles SD-10, SD-11, and SD-12 were previously published as part of a regional synthesis of deep crustal structures on the basis of seismic-reflection data (Herman, 1992). Some aspects of these earlier interpretations are revised here.

The regional sole fault is reinterpreted to be entirely confined within Proterozoic basement rather than piercing the lower Paleozoic sequence beneath

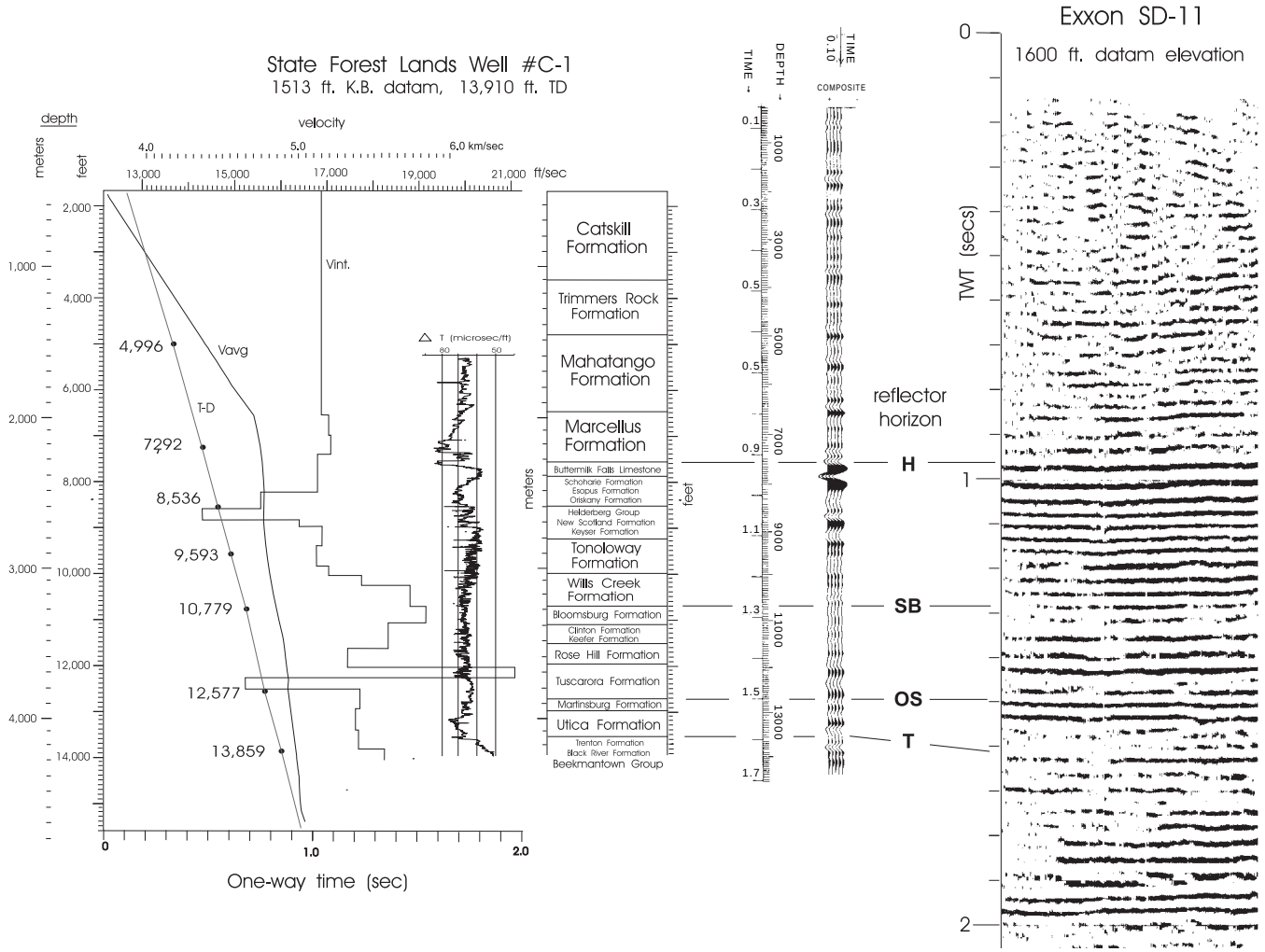

Figure 6. Borehole data for the Texaco well C-1 showing a stratigraphic correlation to the northwest end of Exxon profile SD-11. The bore-hole compensated sonic log and conventional velocity analysis are by Texaco. The synthetic seismogram was generated by Exxon. See text for further discussion.

the Valley and Ridge province (Figs. 7–10). In addition, many northwest-dipping (antithetic) blind faults beneath the Pocono Plateau are reinterpreted to extend upward from the basement into lower Paleozoic cover rocks (Figs. 7–10). These faults locally offset reflection signals at the base of the cover and form gently to moderately dipping boundaries between acoustic domains in basement. The profile trace of these interpreted faults normally intersect localized diffraction events. The acoustic domains in basement contain arched reflectors with broad and open reflection configurations (Figs. 7–9) resembling "roll-over" or "reverse drag" along normal faults (Gibbs, 1984; Hamblin, 1965). These faults may be Proterozoic rift structures that were locally reactivated as late Paleozoic contractional faults because in places there is no apparent offset of the cover along their up-dip projection (Figs. 8–10). Most of these basement structures therefore apparently predate Paleozoic deposition and contraction.

Profile SD-10 extends southeast from the Pocono Plateau into the Valley and Ridge province of New Jersey (Fig. 2). The southeast end of the profile crosses the Paulins Kill thrust belt (Fig. 11A), where the last map trace of thrust-faulted lower Paleozoic carbonates occurs in the New Jersey foreland. Profile SD-10 shows that the blind faults cutting Paleozoic cover rocks extend for at least 10 km farther into the plateau (Fig. 7). Ordovician rocks of the Martinsburg Formation are probably tectonized where splay faults locally thicken the cover and underlie broad and open folds in the Silurian–Devonian sequence (SP 2300 to 2600). The system of blind faults is most complex beneath the northwest part of the Valley and Ridge province (SP 2600 to 3000), where it defines a structural transition between synthetic basement faults to the southeast and antithetic basement faults to the northwest. The sets of antithetic faults beneath the Pocono Plateau are interpreted as isolated reverse faults, whereas those to the south are interpreted as a linked decollement thrust system (Herman, 1992). The southeast end of SD-10 shows a pair of open folds involving the Cambrian–Ordovician carbonates (Fig. 7). Only the southeast limb of the synform and the northwest limb of the antiform are interpreted with certainty. The intervening fold limbs are based on field mapping and geophysical data from the exposed fold-and-thrust belts. A northeast-plunging anticline in cover rocks directly southwest of SP 3300 in line SD-10 (Figs. 2 and 11A) is projected into the profile interpretation (Fig. 10) Thrust faults are shown directly to the southeast, although they are not apparent in the seismic record.

Exxon profiles SD-11, SD-12, and SD-13 span the structural transition from the Pocono Plateau to the Hudson Valley in southeastern New York (Fig. 2). A slight mismatch of the seismic stratigraphy is apparent where

TABLE 1. SUMMARY OF ROCK UNITS IN THE STUDY AREA, CORRESPONDING SEISMIC UNITS, KEY REFLECTION HORIZONS, AND CHARACTERISTIC SEISMIC-REFLECTION CONFIGURATIONS USED FOR INTERPRETATION OF THE SEISMIC-REFLECTION DATA

Age	Seismic units, rock types, and reference reflector horizons (unit boundaries)	Reference sections, lithic groups, formations, and group thickness values (m)				Stratigraphic notes and characteristic seismic relection configurations
		Texaco State Forest Lands well C-1		New Jersey Valley and Ridge		
Devonian	D—sandstone, conglomerate, siltstone, shale, quartzite	Catskill Formation, Trimmers Rock Formation, Mahantago Formation, Marcellus Formation	2316*	Marcellus Formation	274	Coarsening-upward flyche to molasse. Simple-layered reflectors lower in unit generally become more chaotic upward.
	H					
Silurian–Devonian	SD—limestone, dolomite, calcareous siltstone, and shale	Buttermilk Falls Limestone, Schoharie Formation, Esopus Formation, Oriskany Group, Helderberg Group, New Scotland Formation, Keyser Formation, Tonoloway Formation, Wills Creek Formation	984	Buttermilk Falls Limestone, Schoharie Formation, Esopus Formation, Oriskany Group, Helderberg Group, Rondout Formation, Decker Formation, Bossardville Limestone, Poxono Island Formation	616	Mostly calcareous rocks. Pronounced, simple-layered reflectors become more chaotic eastward and at shallow reflection depths.
	SB					
Silurian	S—sandstone, siltstone, shale, quartzite	Bloomsburg Formation, Clinton Formation, Keefer Formation, Rose Hill Formation, Tuscarora Formation	622	Bloomsburg Red Beds, Shawangunk Formation	884	Coarse- to fine-grained siliceous rocks with simple, oblique, and sigmoidal reflection configurations. Truncated reflectors and pinchouts.
	OS					
Ordovician	O—siltstone, shale, and sandstone	Martinsburg Formation, Utica Formation	259	Martinsburg Formation	1372	Fine- to coarse-grained siliceous clastic rocks with minor carbonate rocks. Complex reflectors resembling stratigraphic onlaps and pinchouts.
	T					
Cambrian–Ordovician	CO—dolomite, limestone "stiff layer"	Trenton Formation, Black River Formation, Beekmantown Group	109*	Jacksonburg Limestone, Sequence at Wantage, Beekmantown Group, Allentown Dolomite, Leithsville Formation, Hardyston Quartzite	1220	Carbonate rocks with minor siliceous interbeds. Continuous simple-layered reflectors toward top of unit. Generally discontinuous reflectors in lower part of unit.
	B					
Proterozoic gneiss and granitoid Grenville basement. Generally chaotic reflectors locally showing simple-layered configurations. Local intervals with reflectors arranged in broad and open arches resembling "roll-over" in the the hanging wall of normal faults.						

*Total thickness penetrated in well.

profiles SD-11 and SD-12 are edge matched and the Paleozoic cover is deeper to the southwest (Fig. 1). This trend is consistent throughout the region, as shown by comparison of the serial profile interpretations (Fig. 10).

Structures in profiles SD-11, SD-12, and SD-13 are similar to those in SD-10, but also differ notably. For example, the structural transition between synthetic and antithetic basement faulting occurs farther northwest in New Jersey than in New York (Fig. 10). Similarly, faulting in cover rocks beneath the Pocono Plateau generally extends farther northwest in Pennsylvania than in New York. These trends show that foreland-translation strain related to the Alleghany orogeny decreases northeastward from the Pennsylvania salient (Wilson and Shumaker, 1988) into the central part of the New York recess. However, faulting of Silurian rocks (profile SD-13) occurs farther northwest than it does in the other profiles, and the amount of tectonic deformation in the Silurian–Devonian foreland apparently increases northeast of profile SD-13 in the Shawangunk Mountain region of New York (Salkind, 1979; Marshak and Tabor, 1989). Therefore, a cross-strike tectonic axis within the foreland of the New York recess seems to coincide with the trace of profiles SD-11 and SD-12. This observation is elaborated on below with respect to other work in the region.

