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Megaboudins and lateral extension along the leading edge of a crystalline thrust sheet, Hudson Highlands, New York, U.S.A.

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Abstract—Megascopic lenses of crystalline rock along the leading edge of the Hudson Highland thrust sheet, New York, are boudins that formed as the result of lateral extension during Late Paleozoic compression. These 'megaboudins' range from 50 m on each side to 1.2 × 3.2 km and form a NE-trending chain along the northwest side of the Green Pond outlier and Hudson Highlands. The crystalline Hudson Highlands were first thrust northwestward onto shales and siltstones of the Martinsburg Formation during the Middle Ordovician Taconian Orogeny, and later eroded leaving a NE-trending elongate klippe along the leading edge. During subsequent compression, the klippe was laterally extended into a chain of fracture boudins with $\lambda = 3.3$. The cleavage and bedding in the surrounding shales and siltstones wraps around the boudins and into the boudin gaps. The cleavage and bedding wrap through 61–114° forming shallow to moderately NE-plunging fold axes on the northeast side of the gaps and shallow to moderately SE-plunging fold axes on the southeast side of the gaps. Strike-slip shear indicators at the boudin corners support the mass movement of shale and siltstone. In the wider boudin gaps, conjugate NW-striking normal faults form cross-strike grabens that juxtapose overlying Silurian strata into the gap areas. Fragments of brecciated gneiss from the boudins are also transported into the gap areas along these cross-strike normal faults. The boudins, dextral strike-slip stretching faults along the southeastern margin of the boudins, and asymmetric gap fill geometries are prime criteria for the recognition and characterization of lateral stretching in contractional fold and thrust belts. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

Tectonic lenses on the scale of kilometers have been interpreted as megaboudins in such environments as subduction complexes (Cowan 1985) and the metamorphic core complexes of the southwestern United States (Davis & Coney 1979, Davis 1980). Such associations are expected because these environments are characterized by fragmentation of units and extension of units respectively. On the other hand, foreland fold and thrust belts are considered to undergo largely shortening, and large scale stretching features like boudins would be less likely (Boyer & Elliott 1982). Woodward *et al.* (1988) showed that extensional features can occur parallel to compressional features in fold and thrust belts. Extensional features perpendicular to the contractional structures, forming along strike discontinuities, have also been proposed. Many large-scale tectonic lenses in several thrust belts are interpreted as megaboudins by their shape and matrix cleavage pattern. The cleavage in the matrix characteristically wraps around individual boudins and fills the gap area between them. Blocks of Triassic limestone between the upper and lower Austro–Alpine nappes in Switzerland (Trumpy & Trommsdorf 1980) and similar blocks in the external Piedmont zone in France (Tricart & Lemoine 1986) were interpreted as megaboudins. Several examples of lenses were also interpreted as megaboudins in the nappe sequences of the Scandinavian Caledonides (Gee 1978, 1982, Katusky 1978, Rice 1986). Gilotti (1989), however, showed that boudins, horses and augen can all meet these criteria of physical isolation and wrapping of cleavage. Small-scale kinematic analysis around the lens rather than large-scale geometric analysis is required to prove boudinage.

Identification of megaboudins in thrust belts is important for structural analysis and tectonic interpretation. Extensional deformation directed perpendicular to contraction constitutes lateral extension in an otherwise contractional orogen (Burke & Sengor 1986, Merle 1986, Ratschbacher *et al.* 1989, 1991). The amount of lateral stretching during deformation of a thrust belt is significant for strain and mass distributions as well as regional tectonic studies (Ramsay 1967). It could be even more significant for quantitative analysis of fold and thrust belts. For down-plunge projection and balanced cross-sections (Mackin 1950, Dahlstrom 1969, Hossack 1979, Woodward *et al.* 1989), if the lateral expansion is not relatively consistent for all units involved in deformation, there may be differential movement out of the section. These methods assume that all adjacent across strike features after deformation were adjacent prior to deformation.

This study describes a chain of crystalline megalenses along the northwestern edge of the Hudson Highlands massif, New York that were previously interpreted as erosionally separated klippen (Jaffe & Jaffe 1973, 1989). In reinterpreting these structures as boudins, the existing criteria for the recognition of large-scale boudinage are reviewed and new criteria are proposed to document the processes and determine the sequence of structures in the formation of megaboudins. Criteria for recognizing and evaluating lateral extension in contractional orogens are also proposed.

REGIONAL GEOLOGY

After consolidation, deformation and metamorphism of the Grenville crust, the Reading Prong segment in southern New York was actively involved in subsequent deformation of the Early Paleozoic cover sequence. Intense deformation occurred during the Ordovician Taconian Orogeny when the basement of the Reading Prong was thrust tens of kilometers northwestward on to the shales of the Martinsburg Formation, which acted as a locus for the decollement surface (Rodgers 1971, Drake & Lyttle 1981, Drake 1984). Silurian fluvial molasse deposits (Shawangunk Formation) were shed westward from the mountains over this area subsequent to deformation. The clastic wedge produced by the Silurian–Devonian Acadian Orogeny (Bellvale and Schunemunk Formations) is also well developed in this area, but Acadian deformation did not affect the pre-existing rocks. The Carboniferous–Permian Alleghanian Orogeny caused NW-directed thrusting, local strike-slip faulting and pervasive intense deformation of all rocks in the area (Marshak 1986, Mitchell & Forsythe 1988, Malizzi & Gates 1989). This deformation produced the major folds in the area which comprise the synclinal outlier of Silurian–Devonian strata (Green Pond outlier; Mitchell & Forsythe 1988, Herman & Mitchell 1991) (Fig. 1) and the observable folds in the Valley and Ridge province to the west (Drake & Lyttle 1981). These folds are asymmetric to overturned towards the northwest and are associated with extensive SE-dipping cleavage and NW-directed thrust faults (Offield 1967, Jaffe & Jaffe 1973, Drake & Lyttle 1981). Drake & Lyttle (1981) found that virtually all of the deformation features observed in outcrop were attributable to the Alleghanian Orogeny. Finally, deformation related to a second phase of the Alleghanian Orogeny (Mitchell & Forsythe 1988) or Mesozoic extension (Malizzi & Gates 1989, Gates 1992) occurs in uncommon localized zones as spaced E-striking crenulation cleavage, normal faults, strike-slip faults, and rare N-directed thrust faults.

STRATIGRAPHY

The stratigraphy of the western Hudson Highlands spans Proterozoic through middle Devonian and is complex (Fig. 2). The Proterozoic Grenville gneisses of the Reading Prong have a complex stratigraphy of their own that is subject to debate. The Grenville gneisses in and around the study area include tonalitic and less common granitic gneisses with pyroxene, hornblende and/or biotite, and locally contain scapolite, graphite and/or sphene. Less common rock types include quartzite, sillimanite–K-spar gneiss, meta-anorthosite, and amphibolite (Darton 1894, Offield 1967, Jaffe & Jaffe 1973). All rocks are complexly deformed under conditions of granulite facies metamorphism.