The interpretation of structures in the southeast part of profiles SD-12 and SD-13 is complicated by a seismic data gap and by probable complex fault and fold structures in the Martinsburg Formation (Epstein and Lyttle, 1987). The southeast end of profile SD-13 is located about 2 km northeast of the Middletown, New York, gas well (Crom-Wells 1 Fee in Fig. 1). Sanders (1983) interpretation of the Hudson Valley region near the well is based on the lithologic well log and geologic mapping (Offield, 1967). The favored interpretation depicts a regional, subhorizontal detachment fault near the base of the Martinsburg Formation that accommodated northwestward foreland-thrust translation and is linked to a southeastern overthrust system rooted in Proterozoic basement (Fig. 7 of Sanders, 1983). This detachment was proposed to separate northwest-inclined hanging-wall rocks from subhorizontal footwall carbonates. The Exxon profiles show considerable structural complexity above the proposed detachment horizon, although resolution of continuous, discrete structures is hampered by poor seismic resolution above 0.8 s TWT (Figs. 7–9). Nevertheless, this stratigraphic horizon commonly shows localized shear strain in the Kittatinny Valley whereas other wedge faults and folds affect the entire Cambrian–Ordovician cover sequence (Herman and Monteverde, 1989).

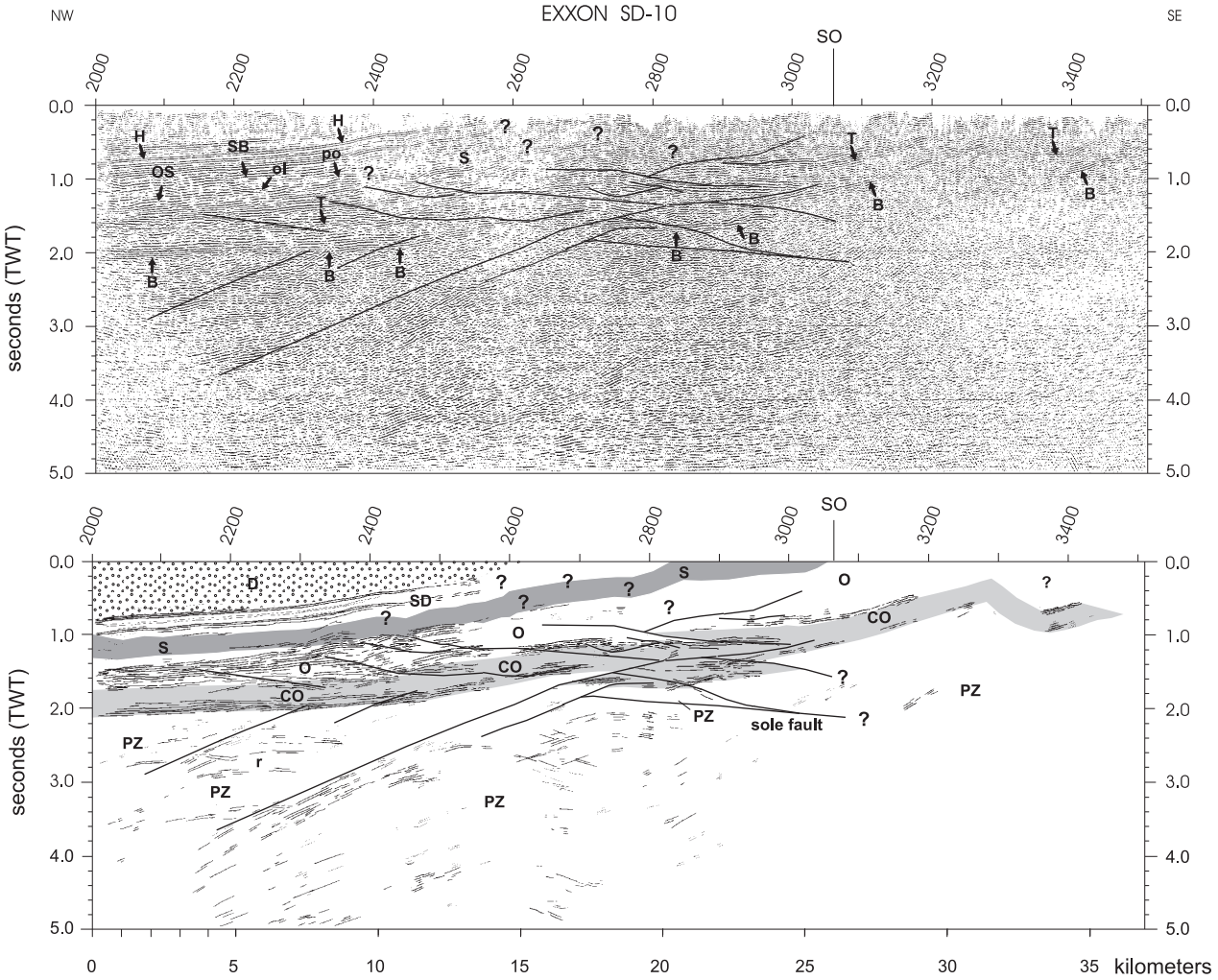

Figure 7. Exxon seismic-reflection profile SD-10. TWT—two-way traveltime. Geologic interpretations are shown for both the migrated, full display (top) and the conventional line drawing of the unmigrated profile (bottom). PZ—Proterozoic, CO—Cambrian–Ordovician carbonates, O—Ordovician flysch, S—Silurian molasse, SD—Silurian–Devonian undivided, D—Devonian undivided. Reflection horizons H, SB, OS, T, and B correspond to the seismic unit boundaries shown in Table 1. r—rollover reflection configuration, ol—onlap reflection configuration, po—pinch out reflection configuration. SO is the map location of the Silurian-Ordovician contact. Heavy lines show faults.

The seismic-reflection data show that the lower Paleozoic cover dips gently northwest from the Valley and Ridge province beneath the Pocono Plateau. This foreland interval developed structural relief from contraction and wedging of basement and cover rocks on a complex system of blind faults that form the foreland boundary of the regional fold-and-thrust belt. Estimates of translation displacement related to blind thrusting beneath the Pocono Plateau ranges upward to 5 km, with strain decreasing northeastward along strike.

PALEOZOIC FOLD-AND-THRUST BELT IN NEW JERSEY

The Paleozoic fold-and-thrust belt in New Jersey consists of abundant low- to moderate-angle reverse faults in lower Paleozoic rocks of the Kittatinny Valley and southwest part of the New Jersey Highlands (Drake and Lyttle, 1980; Herman and Monteverde, 1989; Monteverde et al., 1994; Drake et al., 1994). Elsewhere in the highlands, lower and middle Paleozoic cover rocks generally contain moderately to steeply dipping faults that commonly display complex fault-slip motions resulting from superimposed noncoaxial strain (Ratcliffe, 1980; Hull et al., 1986; Mitchell and Forsythe, 1988; Herman and Monteverde, 1989; Mallizzi and Gates, 1989; Herman and Mitchell, 1991). The Paulins Kill and Jenny Jump–Crooked Swamp thrust belts are in the central and southeast parts of the Kittatinny Valley, respectively (Fig. 11).

The Paulins Kill thrust belt marks the northwest limit of exposed thrust faulting. It consists chiefly of imbricated Cambrian–Ordovician carbonates underlying the Paulins Kill Valley (Fig. 2). Although no basement rocks are mapped at the surface, positive aeromagnetic anomalies directly correlate with the map traces of open and upright cover anticlines, indicating regional basement involvement in both cover folding and thrust faulting (Figs. 11B and 12). Thrust faults mostly dip southeast and are symmetrically arranged behind a central, parautochthonous footwall sequence in the northwest part of the valley (Figs. 2 and 10). Thrust faults terminate laterally into fault-propagation folds in the Martinsburg Formation (Fig. 11A). Northwest of the valley, the Martinsburg Formation dips gently to moderately northwestward, and locally

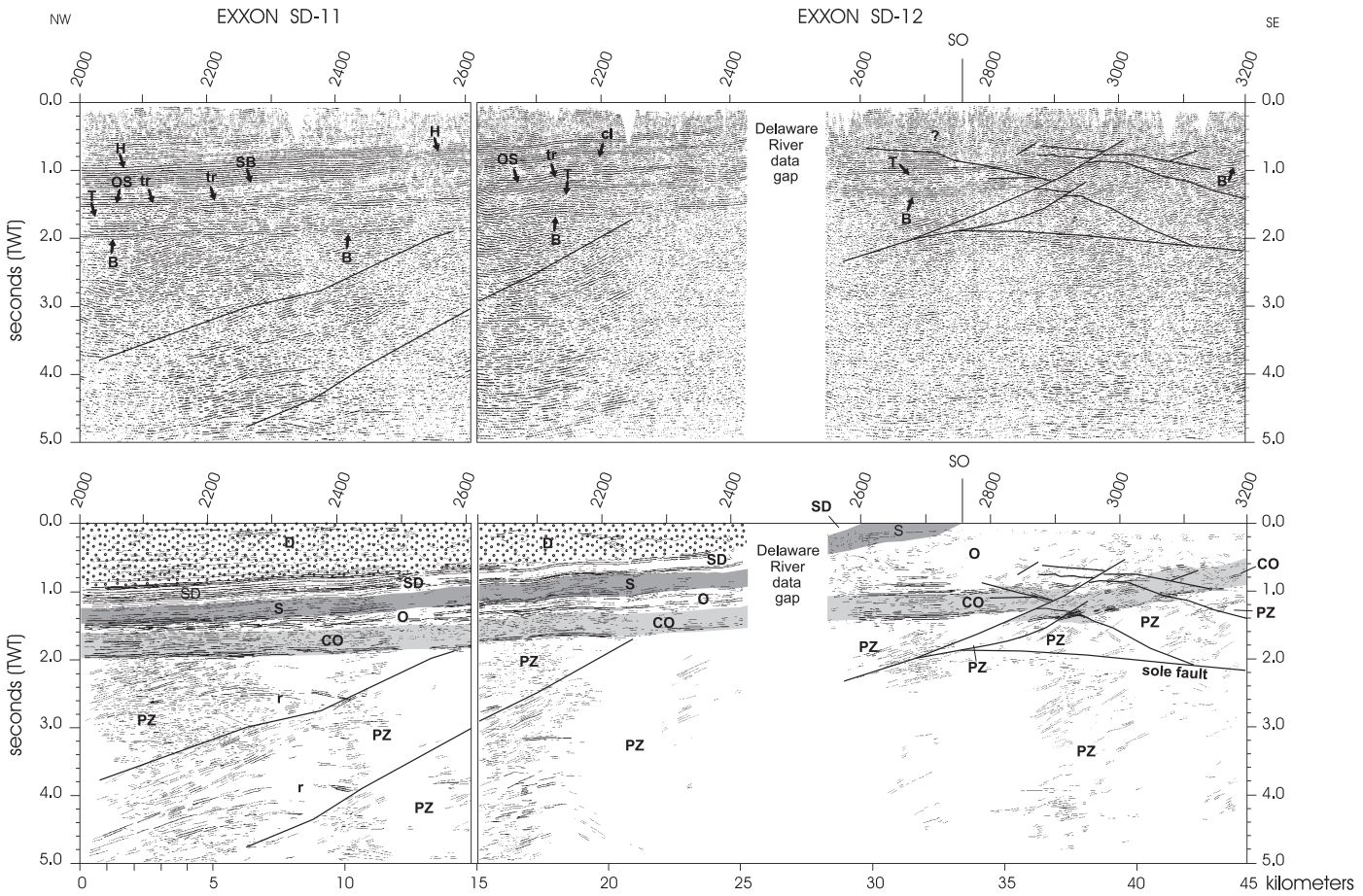

Figure 8. Exxon seismic-reflection profiles SD-11 and SD-12. TWT—two-way traveltime. Geologic interpretations are shown for both the migrated, full-display (top) and the conventional line drawing of the unmigrated profile (bottom). Abbreviations and symbols as in Figure 7, except tr—truncated reflectors, cl—complex layering reflection configuration.

contains upright to steeply inclined folds and pervasive S1 cleavage (Drake et al., 1969, 1985; Epstein and Epstein, 1969; Herman et al., 1994). To the northeast, the Martinsburg Formation contains a system of fold culminations and depressions with fold geometry and cleavage relations similar to those in the Paulins Kill foreland (Herman and Monteverde, 1989; Drake and Monteverde, 1992). The Beemerville carbonatite-alkalic rock complex also underlies parts of this region and locally crops out, most notably near the Taconic unconformity (Maxey, 1976; Ghatge et al., 1992; Drake and Monteverde, 1992; Drake et al., 1994). The Stone Church–Halsey synclinorium borders the Paulins Kill thrust belt to the southeast and the Jenny Jump–Crooked Swamp to the northwest (Fig. 11A). This interval is structurally more complex, commonly showing steeply to gently inclined folds and multiple cleavage sets (Broughton, 1946; Maxwell, 1962; Davis et al., 1967; Epstein and Epstein, 1969; Groshong, 1976; Beutner et al., 1977; Beutner, 1978; Drake, 1969; Drake et al., 1985; Beutner and Diegel, 1985; Drake and Lyttle, 1985; Herman and Monteverde, 1989; Herman et al., 1994).

The Jenny Jump–Crooked Swamp thrust belt exposes Proterozoic basement, lower Paleozoic Cambrian–Ordovician carbonates, and the Ordovician Martinsburg Formation (Fig. 11A). Most of the mapped faults dip southeast and comprise arrays of diverging, connecting, and rejoining splay faults that locally form duplex structures (Herman and Monteverde, 1988; 1989). The imbricate thrust sheets of the Jenny Jump–Crooked Swamp generally plunge northeastward, so that successively higher and presumably older thrust sheets occur in that direction. The relative age of the stacked thrust-fault slices assumes a general break-forward sequence of structural development only for the overthrust phase of deformation. Other wedge faults show apparent "out-of-sequence" structural developments (Morley, 1989), including subsidiary synthetic splay faults and antithetic, break-back thrusts modifying overthrust fault slices. These wedge faults locally delaminated the cover, resulting in a tectonically shortened and a thickened lower Paleozoic sequence. They are common in convergent foreland terrain at widely varying scales (Cloos and Broedel, 1943; Price, 1986). The full range of structures is best represented in the footwall of the Jenny Jump thrust fault, where a series of klippen, mostly composed of lower Paleozoic dolomite, lie within a synformal cleavage fold or "cleavage trough" in the Martinsburg Formation (Fig. 4). The thrust faults that sole the klippen along the foreland margin of the Jenny Jump–Crooked Swamp originated at lower crustal levels and rose to their current structural position near the base of the Martinsburg Formation. The presence of these structures demonstrate the likelihood of blind detachment faults existing at the base of the Martinsburg Formation in adjacent regions (Sanders, 1983). Another set of map-scale cleavage folds occurs in Martinsburg cover immediately foreland of the northeast part of the Paulins Kill thrust belt (Fig. 11A). The structures depicted in the footwall of the Jenny Jump overthrust are probably also developed here.

The boundary interval between the Jenny Jump–Crooked Swamp and the New Jersey Highlands is complex where it involves overthrust faults and

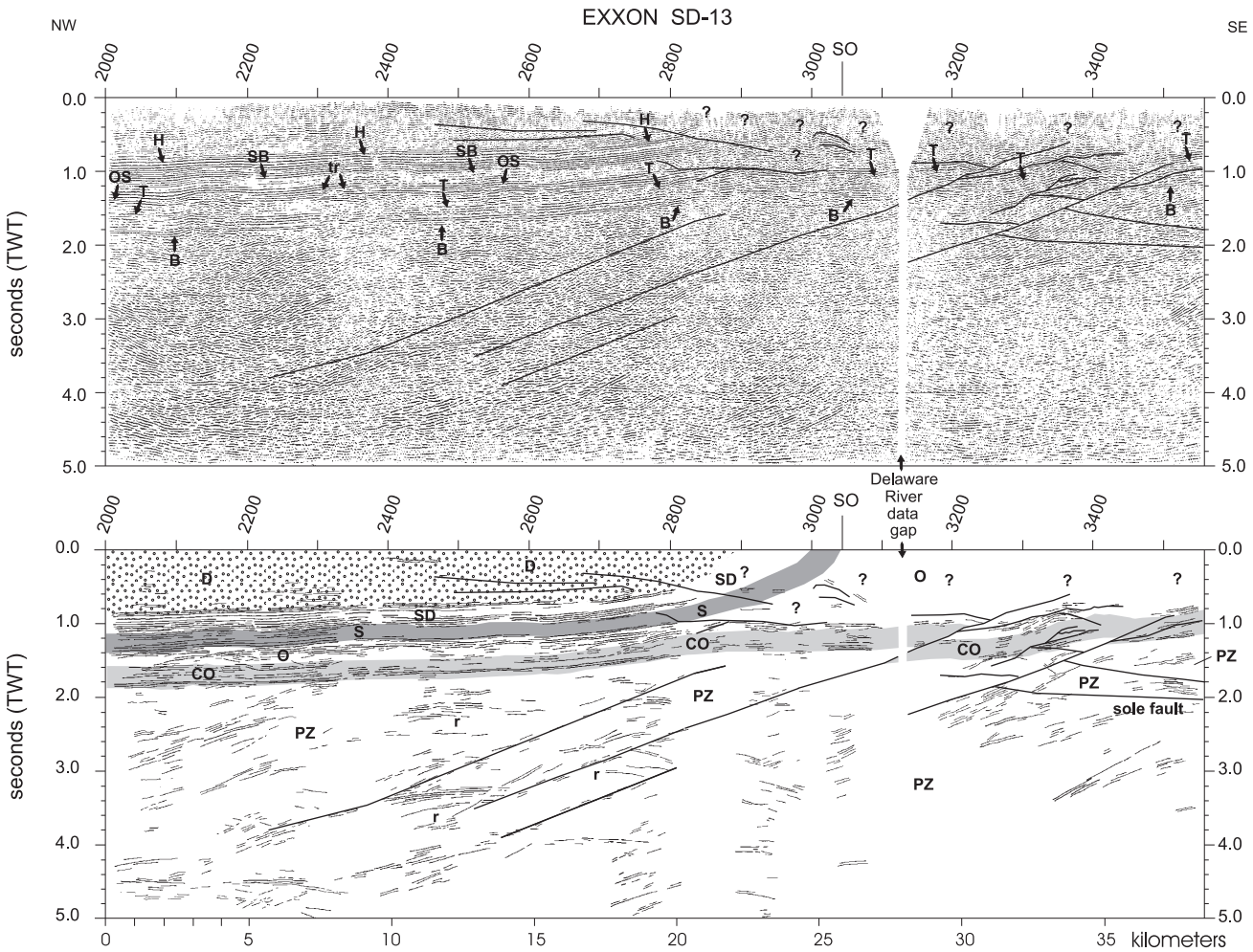

Figure 9. Exxon seismic-reflection profile SD-13. TWT—two-way traveltime. Geologic interpretations are shown for both the migrated, full display (top) and the conventional line drawing of the unmigrated profile (bottom). Abbreviations and symbols as in Figures 7 and 8.

other moderate- to high-angle splay faults that locally juxtapose basement and cover (Figs. 2, 4, 11A, and 12). The overthrust faults are more common in the southwest, whereas the high-angle splay faults are abundant in the northeast. The latter set of faults mostly shows normal dip slip, with basement in the footwall and cover in the hanging wall (southeast end of cross sections E and F in Figs. 11A and 12). Although the thrust faults probably result from Alleghanian tectonism, the more steeply inclined normal faults probably have a complex history that may involve episodic tectonic movements ranging from Proterozoic through Mesozoic time (Hague et al., 1956; Ratcliffe, 1981; Gillespie, 1987).

The southwest part of the New Jersey Highlands contains complex, anastomosing shear zones within basement that locally produce open and upright folds in overlying cover (Fig. 13). The shear zones are similar in geometry and metamorphic grade to ductile deformation zones in basement rocks of the Appalachian Blue Ridge Province, where they occur at a wide range of tectonic scales away from major fault zones (Mitra, 1979; Boyer and Mitra, 1988). Such shear zones produce bulk, noncoaxial, inhomogeneous shortening (Bell, 1981), which is compatible with the variably plunging nature of the overlying fold axes in the cover (Fig. 13). The age of the shear zones and related cover folds is unknown. However, both may stem from early Paleozoic tectonism, on the basis of the regional observation that an early set of cover folds is cut and translated northwestward by later thrust faults (Merchant and Teet, 1954; Herman and Monteverde, 1989). Faults mapped in basement elsewhere in the New Jersey Highlands are commonly steeply inclined and have cataclasite and mylonite fault fabrics that contain retrograde mineral assemblages of pyroxene, amphibole, mica, chlorite, epidote, and quartz (Hull et al., 1986; Mallizi and Gates, 1989; Gates, 1993). These faults also have complex geometry and underwent movements of unknown age.