The Paleozoic stratigraphy in the study area is, by comparison, relatively simple. The basal Cambrian Poughquag Quartzite is thin and uncommon. In many cases, the overlying Wappinger Group carbonates (limestone, dolomite, and cherty limestone) lie directly on basement. The overlying Martinsburg Formation (Offield 1967) is Middle Ordovician in age and referred to by several other names within and around the study area (Kothe 1960, Jaffe & Jaffe 1973). The massive shale is interbedded with thin siltstone to medium sandstone layers upward in the section and is capped by a massive gray sandstone (Offield 1967, Jaffe & Jaffe 1973). Although there are several Silurian units to the south, the conglomerate and quartzite of the Shawangunk Formation constitute the only Silurian rocks in the study area. The Devonian section contains many units with complex relations. In the study area on the west side of the Green Pond outlier, only the black carbonaceous Esopus and Cornwall shales and gray Bellvale sandstone are present. To the east and north, many other Devonian units are present.

The multitude of units makes interpreting structural configurations easier because structurally controlled stratigraphic irregularities and even small fault offsets can be identified. On the other hand, the stratigraphy is rheologically simple. Although the Grenville gneisses are complex, they all responded to Paleozoic deformation by jointing and faulting. The overlying thin and discontinuous Poughquag Quartzite apparently behaved the same as the Grenville gneiss; deformation is expressed in faults and joints. The carbonates folded and were cleaved during deformation but more commonly underwent fracturing and veining. The Martinsburg Formation, which is the thickest unit in the area (Offield 1967), is highly incompetent and formed extensive tight to isoclinal folds, shear zones, and slaty cleavage. The Shawangunk Formation deformed by open folding and both ductile and brittle faulting. The Devonian siltstones and shales formed extensive tight to isoclinal folds, shear zones, and slaty cleavage similar to the Martinsburg Formation. The Devonian sandstones deformed largely by faulting, but locally folds and spaced cleavage are well developed. The Devonian units, however, are nowhere in contact with the megalenses (Figs. 1 and 2).

STRUCTURAL GEOLOGY OF THE BASEMENT BLOCKS

The megalenses of Grenville gneiss investigated in this study, form a NE-trending chain along the northwest side of the Green Pond outlier and extend approximately 35 km along strike (Fig. 1). Because of heavy glaciation, the exposure around the margins of the lenses is commonly poor. However, a 12 km-long segment in the central part of the chain is relatively well exposed (Figs. 1 and 2) and the basis for this study. Topographically, these lenses are marked by small hills of 50–100 m elevation in an otherwise relatively flat (± 20 m) terrain. They range from 50 m on each edge to 1.2×3.2 km, with their long axes parallel to the regional strike. There is no discernible pattern to the size of the lenses. The gaps between the lenses are up to 2 km wide with no local

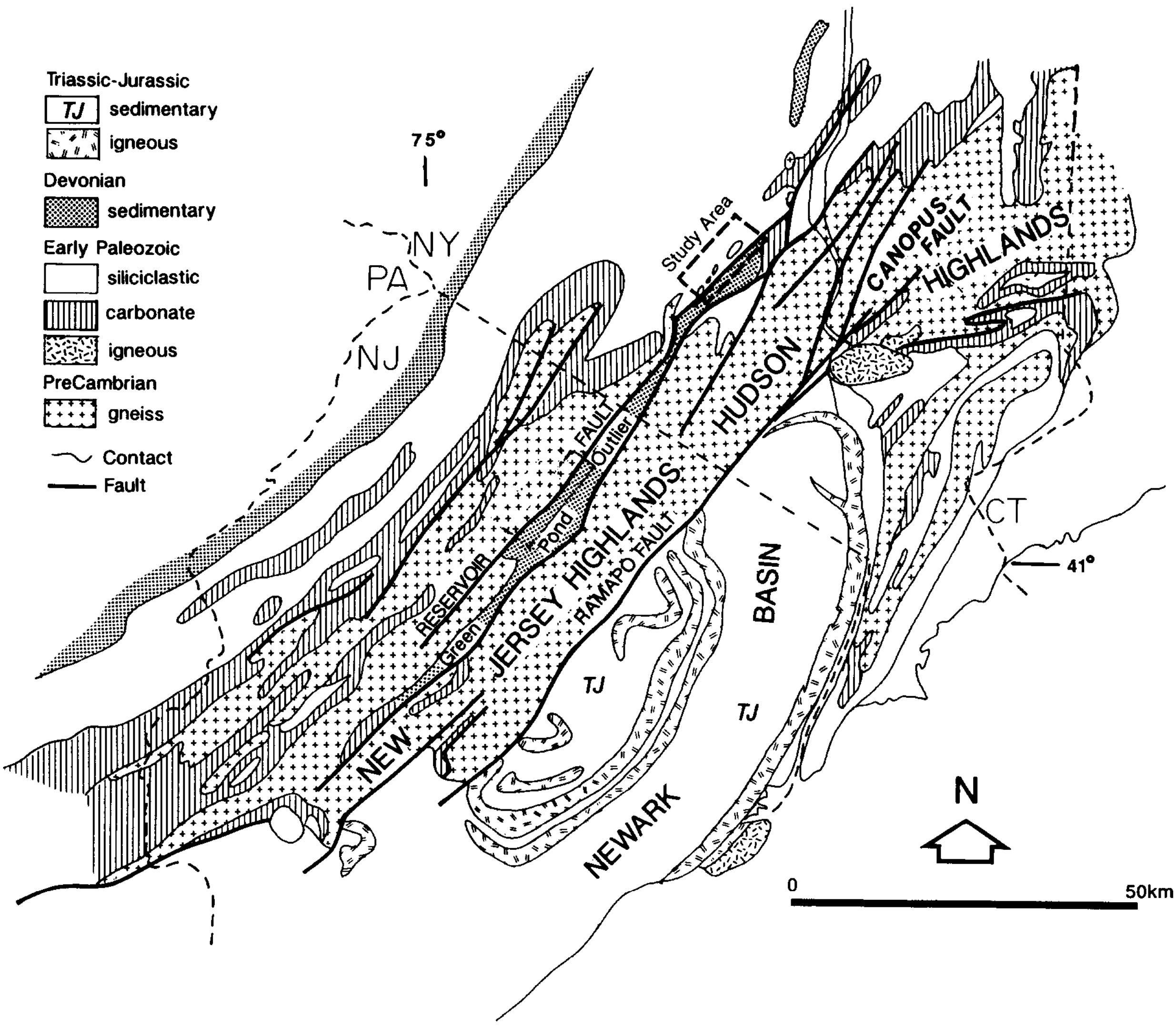

Fig. 1. Geologic map of the Reading Prong in Pennsylvania, New Jersey and New York, showing location of the study area (Fig. 2).

order, but they generally decrease in size towards the southwest. Jaffe & Jaffe (1973) interpreted the lenses as individual erosionally separated klippen from the Hudson Highlands crystalline thrust sheet to the southeast. The northwest contacts are primarily with the Martinsburg Formation. Bedding and cleavage of the Martinsburg shales and siltstones dip shallowly southeast beneath the Grenville gneiss of the lenses. The chain of crystalline lenses is offset at the south end of the study area approximately 1.5 km by a WNW-striking, dextral-reverse fault of apparent Late Permian–Mesozoic age (Gates 1992) (Fig. 1).

To the northwest and outside of the influence of the chain of megalenses, the Martinsburg Formation shows two clear periods of deformation. The latest foliation (S_2) is a spaced crenulation cleavage that is locally continuous in shale but which is absent in coarser units. Poles to S_2 form a single cluster with an average orientation of 044 73SE (Fig. 3a). The first cleavage (S_1) which is slaty and pervasive was folded during the formation of S_2. Poles to S_1 form a girdle with an axis of 10°/047 and a maximum spread in orientations of 46° (Fig. 3b). NE-trending tight to locally isoclinal folds are visible on the mesoscopic and macroscopic scale. Poles to bedding form a single uniform girdle with a fold axis of 2°/047 (Fig. 3c).