CROSS-SECTION INTERPRETATIONS

Overthrust faults are most apparent where older rocks overlie younger ones along moderately to gently dipping structural discontinuities. Overthrust faults are less apparent where they have cut through previously folded strata and juxtaposed fold-limb segments, because the resulting map pattern often contains areas showing "out-of-sequence" geometry when compared to simple break-forward thrust-fault relations in flat-lying strata (Figs. 2 and 3 of Morley, 1989). Thrust faults within the Kittatinny Valley, New Jersey, have northwest-verging, gentle- to moderate-dipping tectonites locally preserved in outcrop. Invariably, associated fault traces for "out-of-sequence" structures strike into areas where they show ordinary older over younger structural relations, as for the leading edge and margins of the Crooked

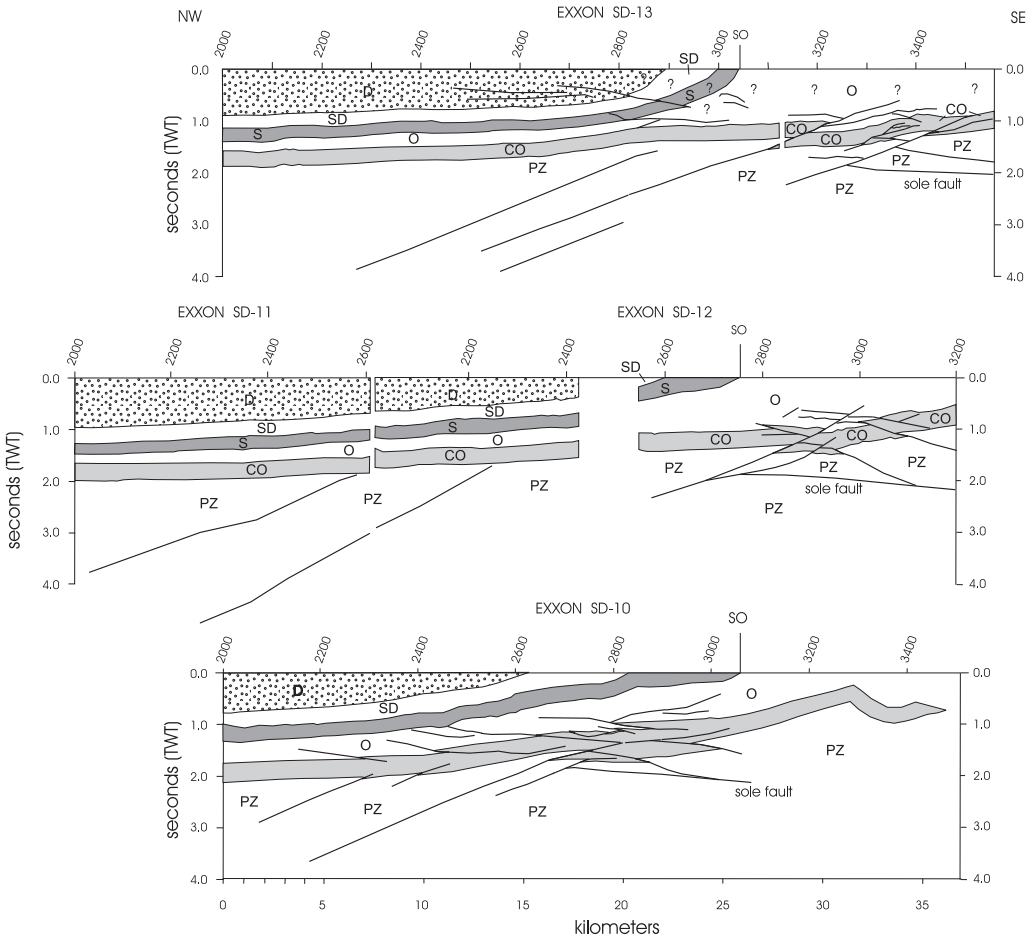

Figure 10. Geologic interpretations of the Exxon seismic-reflection profiles shown in serial arrangement. TWT—two-way traveltime. Profiles are aligned to the map trace of the Taconic unconformity (SO). Abbreviations and symbols as in Figure 7.

Swamp syncline (Figs. 11A and 12). The tectonites are commonly composed of Middle Ordovician Jacksonburg Limestone that contains mesostructures showing high shear strain through subparallel alignment of bedding and spaced cleavage, top-to-the-northwest fold drag, down-dip lineations, and strained fossils locally.

Cross-section analysis of these multiply deformed structures requires at least two stages of palinspastic reconstruction. The first stage removes translation strain and related fold strains (F2) stemming from thrust faulting and requires the construction of blind structures to restore early (F1) cover folds (Fig. 12). Secondary reconstruction models then try to account for other folding strains stemming from F1 sinuosity. Penetrative strains related to intragranular bulk deformation and regional cleavage development need more study before their effects can be integrated into multiple palinspastic reconstructions.

Four regional cross sections are shown for those parts of the fold-and-thrust belt in New Jersey where lower Paleozoic cover rocks are abundant (A, B, C, and D in Fig. 2). The cross sections depict three tectonic stages: (1) present-day structures (Fig. 14); (2) palinspastically reconstructed fault trajectories affecting early (F1) cover folds and subjacent basement (d2 of Fig. 15); and (3) a broadly arched Cambrian–Ordovician passive margin showing convex-upward curvature (d1 of Fig. 15).

All the interpretations show the current position of the sole thrust detachment fault, the location of which is based on regional seismic reflection data (Herman, 1992). Any vertical strains associated with crustal flexure stemming from thermal effects, exhumation, or sedimentary loading are beyond the scope of this paper and require further study.

Tectonic contraction values for the region stem from palinspastic reconstruction of the Cambrian–Ordovician carbonate part of the cover layer. This part of the cover chiefly consists of dolomite, and is stiff in comparison to the overlying Ordovician flysch. This "stiff layer" is assumed to have undergone negligible (<10%) amounts of secondary intragranular bulk strain. Mesoscopic cleavage in the stiff layer is commonly restricted to near-fault intervals and to the hinge regions of F2 folds (Herman et al., 1994).

The cross sections are oriented approximately normal to regional strike to minimize inaccuracy in apparent stratigraphic thickness and to permit evaluation of tectonic contraction strain (Geiser, 1988). Interpretations of both current and F1 structures rely upon standard methods of down-plunge projection for planar and parallel-folded structures (Ragan, 1985; Ramsay and Huber, 1987). The projection of F1 folds is along the bearing and plunge of S0 and S1 intersection lineations, which are based on field measurements. The projection of F2 structures and thrust-fault planes is along the bearing and inclination of S1 and S2 intersection lineations and fault-plane measurements that are available. Apparent-dip values for bedding, cleavage, and fault-dip data are based on the apparent dip calculation of De Paor (1988, equation 9). Structures are interpreted for both the current and restored structures at the same time using trial and error geometric alignment (Woodward et al., 1985).

Fundamental cross-section modeling assumptions include plane strain and the conservation of both volume and the length of cover beds between current and restored cross sections. Plane strain restricts bulk deformation to planes parallel to each section. Finite-strain studies of regional cleavage within the Martinsburg Formation support the use of constant volume and

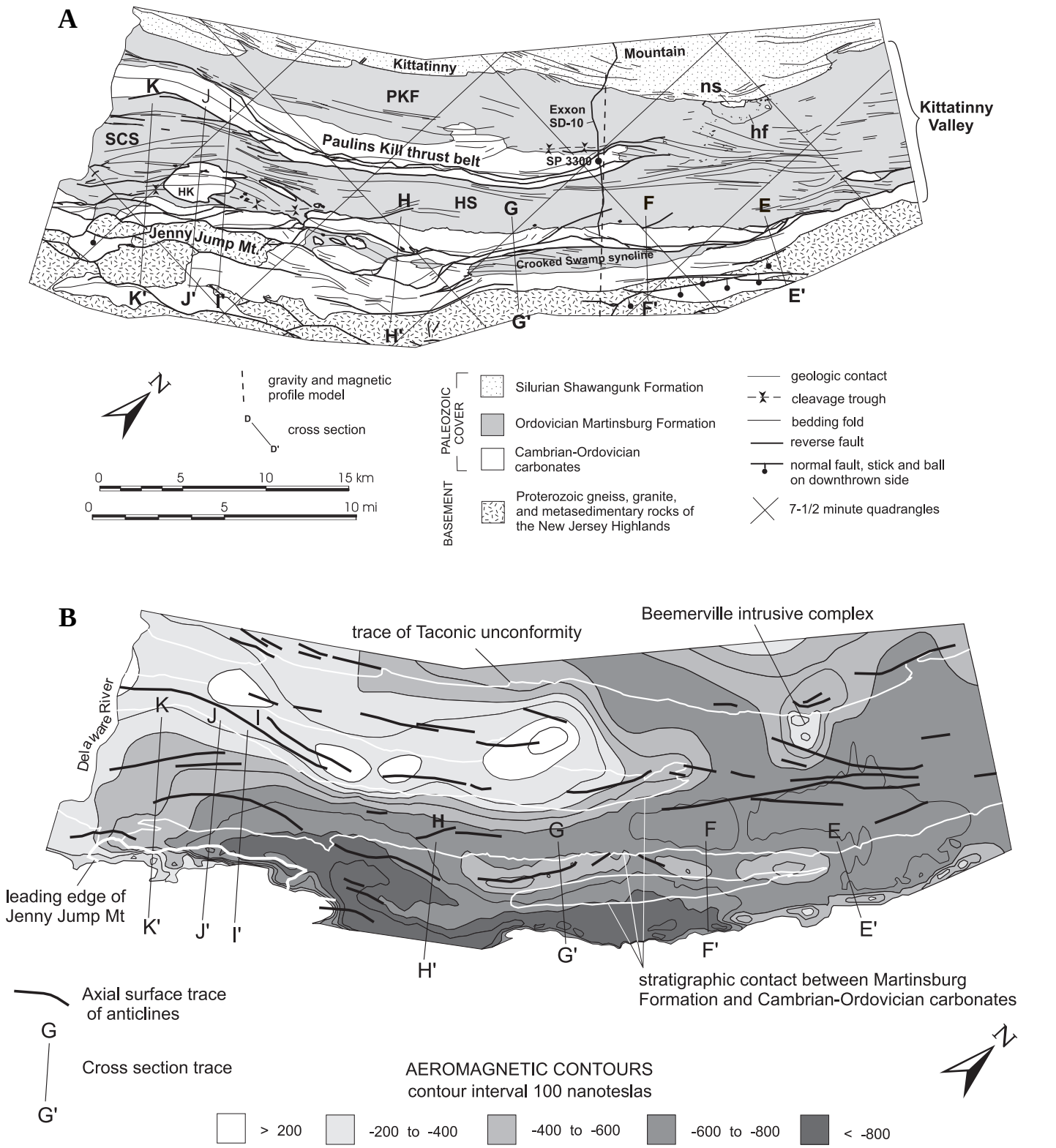

Figure 11 (A) Tectonic map of the Kittatinny Valley, New Jersey. The geology is modified from Herman and Monteverde (1989) and Drake et al. (1994). PKF—Paulins Kill foreland, ns—nepheline syenite, hf—Martinsburg Formation hornfels, HK—Hope klippe, SCS—Stone Church syncline, HS—Halsey syncline. (B) Aeromagnetic map of the Kittatinny Valley, New Jersey. Aeromagnetic data are modified from Snyder (1997).