The bedding and cleavages in the Martinsburg Formation clearly dip beneath the crystalline rocks of the Hudson Highlands where the northwestern contact is exposed. The contact is sharp, and Martinsburg Formation rocks show numerous slickensided fault planes and intensified cleavage (S_1) and folding relative to other areas. The faults strike consistently northeast and dip shallowly to moderately southeast as well as moderately northwest (Fig. 3d). The gneiss above the contact is extensively jointed, contains numerous epidote and quartz-filled veins and locally contains breccia. The breccia is chlorite-cemented and typically occurs in discontinuous pockets 5–15 cm long and with sharp boundaries.

The Round Hill lens shows a pinch and swell type map pattern (Figs. 1 and 4a). The thinner 'pinch' area of the crystalline lens is characterized by extensive normal faulting, jointing and epidote–chlorite alteration. Because the basement rocks have experienced several

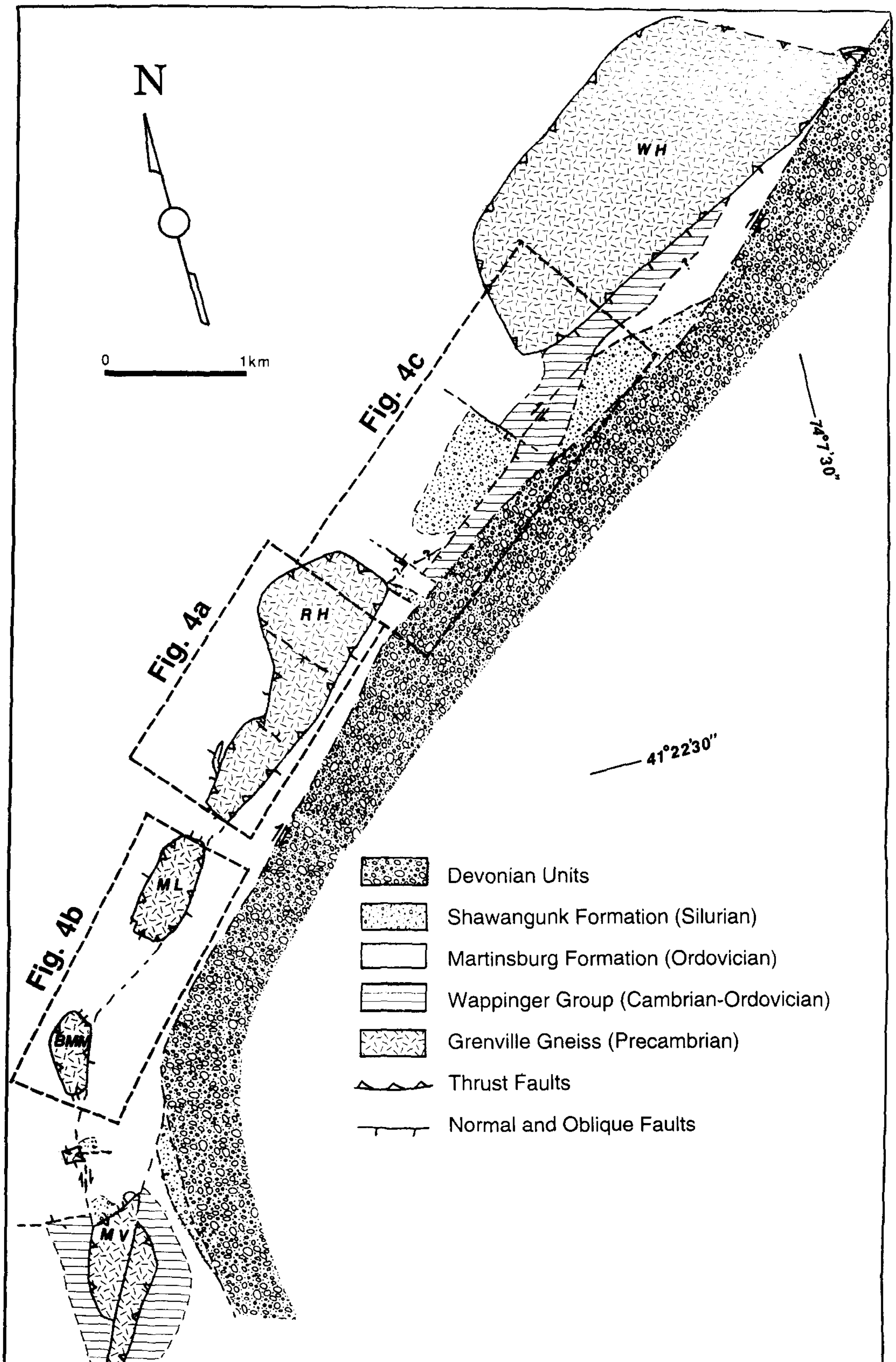

Fig. 2. Geologic map of the study area north of Monroe, New York, showing a 12 km segment of the chain of megaboudins and locations of areas for Fig. 4(a–c). Block labels: WH = Woodcock Hill, RH = Round Hill, ML = Merriewold Lake, BMM = Bull Mine Mountain, MV = Museum Village.

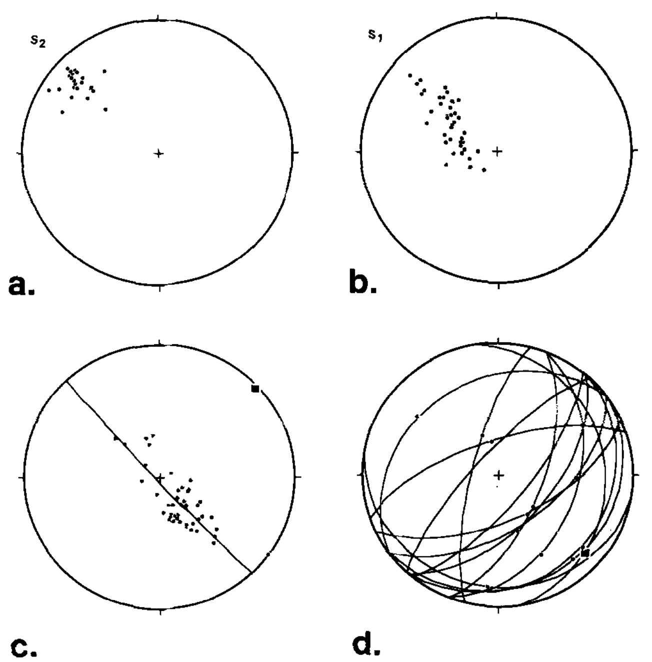

Fig. 3. Equal area projections of poles to tectonic surfaces in the Martinsburg Formation to the northwest and outside the influence of the megalens chain and averaged for each outcrop or group of outcrops (typically 1 to 8). (a) Poles to S_2 crenulation cleavage, $n = 23$. (b) Poles to S_1 pervasive foliation, $n = 41$. (c) Poles to bedding, $n = 46$, box = fold axis with plunge/trend of 2°/047. (d) Plot showing the geometry of the reverse and thrust faults that separate Martinsburg Formation from crystalline rock and dip beneath the boudins. Each great circle denotes a fault plane, and each dot denotes the slickenside lineation on that fault.

compressional and extensional events during the Paleozoic and Mesozoic, brittle structures abound. It is impossible to accurately assign individual fractures to a deformational event. However, by comparing the orientation maxima of fractures to observable faults and joints in the cover rocks that are clearly related to the block extension, data from the crystalline rocks can be used to support an inference of lateral extension. Faults in the gneisses are single chlorite- or epidote-mineralized fracture planes with rare slickenfibers. Using the combination of grooved slickensides with tapered prod marks (Means 1987) and R criteria of Petit (1987), shear sense on some faults can be determined. Two sets of steeply-dipping normal faults are common in all of the crystalline blocks in the chain; those parallel to the regional trend (with northeast strikes) and those perpendicular to the regional trend (with northwest strikes) (Fig. 5a). Although joints exhibit a variety of orientations, two maxima with steep northeast and northwest strikes are apparent (Fig. 5b). The density of the faults and joints is greater in the thinner 'pinch' area of the block, which is also marked by steeply NE- and SW-dipping faults that offset the basement-cover contact. Normal faulting is also evident along the NE-trending margins of the block. Steeply-dipping slickensided surfaces and extensive jointing are especially common along the northwest margins. In one location, gneiss has been juxtaposed with Martinsburg Formation through normal faulting (Fig. 4a). There is a repeated succession of fault-separated gneiss and shale in the southwestern corner of the Round Hill block. The repeated gneiss–shale sequence is separated by an observable normal fault; the other contacts are older thrust faults.

Where the gaps between the lenses are small, the bedding (S_0) and cleavage (S_1) in the shale swing from NE-strikes along the sides of the blocks towards, and in some cases to, NW-strikes in the gaps. The swing of the fabric in the Round Hill block is progressive into the pinch or gap area producing a wrapping geometry (Figs. 4a and 6a). The rotation of S_1 cleavage from the sides of Round Hill into the gap to the south covers a 61° spread and forms a fold axis of 37°/064 (Figs. 6a and 7). Although the general geometry of the girdle of poles to cleavage around Round Hill is similar to that for cleavage unaffected by the crystalline lenses (Fig. 3b), the orientation and maximum spread of the girdle is not. Strike-slip shearing is evident along the shale–gneiss contact at the corners of the blocks by slickensided planes, drag of foliation, and brecciated gneiss. Strike-slip motion is oppositely directed on facing corners. On the northwest side of a gap, the northern corner shows sinistral movement and the southern corner shows dextral movement.

In the larger gap between the Bull Mine Mountain and Merriewold Lake blocks, the contacts of the gneiss with the rocks in the gap form sharp, NW-striking, nearly vertical planes (Figs. 1 and 4b). The Martinsburg shale fills the gap between these blocks. As with the Round Hill block, cleavage in the Martinsburg Formation swings from NE-striking along the sides of the blocks to NW-striking in the central gap area. Cleavage swings from NE-striking adjacent to Bull Mine Mountain through E–W to NW-striking in the gap, through about 77° (Figs. 6b and 7). The fold axis formed by the swing of cleavage is oriented 23°/149. To the north of the gap, cleavage swings from NE-striking adjacent to the Merriewold Lake block through N–S and to NW-striking in the gap, through about 69° and forming a fold axis oriented 16°/052 (Figs. 6c and 7). The S_2 crenulation cleavage is well developed and the exposure good enough that the same swing into the gap can be demonstrated in plots of poles to S_2 (Figs. 6d and 7). The swing of orientations covers a range of 74° and forms an axis with an orientation of 14°/068. The folding of S_2 around the crystalline lenses contrasts sharply with that outside of the chain (Fig. 3a). The reorientation of S_2 into the gaps is strong evidence that the boudinage postdates thrusting and is a late deformational feature.

The traces of cleavage in a horizontal plane bow into the gaps at both their northeast and southwest ends. The map-view deflection of cleavage from its regional trend, however, is not symmetric. For example, the area of deflected cleavage southwest of the Merriewold Lake block is much larger than the area of deflected cleavage northeast of the Bull Mine Mountain block (Fig. 4b). The geometrical center of the gap based on flow patterns is closer to Bull Mine Mountain. In addition, unlike around the Merriewold Lake block and in the Round Hill block (Fig. 4a) and what would be expected for classic fracture boudins (Cloos 1947, Rast 1956), the shale swings

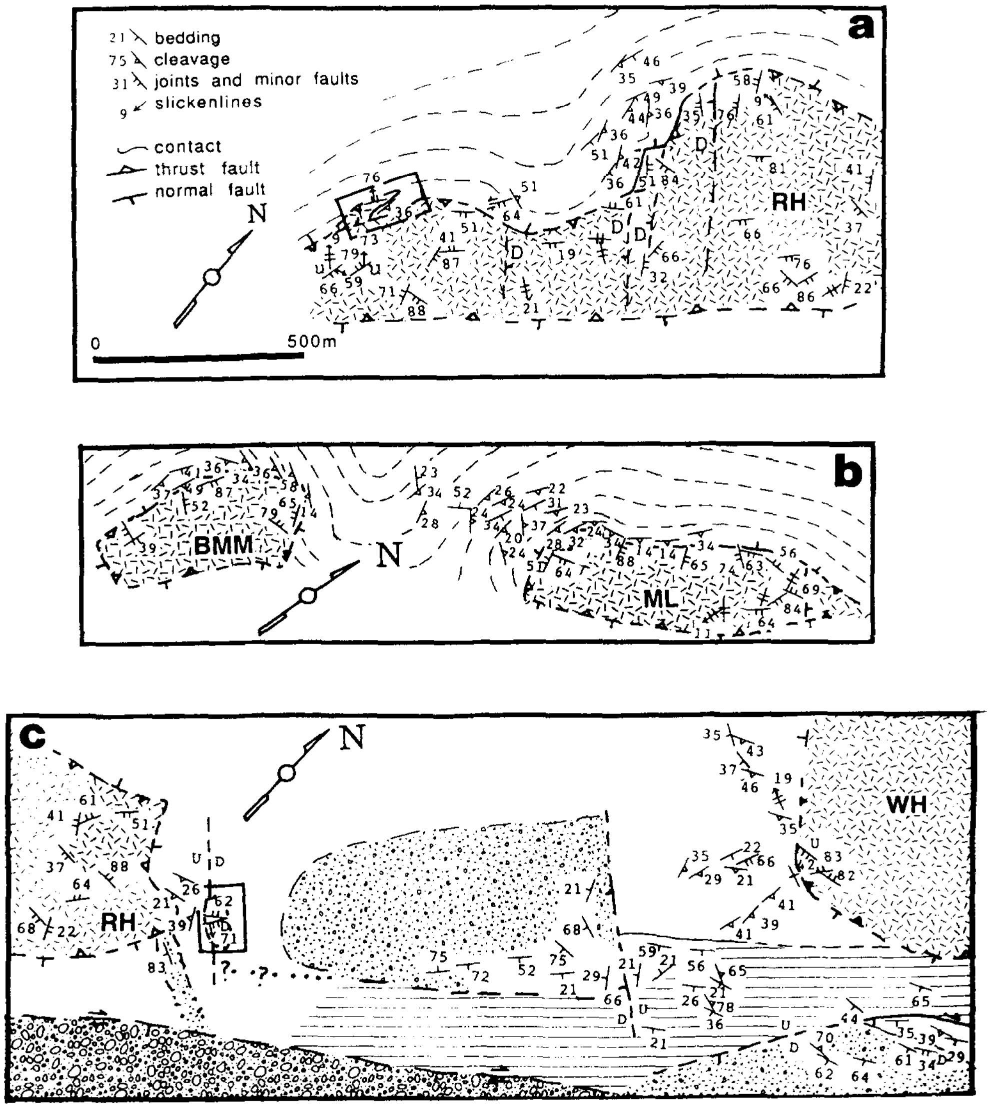

Fig. 4. Detailed geologic maps of crystalline lenses and gaps between them (see Fig. 2). (a) Round Hill block and extension (southwest). Boxed area shows the repeated succession of fault separated gneiss and shale. (b) Bull Mine Mountain and Merriewold Lake blocks and gap. (c) Woodcock Hill and Round Hill blocks with gap. Boxed area shows NE-dipping normal fault that offsets a small block of brecciated granitic gneiss from the northeastern margin of the Round Hill block.