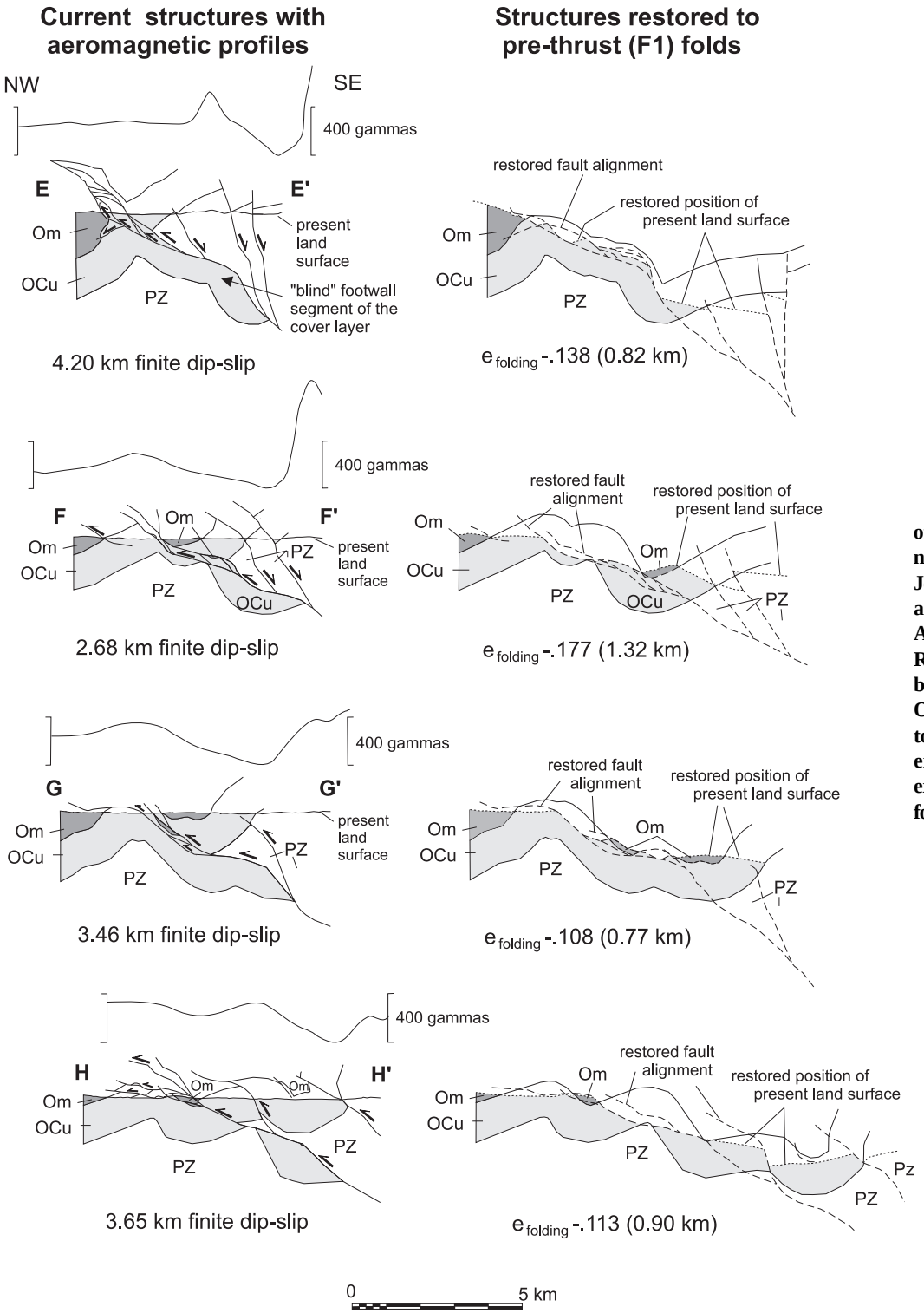

Figure 12. Balanced cross sections of the Crooked Swamp thrust belt, northeast Kittatinny Valley, New Jersey. The locations of the profiles are shown in Figures 2 and 11A. Aeromagnetic data are from LKB Resources (1980). Om—Martinsburg Formation, OCu—Cambrian–Ordovician carbonates and Hardyston Quartzite undivided, PZ—Proterozoic basement undivided, e—extensional strain from pre-thrust folding.

plane strain in the cover (Beutner et al., 1977; Beutner, 1978; Beutner and Diegel, 1985). Out-of-plane deflections at oblique thrust ramps only cause small strain deviations when applying a plane strain assumption (Elliott, 1976; Apotria et al., 1994). Constant bed lengths are maintained between current and retrodeformed structures following the methods of Dahlstrohm (1969) and Boyer and Elliott (1982) only for the Cambrian–Ordovician stiff layer. Penetrative layer-parallel shortening strains in the overlying Jacksonburg Limestone and Martinsburg Formation require special attention for palinspastic reconstruction. Cambrian–Ordovician dolomites commonly contain joints and shear fractures, whereas Middle Ordovician limestone and clastic rocks are more cleaved (Herman et al., 1994). Pervasive, penetrative rock fabrics in the dolomite stiff layer are usually restricted to near

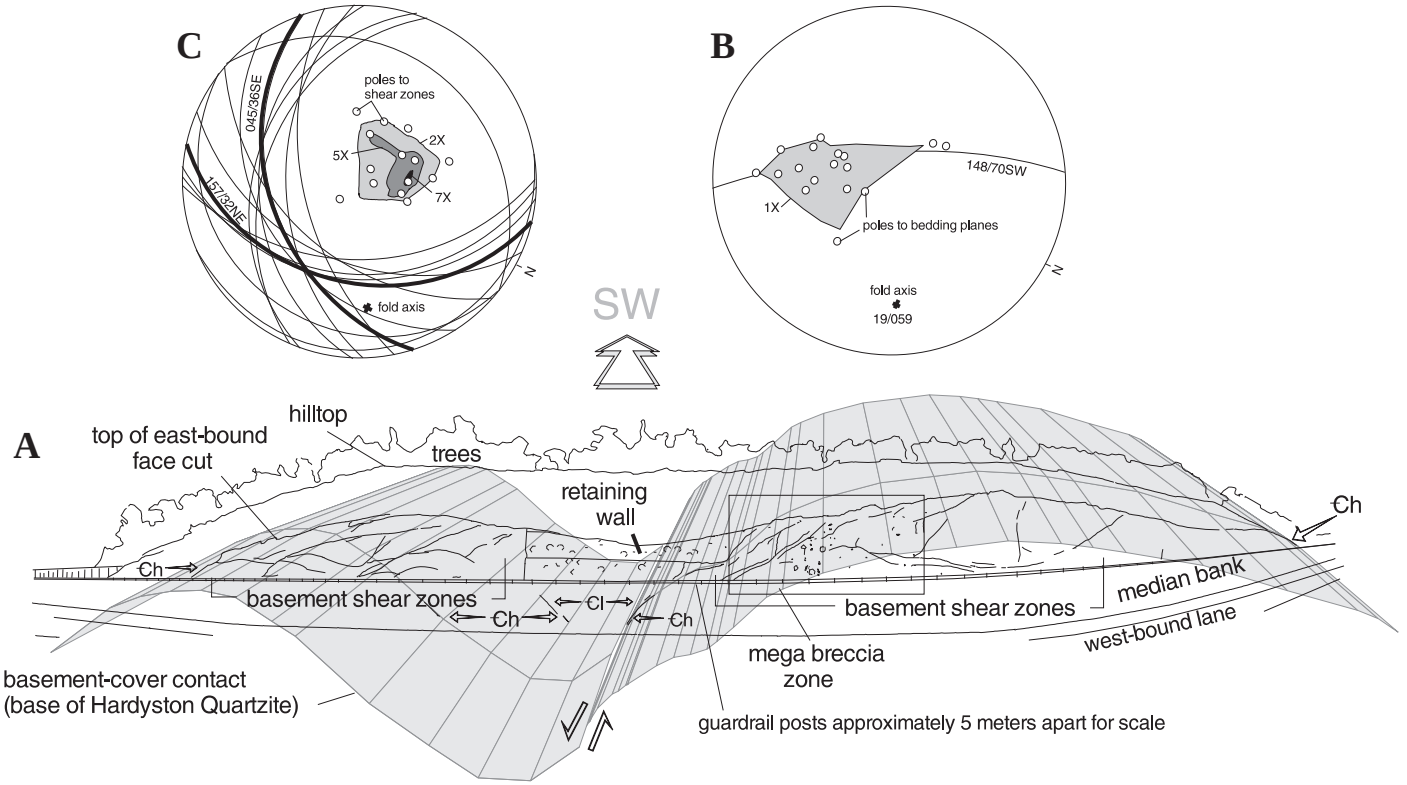

Figure 13. Diagram showing the geometric link between cover-layer folding and basement shear zones at Morgan Hill, Pennsylvania, along the Route 78 road cuts. The location of Morgan Hill is shown in Figure 2. The similar orientations of the cover-layer fold axis enveloping the northeast end of Morgan Hill (B) and underlying basement shear zones (C) demonstrate their structural link. Lower diagram (A) is a two-and-a-half dimensional rendering of the basement-cover contact, based on six outcrops located with arrows. The basement shear zones are traced in the east-bound face cuts. The stereographic diagrams are lower-hemisphere, equal-angle projections. The cover-layer fold axis is plotted as the pole to 17 great circles for bedding mapped around the termination of Morgan Hill. The intersection maximums of the basement shear zones are shown for 14 planes measured along the base of the east-bound face cut. The structural maxima were determined using a contouring algorithm based on multiples (one, two, five, or seven times) of the average relative density of points (poles) plotted on a spherical surface (Gray and Lewis, 1985).

faults and fold hinges. A modeling assumption was therefore made to equate S2 penetrative strains and fault-propagation fold strains in the Martinsburg Formation to brittle shear strains and fault-bend fold strains in the stiff layer when restoring present structures to a prethrust (d2) configuration. This assumption is supported by the lack of regional detachment faulting at the contact of the stiff layer with overlying shales and slates. Localized shear strains mapped at this horizon are spatially linked to underlying wedge faults in the stiff layer (Herman and Monteverde, 1989; Monteverde et al., 1994). The manner in which penetrative strains from S1 cleavage are treated for palinspastic reconstruction is discussed below.

Other modeling assumptions include using a break-forward sequence of structural development for the largest overthrust faults branching from the sole fault. In addition, second- and third-order cover folds are mapped as F1 structures if their axial-surface traces are cut by overthrust faults or if Middle Ordovician stratigraphic pinchouts, facies changes, and extensive paleokarst development mark these structures (Hobson, 1963; Monteverde and Herman, 1989). F1 structures are generally broad and open in the Kittatinny Valley and become more closed and gently inclined southeastward toward and into the highlands (Herman and Monteverde, 1989). Broad and open F1 cover folds in the Kittatinny Valley show a direct correlation with positive magnetic potential-field anomalies. These trends support the assumption that basement is generally attached to the overlying cover in normal stratigraphic succession, and that cover-layer anticlines are cored by basement rocks with higher magnetic susceptibilities than cover-layer rocks (Telford et al., 1976; Jagel, 1990; Ghatge et al., 1992).

The projection, construction, and restoration of the F1 structures are intricate because of their doubly plunging fold geometry, and because "blind" F1 segments are locally concealed beneath footwall regions of overthrust faults. Complications are few where imbricated thrust sheets compose duplex fault arrays showing hanging-wall and footwall fold segments in adjacent positions (e.g., Fig. 11A between Jenny Jump Mountain and the Crooked Swamp syncline). However, the interpretation of F1 footwall structures is elusive where faults show few or no lateral variations in dip throughout large areas and where erosion has removed a substantial part of the F1 hanging wall. In some cases, the wavelength and extent of the blind F1 footwall sequence are locally constrained with magnetic profiles (Fig. 12), or by use of a "minimum fold solution" for sections lacking useful magnetic data. In this case, restored F1 fold structures are also constrained by the fold geometry of the hanging wall. For example, the duplex thrust structure shown in Figure 12 (E–E′) retrodeforms to a F1 anticlinorium with a southeast-dipping fold limb. Because the aeromagnetic data for this area are ambiguous compared to the southwest, only a single syncline is required for the blind footwall segment to complete a F1 fold structure. More complicated reconstruction can be developed using additional fold

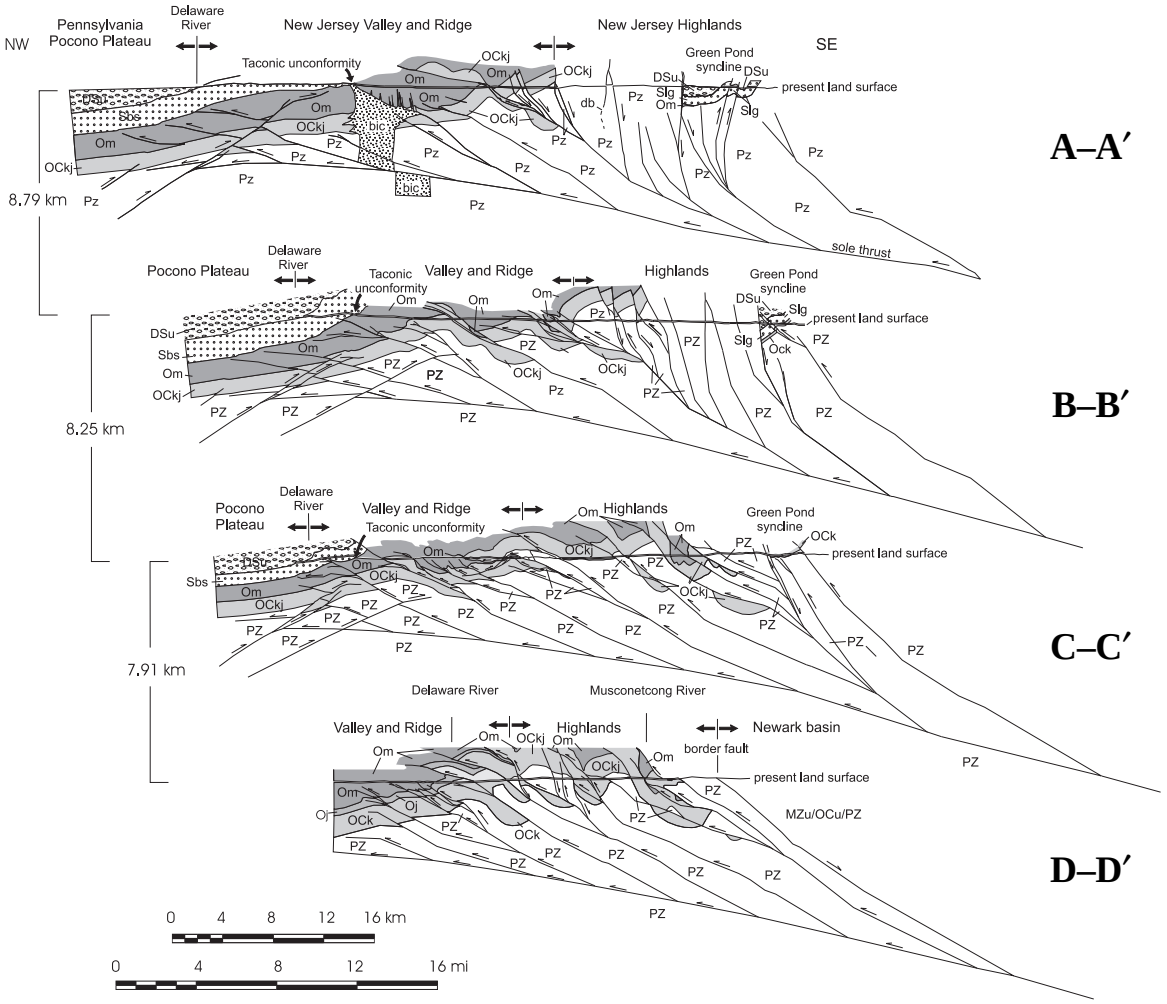

Figure 14. Present-day cross sections A–A′ to D–D′ in the foreland region of the New York recess. Structures are area and line-length balanced with respect to earlier structures shown restored in Figure 15. The locations of the cross sections are shown in Figures 1 and 2. DSu—Devonian and Silurian undivided. Sbs—Silurian Bloomsburg Red Beds and Shawangunk Formation. Slg—Silurian Longwood Shale and Green Pond Conglomerate. Om—Ordovician Martinsburg Formation, Oj—Jacksonburg Limestone (section D–D′ only). OCkj—Ordovician Jacksonburg Limestone, Cambrian–Ordovician Kittatinny Supergroup, and Cambrian Hardyston Quartzite. PZ—Proterozoic basement. bic—Beemerville intrusive complex. db—diabase dike. MZu/OCu/PZ—undivided Mesozoic, Paleozoic, and Proterozoic rocks southeast of the Newark basin border fault.

pairs, as long as thrust translation strains between adjacent, serial sections demonstrate uniformity (e.g., Fig. 12, sections F–F′, G–G′, and H–H′). This technique commonly results in a geometric solution resulting in minimal thrust-translation values. The final geometry of "blind" F1 structures is refined by simultaneous adjustment of bed lengths, profile areas, and bedding and fault cut-off geometry between current and restored sections (Woodward et al., 1985). The interpretation of "blind" folds also assumes geometric similarity with exposed structures, because they occur in the same tectonic environment, consist of the same lithologic units, and belong to the same structural family (Woodward et al., 1985).

F2 cover folds include fault-bend, fault-propagation, and drag folds. Fault-bend folds are most widespread in the Cambrian–Ordovician stiff layer, where they are relatively broad and smooth in contrast to the sharper, kink-style fault bends described for fault trajectories in flat-lying sedimentary wedges (Rich, 1934; Suppe, 1983). The geometry of these folds depends on the trajectory of thrust faults in the cover, which are generally subparallel to inclined limbs and broadly flatten and splay through fold hinges (Figs. 4 and 12). F2 fault-bend folds originate at thrust-fault inflection points and affect all earlier structures in overlying rocks, following the assumption of the break-forward tectonic sequence. Palinspastic F1 structures for the Cambrian–Ordovician stiff layer are restored first and serve as a guide for helping constrain the reconstruction of the overlying Martinsburg Formation. F1 folds are restored by unfolding their limbs by the amount of F2 interlimb angles along the trace of the F2 axial surfaces during simultaneous line-length and area-balancing iterations.

F2 fault-propagation folds are frequently mapped as third- and fourth-order structures in blind-thrust Martinsburg rocks of the Kittatinny Valley. Palinspastic reconstruction of these structures relies on trial and error alignment of unit contacts while preserving sinuous bed lengths and profile areas between current and restored sections. F2 drag folds are minor structures that primarily occur near the footwall of exposed thrust faults or with swarms of strain-slip cleavage (Herman and Monteverde, 1989). Penetrative strains from drag folding are restricted in occurrence near faults and are ignored because of their relatively small scale.

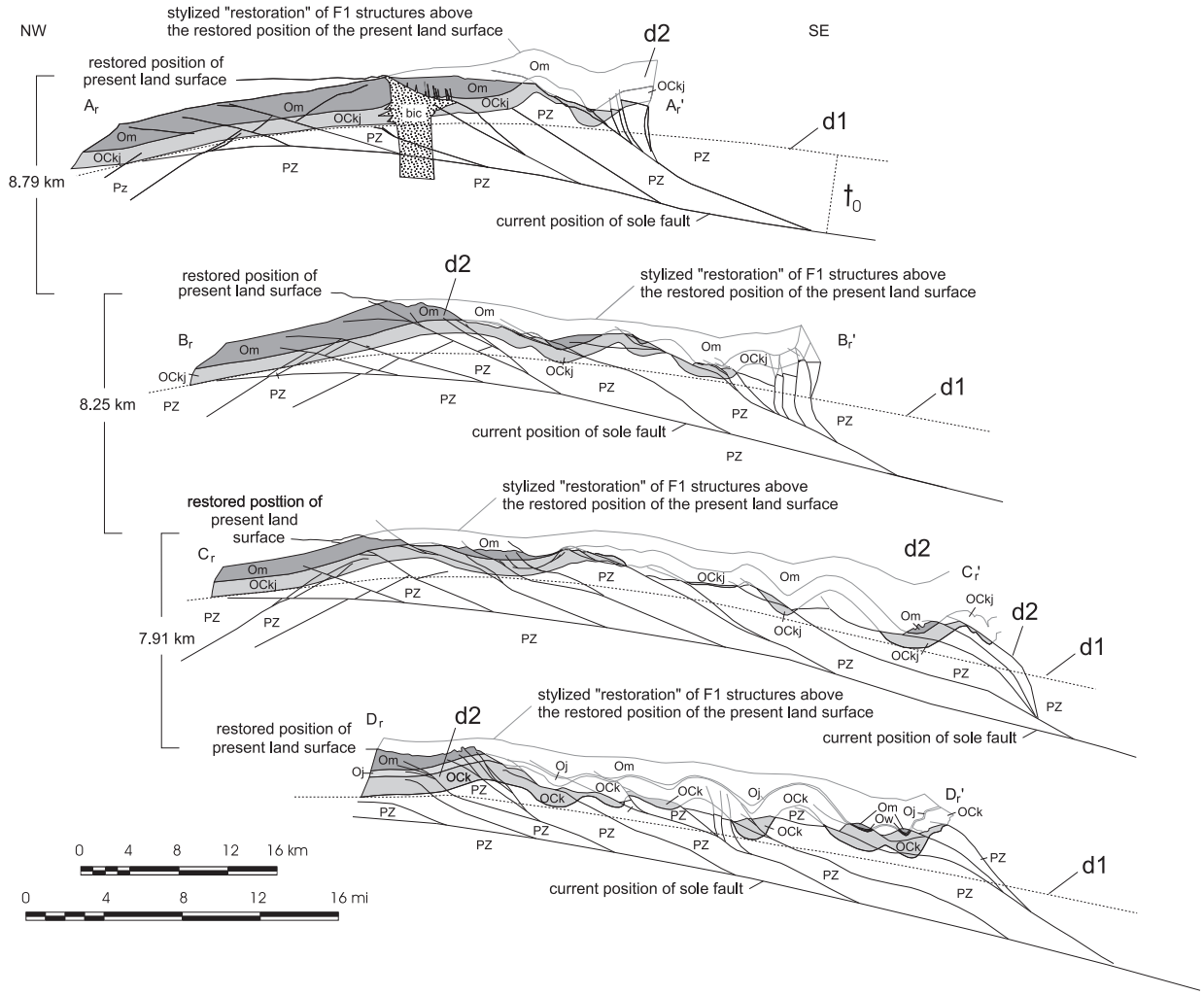

Figure 15. Retrodeformed cross sections Ar–Ar′ to Dr–Dr′ structures (d2 and d1) in the foreland region of the New York recess. The d2 structures reconstruct d3 (Alleghanian) thrust-fault trajectories and related F2 fold and S2 cleavage strains. The d2 structures with F1 cover folds include the finite state of S1 penetrative strains. The d1 structures depict the alignment of the basement-cover contact from which shortening related to F1 folding was calculated. The d1 structures arch upward beneath the keels of F1 synclines and constrain the amount of basement shear strain accompanying F1 cover folding; t_0 is the difference in depth between the sole fault and d1; it decreases in thickness toward the foreland. Rock-unit abbreviations are as in Figure 7, except Oj—Jacksonburg Limestone, Ow—sequence at Wantage.