towards the northwest midway along the Bull Mine Mountain block rather than in the gap area.

The widest gap occurs between the Woodcock Hill and Round Hill blocks. It also exhibits the wrapping of the cleavage in the Martinsburg Formation around both block margins (Figs. 1 and 4c). To the south of the Woodcock block, cleavage swings up to 115° from NE-striking through N–S to NW-striking, defining a fold axis oriented 35°/122 (Figs. 6e and 7). Unfortunately, there are only four appropriate outcrops of Martinsburg Formation on the north side of Round Hill. The sparsity of data renders the range of orientations unrepresentative. The best-fit fold axis of 22°/186 (Fig. 7) may be significantly in error. Within the center of the gap there is a large exposure of conglomerate and quartzite of the Silurian Shawangunk Formation. The northeastern contact of the Shawangunk Formation is a normal fault that dips steeply southwest and juxtaposes conglomerate against older Wappinger Group limestone. The fault plane is composed of weathered limestone breccia with anastomosing polished and fibrous slickensides showing consistent normal offset. To the northwest, the fault crosses a NE-trending conformable contact between the Martinsburg Formation and Wappinger Group in the footwall. The southwest edge of the block of Shawangunk Formation is not exposed. However, there is a moderately NE-dipping normal fault that offsets a small block of brecciated granitic gneiss from the northeastern margin of the Round Hill block northeastward into the gap area. The breccia is composed of angular fragments of granitic gneiss that show heavy sericitization and alteration to hematite and epidote. The brecciated gneiss is separated from the Round Hill klippe by a band of highly deformed Martinsburg Formation.

The parallel normal faults with opposite dips form a cross-trend graben within the gap. The Shawangunk Formation within this graben exhibits folds that are truncated by and therefore predate normal faulting. The

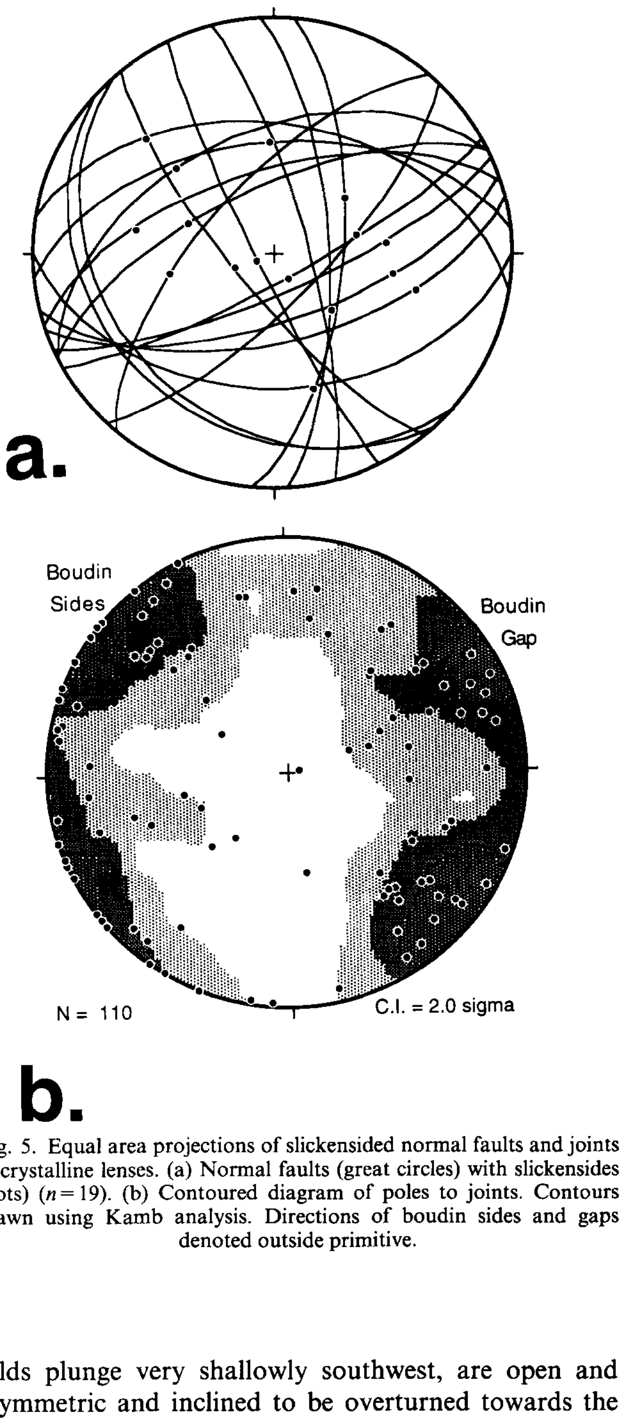

Fig. 5. Equal area projections of slickensided normal faults and joints in crystalline lenses. (a) Normal faults (great circles) with slickensides (dots) ($n = 19$). (b) Contoured diagram of poles to joints. Contours drawn using Kamb analysis. Directions of boudin sides and gaps denoted outside primitive.