The final modeling assumption is that cover-layer segments originated from positions of lower structural relief than they currently occupy (Fig. 16). This assumption limits the ways in which faulted fold limbs can be reconstructed in the absence of having a standard planar reference for reconstruction (such as the passive-margin wedge). Many restored alignments are still possible for adjacent segments of cover folds after applying the structural-relief assumption. However, palinspastic alignment of F1 structures is further constrained by limiting the profile thickness of basement within a thrust sheet to the interpreted thickness between the upper (basement-cover contact) and lower (sole thrust) boundaries (t_0 in Fig. 16).

Tectonic aspects of the regional cross-section interpretations are presented in Table 2. The strain values are partitioned into strain components that include (1) horizontal foreland contraction from thrust translation, (2) the cross-section contraction ratio, and (3) negative extension from prethrust folding. The translation strain for each section is measured linearly, from the most hinterland basement-cover cutoff that shows reverse displacement between the current and restored positions in a horizontal plane relative to the erosion surface. The folding strain values are sinuous bed lengths along the basement-cover contact in the restoration diagrams and do not include penetrative volume-loss strains. The 8°–11° range of wedge taper values for the current sections is close to that of other subaerial accretionary wedges (Davis et al., 1983).

Other geophysical and structural data support these current interpretations. Calculated gravity and magnetic models show close agreement with the geometry of the thrust system between cross sections A–A′ and B–B′ (Fig. 17) and define the three-dimensional geometry of the Beemerville intrusive complex in the northeast Kittatinny Valley (Jagel, 1990; Ghatge et al., 1992). The intrusive complex is shown in cross section A–A′ as having been translated northwestward by Alleghanian thrust faults (Fig. 16). Spink (1967) proposed that the intrusive complex acted as a tectonic buffer, because stratigraphic contacts and fold axes are systematically deflected around it. The Paulins Kill thrust belt has a fault-displacement-length scal-

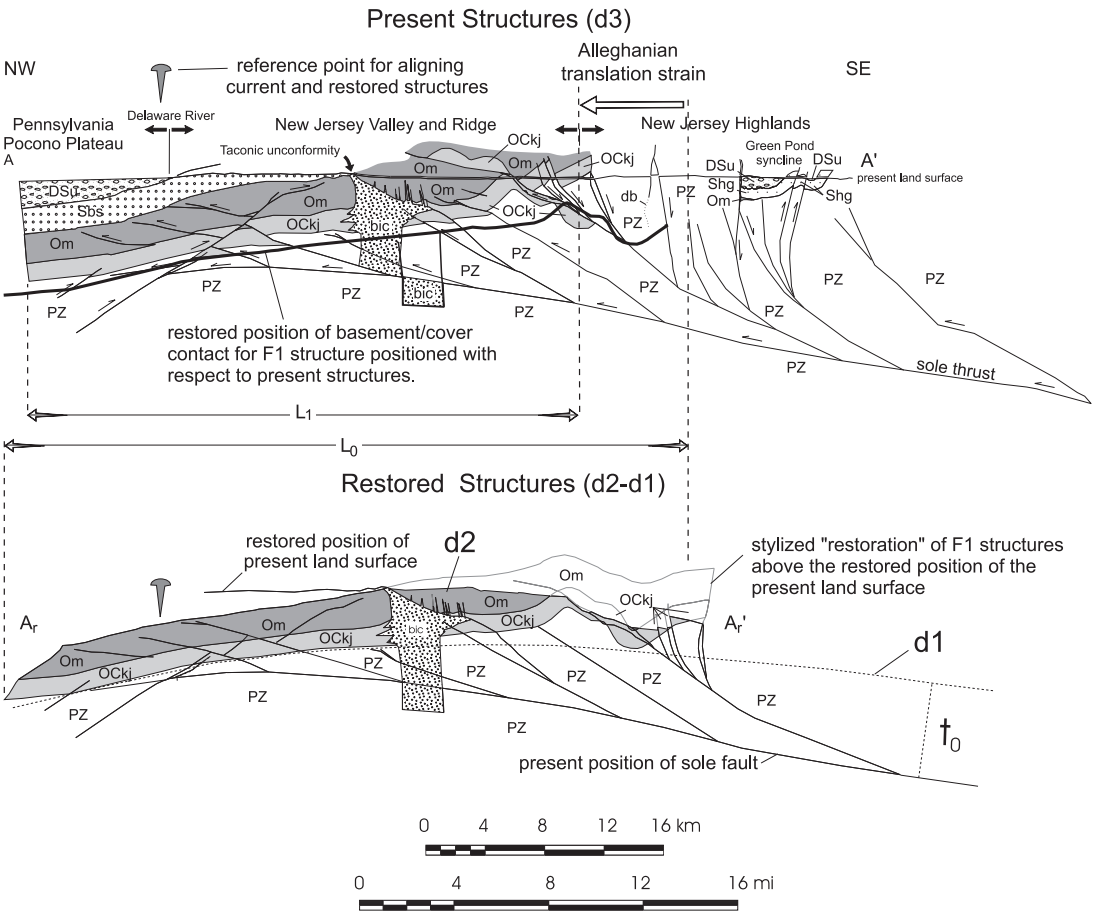

Figure 16. Cross section A–A′ showing present-day and retrodeformed structures and the methods for deriving tectonic dimensions (see Table 2). The d2 position of the basement cover is shown superimposed on d3 (upper figure) to illustrate the structural-relief modeling assumption explained in the text. Rock-unit abbreviations are as in Figure 7.

TABLE 2. TECTONIC DIMENSIONS OF REGIONAL CROSS SECTIONS

Cross section	Minimum foreland translation (km)	Minimum contraction ratio (L_1/L_0)	e (F1) [km]	Wedge taper angle
A–A′	7.3	0.80	–0.05 [1.6]	8°
B–B′	13.8	0.71	–0.08 [2.8]	8°
C–C′	21.8	0.64	–0.04 [1.6]	11°
D–D′	20.9	0.58	–0.11 [5.5]	11°

L_1 = current length, L_0 = restored length, e = extension.

ing ratio of 1:14, or about 7%, which agrees closely with values for other fold-and-thrust belts (Boyer and Elliott, 1982). Length-displacement scaling ratios for the Jenny Jump–Crooked Swamp and fault systems in the New Jersey Highlands are more difficult to determine because faults extend into adjacent areas that have not been mapped in detail, and fault systems having many branching faults are awkward to process for determination of fault-scaling ratios (Elliott, 1976). Nevertheless, an estimate of the fault-displacement scaling ratio for the Jenny Jump–Crooked Swamp was made to test the results of constructing "blind" cover-layer folds that satisfy the "minimal thrust-translation" assumption. The estimated scaling ratio was derived by substituting the strike length of the Cambrian–Ordovician carbonates in the thrust belt (Fig. 1) for the fault-length value. This substitution is used because the length of Cambrian–Ordovician carbonate outcrops in the Paulins Kill thrust belt is approximately the same as the map trace of fault outcrops (Fig. 11A). This approach produces an estimated scaling ratio of 1:19 (about 5%) for the Jenny Jump–Crooked Swamp. This ratio is about 2% lower than the ratio for Paulin Kill thrust belt, suggesting that translation strain reported for the Jenny Jump–Crooked Swamp may be slightly underestimated, and blind cover folds may extend a few kilometers beyond those shown in cross section. This also suggests that the length of the outcrop belt may only be used to constrain the order of magnitude for regional fault-translation values, and is probably not an accurate substitute for fault length when determining length-displacement scaling ratios for a regional fault system.

DISCUSSION

The regional fault system is portrayed here as a subaerial accretionary wedge with a basal detachment entirely contained in basement (Fig. 18). Mapped faults in the New Jersey foreland are shown here to be linked to blind faults beneath the Pocono Plateau. The relative lack of structural relief beneath the plateau or its foreland restricts the origin of any structures that could accommodate regional allochthonous transport to the mapped fold-and-thrust belt. Balanced cross sections of the fold-and-thrust belt show that

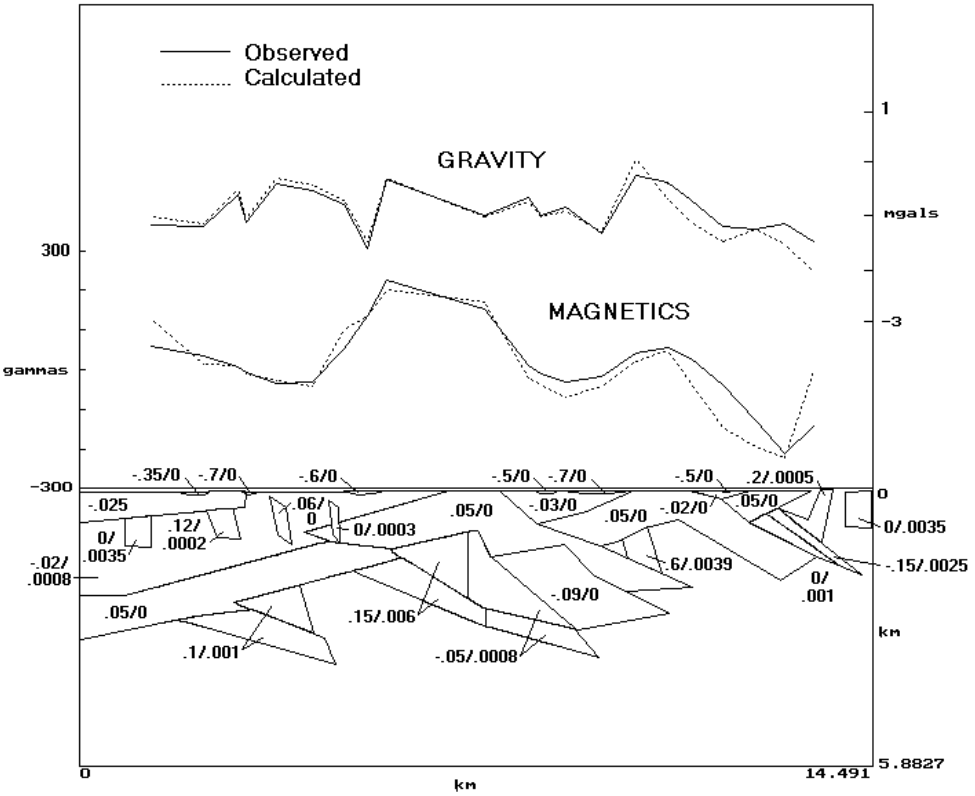

Figure 17. Bouguer gravity anomaly and total intensity magnetic anomaly model for the north-central part of the Kittatinny Valley, New Jersey. Location of the profile is shown in Figure 11A. Observed gravity and magnetic data are from Jagel (1990) and Ghatge et al. (1992). Bouguer residual values are derived from the regional gravity gradient of Jagel (1990). Calculated anomalies are based on two-dimensional, nonlinear, least-squares inversion modeling using commercial software. Polygon-model values are shown with density-contrast and magnetic-susceptibility model values (e.g., –0.35/0.00020). Density contrasts are shown in grams per cubic centimeter relative to an average model density value of 2.67 g/cm^3.