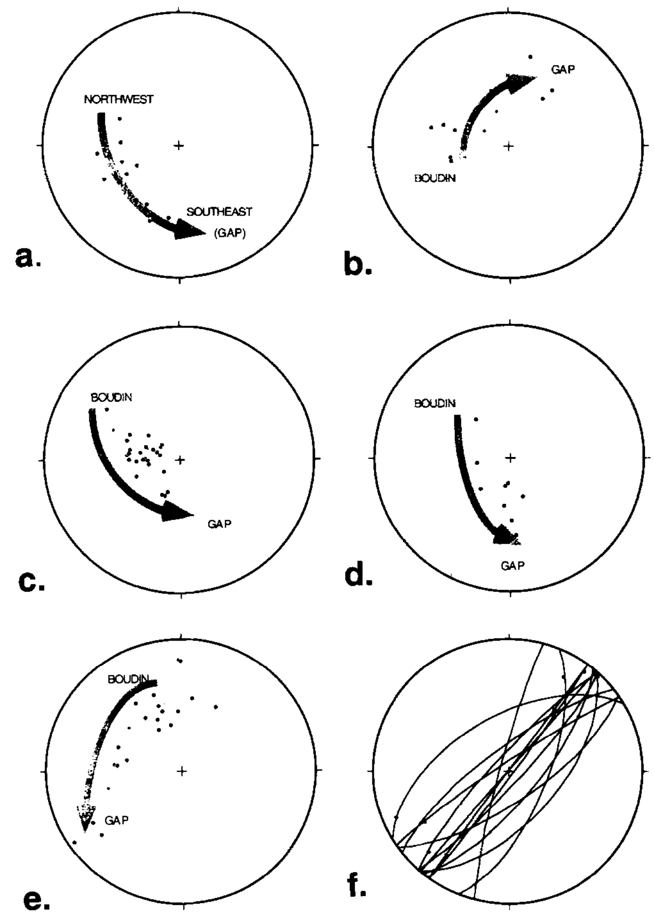

Fig. 6. Equal area projections of poles to cleavage in Martinsburg Formation (dots) around the megalenses with arrows showing rotation (wrapping) of cleavage from the flanks of the boudins and into the gap areas as indicated. Each dot represents averaged cleavage orientations for single or closely spaced groups of outcrops (typically one to 10 measurements). (a) S_1 cleavage in the center (northwest side) of the Round Hill block. (b) S_1 cleavage along the northwest side of Bull Mine Mountain block and northward into the gap. (c) S_1 cleavage along the northwest side of the Merriewold Lake block and southward into the gap. (d) S_2 cleavage along the northwest side of the Merriewold Lake block and southward into the gap. (e) S_1 cleavage around the west and southwest margin of the Woodcock Hill block. (f) Equal area projection of dextral strike-slip faults along the southeast flank of the megalens chain. Great circles = faults, and dots = slickenside lineations on faults.

folds plunge very shallowly southwest, are open and asymmetric and inclined to be overturned towards the northwest. They resemble typical Alleghanian folds in the Green Pond outlier to the southeast (Jaffe & Jaffe 1973, Mitchell & Forsythe 1988) and the Valley and Ridge province to the west (Drake & Lyttle 1981).

Much of the southeastern side of the chain lies beneath glacial cover. On the southeast side of the Museum Village block as well as the Goose Pond block (not shown) to the south of the Museum Village fault, Wappinger Group and locally, Martinsburg Formation are juxtaposed against the gneiss by normal faults (Figs. 1 and 2). To the southeast of the unnamed block between the Museum Village and Bull Mine Mountain blocks, conglomerate and quartzite of the Shawangunk Formation are juxtaposed against the gneiss. The fault must have had some normal movement to drop the Shawangunk Formation down to the level of the Precambrian blocks but slickensides and drag folds in the Shawangunk indicate dextral transcurrent movement. A thin EW-trending band of Shawangunk Formation also strikes into the side of the Round Hill block and appears to have suffered strike-slip offset. At the north end of the Woodcock Hill block, a similar E–W band of Shawangunk Formation is faulted against Wappinger Group carbonates and Martinsburg Formation shales. Normal faulting is required to move the Silurian rocks deeper into the section, and the observed dextral transcurrent faulting explains the current distribution. Several other exposures along the southeast margin of the chain of crystalline megalenses both within and south of the study area also contain slickensides and small pockets of breccia that show dextral movement along NE-striking planes (Fig. 6f), but exposure is too poor to fully evaluate the extent of faulting. If the band of quartzite at Round Hill was sheared from the exposure that trends into the

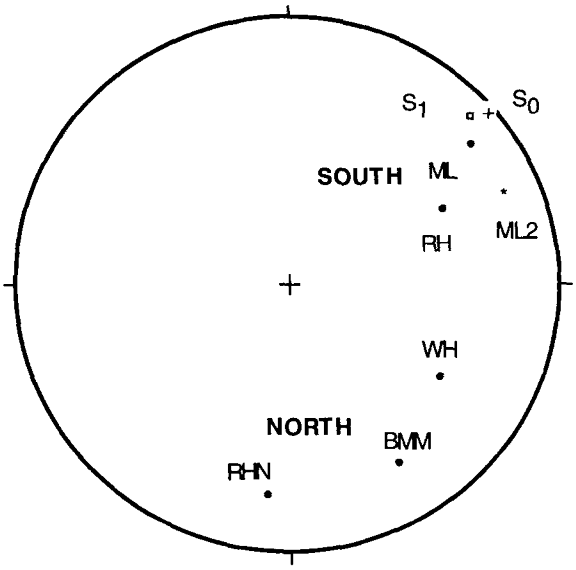

Fig. 7. Equal area projection of fold axes for rotation (wrapping) of S_1 cleavage in Martinsburg Formation from the boudin flanks and into the gaps (dots). Box shows axis for S_2 cleavage around the Merriewold Lake boudin. Star shows axis for regional S_1 cleavage.

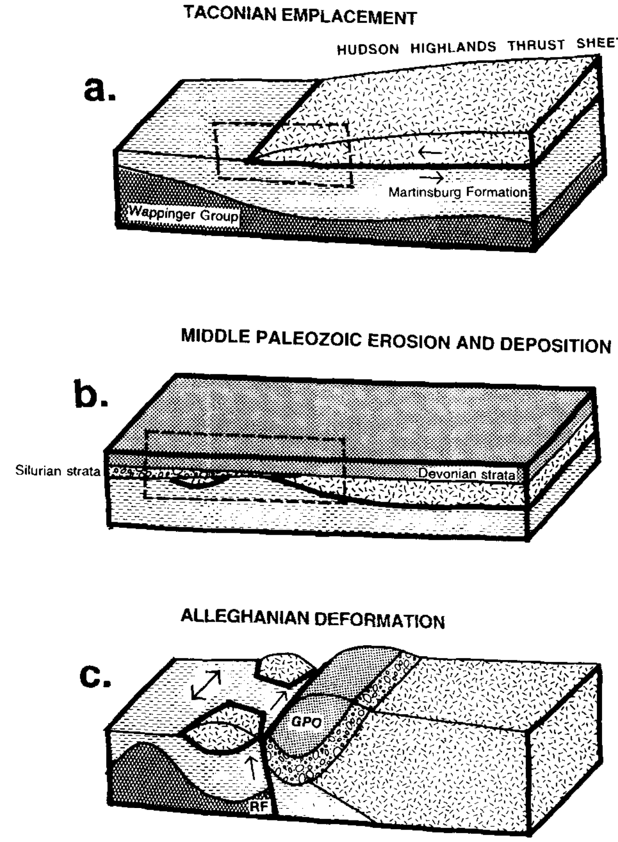

Fig. 8. Developmental model for the megaboudin formation. (a) Taconian (Middle Ordovician) emplacement of the Hudson Highlands thrust sheet northwestward on to Paleozoic sedimentary rocks of the Valley and Ridge Province. Boxed area shows the location for Fig. 8b. (b) Silurian through Devonian erosion and deposition of sedimentary rocks. Boxed area shows the location for Fig. 8c. (c) Alleghanian (Carboniferous–Permian) deformation produces the syncline that forms the Green Pond outlier (GPO), reactivates the Reservoir Fault (RF), and causes boudinage of the crystalline klippe along the leading edge of the Hudson Highland thrust sheet.

same fault at Woodcock Hill, then dextral offset would be up to 2.5 km.