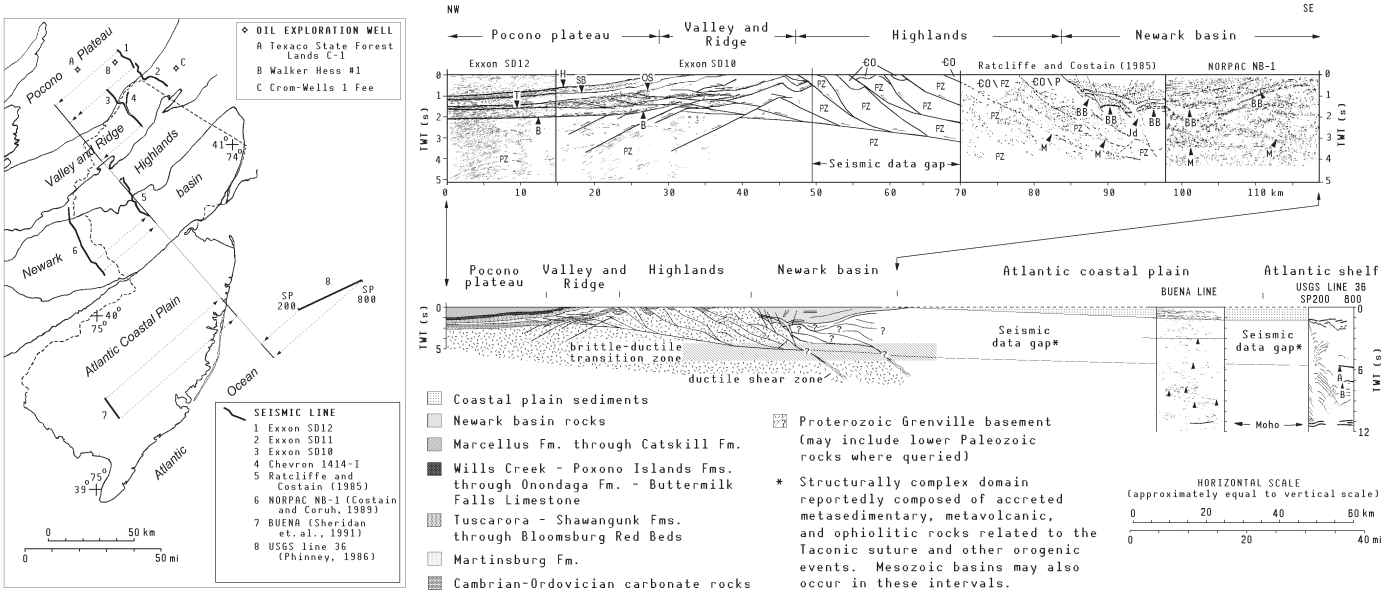

Figure 18. Physiographic-province map and schematic regional cross section of the New York recess modified from Herman (1992). Line drawings from seismic-reflection data are composited northwest of the Atlantic Coastal Plain. Lines of profile projection are shown on the map. Regional cross section shows current data gaps for seismic-reflection database and the location of the brittle-ductile transition based on normal geothermal gradients (Sibson, 1977). Abbreviations are as in Table 1; BB—bottom of the Newark basin, Jd—Jurassic diabase, M—mylonitic fault zone, PZ—Proterozoic basement.

cover rocks occur as localized, segmented fold sequences in the footwall of subsidiary splay thrusts that are soled in Proterozoic basement. Moderate-dipping reverse faults mapped at the surface in the New Jersey Highlands presumably correspond to Paleozoic faults rooted in basement as interpreted from regional seismic-reflection data (Fig. 18). These findings demonstrate that prior allochthonous interpretations for this region depicting hundreds of kilometers of translation strain accommodated by foreland structures (Drake, 1978, 1980; Lyttle and Epstein, 1986; Hatcher et al., 1990) are geometrically improbable. The foreland structure depicted here restricted the involvement of lower Paleozoic rocks to occurring within subsidiary fault slices splayed from a master decollement rooted in Proterozoic basement. This reinterpretation does not preclude allochthonous transport from occurring elsewhere in comparable rocks along strike. It defines a region marked by parautochthonous tectonic contraction in the foreland with more allochthonous roots preserved along the margin and beneath the New Jersey Piedmont. This interpretation points to the need for more work to be conducted in adjacent regions to understand how the allochthonous and parautochthonous regions merge or overlap.

These cross sections depict a set of consecutive structural stages for the upper crust. The uncertainty of the interpretations increases with each palinspastic step and with higher degrees of cover-layer erosion. Near-surface structures are considered most accurate, followed by deeper structures mapped on the basis of seismic-reflection and deep-well data. Other parts of the overall section are based on the extrapolation of variably plunging surface structures, and therefore show one of several possible geometric arrangements that are kinematically admissible. These structures depicted in cross section are the preferred interpretation because they agree with observed seismic-reflection, well-bore, gravity, and magnetic data. However, many interpretive aspects of this model remain unresolved. For example, reconstructed d2 structures assume basement-rooted structural relief prior to Alleghanian thrust faulting. However, it is unclear to what extent cover folds and associated basement deformation occurred in the foreland during the Taconic orogeny, except along the Taconic unconformity and the central part of the Green Pond syncline. It is also unclear how the shear zones from the early tectonic episode relate to later tectonic stages. Shear zones that are assumed to have produced F1 cover folds are not well exposed in the New Jersey Highlands and are therefore poorly understood and omitted in all the cross sections. However, shear zones of the type mapped at Morgan Hill (Fig. 13) may also produce Paleozoic antiforms and synforms in Proterozoic basement where its foliation occurs subparallel to cover bedding before shearing. This helps explain why many open and upright basement folds in the southwest part of the New Jersey Highlands show subparallel alignment with nearby cover folds (Monteverde et al., 1994). The geometric link between cover folding and basement shearing needs to be more closely examined and may lead to reinterpreted ages for many of the folds mapped in Proterozoic basement.

The geometry of F1 folds in d2 reconstructions is based on a restored Cambrian–Ordovician stiff layer and only stylize restored d2 structures for the Martinsburg Formation. The cross sections are derived using spatial constraints and do not address many incremental strains accumulated in the crust. As many as five incremental strains generally require consideration for finite strain analysis of faulted and folded rocks (Beutner, 1978). The palinspastic reconstruction of d2 structures is straightforward for the stiff layer and addresses tectonic compaction and limb rotation, and assumes negligible penetrative strains from S2 cleavage. The d2 structures in the "stiff layer" reflect the finite state of other prethrust incremental strains stemming from sedimentary compaction and pre-cleavage and S1 layer-parallel shortening. Incremental S1 penetrative strains are difficult to account for because they display spatial variability in both the tectonic transport direction and vertically with the cover. S1 may have formed first in more hinterland parts of the region during the Taconic orogeny and developed into the foreland through the Kittatinny Valley during Alleghanian thrust faulting (Drake and Lyttle, 1980). Slaty S1 cleavage in the Bushkill Member claystone is more pervasive than spaced S1 pressure-solution cleavage in overlying graywacke and sandstone of the Ramseyburg and High Point Members. The relative abundance of S1 lower in the formation may indicate the dispersion of strain upward into the Martinsburg in response to underlying contraction faults, resulting in localized thrust faulting and concentrated shear strain at the base of this sequence (Fig. 10). This strain profile is consistent with having upward-diverging cleavage geometry in the hinge of the Stone Church syncline (Fig. 14).

S1 is sparse in Martinsburg Formation hornfels near the Beemerville intrusive complex in the northeast Kittatinny Valley (Drake and Monteverde, 1992) and at places along the Taconic unconformity. Therefore, it is inappropriate to use an average regional value of about 50% (Beutner et al., 1977; Beutner, 1978; Wright and Platt, 1982) of compressive (shortening) strain when palinspastically accounting for S1 penetrative layer-parallel shortening strains throughout the region. Localized variations in S1 shortening probably span a range of values reported throughout the central Appalachians (7%, Wright and Platt [1982] to 75%, Sherwin and Chapple [1968]). The d2 structures for those areas where Martinsburg Formation occurs therefore include the finite state of most S1 penetrative strains, because line lengths and layer thicknesses were retained during section balancing.

In the highlands regions where most of the cover has been eroded or overthrust, d2 cover structures are stylized to depict an Ordovician foredeep developed over a rumpled lower Paleozoic shelf (Fig. 15). These methods and assumptions result in a d2 reconstruction portraying cover structures just prior to thrust fault movement, and therefore only serve to constrain the geometric admissibility of present structures by helping ensure that individual thrust sheets fit together in a kinematically admissible manner. We do not intend d2 structures to portray the continental margin at a specific time, because thrust systems typically develop incrementally through time as they break forward.

The d1 structures depict the lower Paleozoic carbonate shelf as arching broadly upward. This alignment partly stems from the d2 structures retaining a northwestward inclination relative to the position of the sole fault after accounting for d3 fold-and-thrust–translation strains. The d1 arching also stems from extrapolating the restored position of the foreland sequence southeastward beneath the keels of the d2 synclines in conformance with the structural-relief modeling assumption. More work is needed to determine if this positive crustal flexure is a geometric artifact of imposed modeling constraints or if this flexure approximates the architecture of the early Paleozoic peripheral bulge that probably marked this region.

CONCLUSIONS

This work demonstrates that the northwestern margin of the New York recess contains a parautochthonous thrust system of Paleozoic age composed of Proterozoic basement through middle Paleozoic cover. The regional thrust system is probably soled by a master fault within basement rocks. Likely estimates of foreland orogenic contraction for those areas currently underlain by Paleozoic cover range from about 30 km in the southwest to about 10 km in the northeast. Tectonic contraction in the foreland stemming from the Alleghanian thrust faulting dies out rapidly northeastward from the Pennsylvania salient into the New York recess. This strain gradient was accompanied by progressive steepening of basement faults northeastward along strike in the New Jersey Highlands and a concomitant transition from foreland-directed thrusting in the Valley and Ridge to crustal transpression in the highlands. The partitioning of bulk strain between the Taconic and Alleghany orogenies varies in the region; proportionately higher Taconic

strains are recorded in directions toward the map traces of the Taconic allochthons. Tectonic strain in the Kittatinny Valley (Appalachian Great Valley) attributed to the Taconic orogeny is minimal, whereas most strains probably stem from Alleghanian processes. More work is needed, including measuring incremental strains related to S1 with respect to both lithology and structural position, to gain a better understanding of the palinspastic geometry of the Ordovician foredeep and the Taconic foreland.

ACKNOWLEDGMENTS

This work represents part of a group effort in updating the geologic interpretations for the New Jersey region. Most of the data are compiled on 1:24,000 to 1:100,000 scale maps by COGEOMAP (1985–1990) participants from the New Jersey Geological Survey and the U.S. Geological Survey. We thank the staff of the New Jersey Geological Survey for providing data and technical support for this research. This study benefited from field investigations and exchanges of ideas on central Appalachian tectonics with Jack Epstein, Nick Ratcliffe, Peter Lyttle, Ronald Parker, Avery Drake of the U.S. Geological Survey, and the Appalachian tectonics study group. We also thank Richard Nickelson, Steven Boyer, Gautum Mitra, Stephen Marshak, Robert Sheridan, and Michael Carr for their manuscript reviews.

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Manuscript Received by the Society February 2, 1996
Revised Manuscript Received September 16, 1996
Manuscript Accepted January 11, 1997

Printed in U.S.A.