MEGABOUDIN FORMATION

The dipping of units of the Martinsburg Formation beneath the megalenses, the brecciated gneiss and highly cleaved and deformed shales at the contact between the two, and the results of slickenside analysis support previous interpretations that the northern Reading Prong was thrust westward over the Early Paleozoic sedimentary rocks of the Valley and Ridge (Offield 1967, Rodgers 1971, Jaffe & Jaffe 1973, Drake & Lyttle 1981) (Fig. 8a). The timing of emplacement of this crystalline thrust sheet is believed to have been Ordovician and the result of the Taconian Orogeny. Additional movement on the thrust surface may also have occurred during subsequent deformation.

If the megalenses are boudins, they must have been part of a long NE-trending continuous band of Grenville gneiss prior to deformation. The band may have been a keel or infold of the crystalline thrust sheet within the Martinsburg Formation (Ratcliffe, Pers. Comm., 1992) that was separated from the main Hudson Highlands massif by erosional or structural means (Fig. 8b). During subsequent compression, the shale of the Martinsburg Formation flowed and extended along strike. As the band of crystalline rock extended, because of the high competency contrast, it formed a series of fracture boudins (Fig. 8c). The points at which the crystalline rock extended to form the gaps experienced a higher degree of deformation than the rest of the boudin as recorded by the cross-strike normal faults, and extensive jointing. As the gaps opened, the surrounding shale flowed into the gap region and formed the wrapping pattern of cleavage around the boudins.

The shale rotated from NE-striking to NW-striking as it flowed into the gaps in all cases. However, it rotated clockwise to the north of boudins and anticlockwise to the south of boudins. These opposite rotations generally produced distinct fold axes in the cleavage. The clockwise axes have orientations distinct from the regional fold axes (Fig. 7). Whereas the anticlockwise axes have orientations similar to the axes of regional folds of bedding and S_1 (Fig. 7), the late folds also fold S_2, which is not folded on the regional scale, (Figs. 3a and 6) and the interlimb angles of the late folds are greater than those of the regional folds (Fig. 6d). This indicates that boudin formation, at least in part, post-dated S_2 formation.

The boudins and gaps, however, are by no means regular in size. The area of the Woodcock Hill boudin is approximately 5 km^2 whereas the unnamed boudin between the Bull Mine Mountain and Museum Village boudins is about 0.1 km^2. The rest fall somewhere between these two (Fig. 2). The gaps between the boudins are also not regular in size. Ferguson (1981) and Ferguson & Lloyd (1984) have shown for many examples of boudinage that variations in gap spacing reflect variations in the timing of opening of the gaps. The variations in gap sizes between the crystalline boudins described here, may indicate that gaps were initiated early in the deformation but new gaps continued to be initiated throughout the event. The gap between Woodcock Hill and Round Hill would have opened early whereas Round Hill was at the initial stages of gap formation at the cessation of deformation. Smith (1975) proposed that the position of gaps in such chains of boudins may reflect perturbations such as points of weakness or stress nodes. Applying these theoretical and experimental studies to the megaboudin chain requires that the crystalline band had uniform lateral thickness and material properties, that the boundary conditions on the chain were uniform, and that the regional stress field was relatively uniform. Clearly, most of these requirements were not met or cannot be evaluated.

Another irregularity in the boudin chain occurs between the Bull Mine Mountain and Merriewold Lake boudins (Fig. 4b). Cleavage turns from NE- towards NW-striking midway along the Bull Mine Mountain boudin rather than within the gap as expected. Additionally, the wrapping flow pattern of the cleavage is far larger adjacent to the Merriewold Lake boudin than that adjacent to Bull Mine Mountain. One explanation for this gap asymmetry and displacement of flow pattern is that both boudins must have moved northeastward during separation. Normally, when classical pure shear fracture boudins (Cloos 1947, Rast 1956) open, the boudins move apart in opposite directions. Because the gap is a low stress area as compared with the sides of the boudins, matrix material flows into the gap evenly from all sides producing a wrapping geometry into the gap (Ramberg 1955, Stromgard 1973). As the gap widens, the boudins do not provide strain shadows for the gap, and the material in the central part of the gap is commonly flattened parallel to the boudin chain. If both boudins move in the same direction, however, the gap fills from behind the leading boudin only. After the initial opening, the trailing boudin overruns the material in the gap and deforms it or overthrusts it (Fig. 4b). Such a process could be termed 'extrusion boudinage' because bulk motion is unidirectional. Study of the symmetry of flow patterns in boudin gaps can be useful for determining the direction of extrusion in compressional orogens. However, it would require more evidence than that presented here to prove such a process. An alternative solution is that the bend in the Green Pond outlier chain at Bull Mine Mountain caused the boudin to overthrust the gap area as it moved north. The problem is that the bend in the chain appears to be related to post-Alleghanian faulting. In addition, because the boudins moved north, the bend should be a releasing bend rather than a restraining bend and should produce extension rather than compression. If the bending of the chain and Green Pond outlier postdates boudin formation, the deformation that produced the bend may also have thrust the Bull Mine Mountain block northeastward and over the Martinsburg Formation in the gap. No structural features identified can be assigned to such deformation but exposure is not complete. A component of simple shear in the otherwise pure shear deformation would cause rotation of the boudins and consequent compression on certain faces. Asperities and local perturbations in the stress field might also produce the observed geometry. Neither of these alternatives can be discounted.

As the gaps in the Hudson Highland chain opened, the gneiss fractured and normal faulted. In some nascent gaps, extension formed a saddle-like graben across the band of gneiss and normal faults offset the gneiss–shale contact (Fig. 4a). In other gaps, separation appears as abrupt, NW-striking, vertical fractures with no indication of normal faulting and graben formation (Fig. 4b). Regardless, shale flowed into growing gaps. The flow is recorded by the swing of the strike of cleavage from northeast towards northwest within the gaps. Fullagar (1980) describes this flow in terms of vorticity. The vorticity is shown by particle flow from the sides of the boudins into the gaps—a net transfer of material. This displacement is observed in the megaboudins by the strike-slip shearing at the gap faces along the corners of the boudins and the girdles of poles to S_1. Vorticity and flow of material is also documented in the vertical direction by the formation of normal faults along the sides of the boudins. The normal faults suggest that the boudins emerged during deformation. However, depending upon relative movement along the underside of the boudins, this emergence may only be apparent.

As the gaps continued to widen, vertical movements became as important as horizontal movements in the megaboudins. The best example of a wide gap is that between Woodcock Hill and Round Hill (Fig. 4c). Just as in the examples of small gaps (Figs. 4a & b), shale flowed into the gap as shown by the deflection of cleavage from NE-striking along the sides of blocks to NW-striking in the gaps. However, as the gap widened conjugate NW-striking normal faults formed a graben that juxtaposed overlying Silurian conglomerate with older rocks within the gap.

The sequential development of horizontal shale flow followed by vertical offset in the megaboudins appears to be the result of deformation of layered rocks with variable competencies. In the early stages of deformation while the shale flowed into the gap, the conglomerate and quartzite of the Shawangunk Formation deformed on a horizon above the megaboudins. The rigidity of the unit prevented it from filling the gap (Figs. 9a & b). The Shawangunk Formation appears to have folded and deformed under purely compressional conditions above the opening gap, similar to the rocks both southeast and northwest of the megaboudin chain. When a certain critical gap width was achieved, the normal faults were initiated allowing overlying material to drop down (Fig. 9c). The southwestern normal fault dips northwest and appears to have clipped a piece off of the northeastern edge of the Round Hill boudin. The small piece of brecciated gneiss that is contained within the shales was moved along the normal fault along with the quartzite and is now separated from the boudin by a strip of Martinsburg Formation in the footwall.

The total observable gap length is approximately 3.6 km along the 12 km part of the chain considered in this study. Because there is some extension of the crystalline lenses prior to and likely during boudinage, the gaps do not account for all of the extension. In addition, because there are areas that lack exposure along the chain and small fragments of crystalline rock are faulted into the gaps like that northeast of Round Hill and between Bull Mine Mountain and Museum Village, it is possible that all of the crystalline rock is not accounted for (Fig. 2). Late vertical movements in the boudinage process may have removed crystalline rock from the current level of exposure further compounding the potential problem of missing rock. With these shortcomings in mind, an approximate $\lambda = 3.3$ was calculated for the chain using the strain reversal method of Ferguson (1981). Lateral extension in the Martinsburg Formation could be much greater because boudinage was not initiated until extensional stress exceeded the strength of the crystalline block.

The dextral transcurrent faults along the southeastern edge of the megaboudin chain could have resulted from variable lateral extension of the belts of rock in the area as the result of compression. To the southeast of the megalens chain, the Green Pond outlier is composed largely of Silurian–Devonian sandstones and conglomerates. To the southwest, these competent rocks rest directly on more competent basement (Offield 1967, Herman & Mitchell 1991). The incompetent shale of the Martinsburg Formation and enclosed blocks of Grenville gneiss may have expanded to the northeast faster than the rocks in the Green Pond outlier. This difference in stretching of the two belts of rock would have formed a dextral transcurrent stretching fault (Means 1989, 1990) along their contact. Therefore the apparent offset of the Shawangunk Formation across the fault on the southeastern side of the megaboudin chain could have resulted from shearing on a stretching fault and offset would reflect differences in lateral expansion.

Alternatively, the dextral transcurrent shearing may be a continuation of the Alleghanian dextral event documented in the southern and central Appalachian Piedmont (Gates *et al.* 1986, Valentino *et al.* 1994) as proposed by Malizzi & Gates (1989). Deformation appears to be transitional from purely strike-slip in the metamorphic Piedmont to purely compressional in the non-metamorphic Valley and Ridge Province in Pennsylvania (Valentino *et al.* 1994). However, Gates (1987) documented transpressional deformation at the transitional area between strike-slip and compressional deformation in Virginia. The megaboudin chain is in an area that would be expected to be purely compressional but some transpression cannot be ruled out. In this case, there may be components of both transpressional and stretching faults.

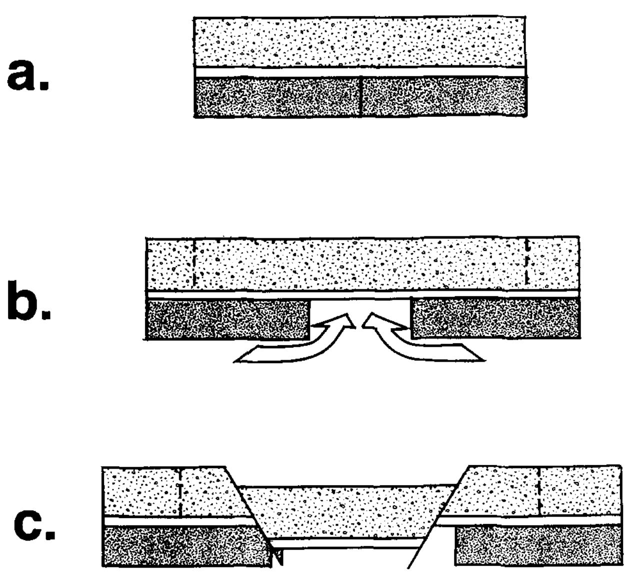

Fig. 9. Three step model showing the sequential filling of a boudin gap in a rheologically layered sequence. Random dashes = crystalline (stiff) layer, unshaded area = incompetent material, conglomerate pattern = competent layer. (a) Layered sequence with a rigid block enclosed in incompetent material showing location of break that will open into a gap. Overlying layer is competent but will stretch without breaking during initial deformation. (b) Initial opening of the boudins and flow of surrounding shale into the gap in a horizontal plane as shown by arrows, no participation of overlying layer in gap filling. Overlying layer may stretch to full size as shown, not stretch and be as wide as the vertical dashed lines, or stretch to some size between. (c) Normal faulting of overlying layer into the gap area creating a cross-trend graben. Stretch of overlying layer as in (b). One normal fault removes an edge piece of a boudin and displaces it into the gap area. This mechanism explains the brecciated gneiss in the gap of Fig. 3(c).

LATERAL STRETCHING IN FOLD-THRUST BELTS

Structural studies on foreland fold and thrust belts have dealt primarily with cross-sectional features and related processes (Ramsay 1967, Rodgers 1970, 1971, Boyer & Elliott 1982). This concentration of effort is not surprising considering that folds, faults and cleavage are more easily interpreted in cross-section than along strike. Lateral stretching in fold and thrust belts was largely overlooked until recently. Merle (1989) and Ratschbacher *et al.* (1989, 1991) documented lateral stretching in the nappes of the Swiss Alps and provided geometric models for spreading. The megaboudins along the northwest margin of the Hudson Highlands provide examples of new criteria for the recognition of lateral extension in fold and thrust belts.

One of the structures for potential documentation of lateral extension is the stretching fault (Means 1989, 1990). This fault is an accommodation structure between materials that stretch at different rates and by different amounts. In a fold belt of rocks with high competency contrast, stretching faults parallel to the orogen should be abundant. However, faults would show opposite senses of movement on either contact of an incompetent unit. For a quantitative analysis of lateral stretching, offset determinations on all faults would be required. These offsets would be absolute minima because they would vary with competency contrast and could only record absolute offset if the incompetent unit was juxtaposed against an unyielding crystalline unit. If offset in one direction on one side of the fold-thrust belt exceeds that in the other direction, then the stretching is not uniform but instead is directed.

The other structures that indicate lateral extension are the crystalline megaboudins. These crystalline blocks are assumed to have undergone no ductile deformation during the subgreenschist facies Alleghanian deformation. They are therefore the best recording devices for extension because they are relatively passive markers. A rough estimate of strain can be compared to strain calculations using retrodeformation of cross-strike structures. This ratio determines the importance of lateral stretching in the belt.

The gap geometries between megaboudins also provide a potential key in the identification and characterization of lateral extension. The asymmetry of the cleavage patterns indicates the direction of movement of extension. Because all boudins in a large segment of a belt must move in the same direction (extrusion boudinage), a single gap can be used to determine extension direction. However, opposite ends of a belt could extend in opposite directions and if segmented, there could be several extrusion directions. To evaluate the entire belt, observations from each segment would be required.

CONCLUSIONS

The chain of tectonic lenses along the northwest margin of the Hudson Highlands thrust sheet comprises megaboudins produced by lateral extension during Alleghanian shortening. These boudins illustrate several important processes of boudin formation and potential lateral extrusion.

(1) There is a sequential filling of a boudin gap in a layered sequence of rheologically variable units. The less competent material fills the gap first and the more competent material only moves into the gap at some critical gap width depending upon thickness and competency of the unit.

(2) To evaluate lateral extension within fold and thrust belts, the most useful features are boudins, stretching faults, and boudin gap fill geometries. In combination, these structures can determine direction and degree of orogen parallel movement.

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