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Foreland deformation in the Appalachian Plateau, central New York: the role of small-scale detachment structures in regional overthrusting

WILLIAM BOSWORTH

Department of Geology, Colgate University, Hamilton, NY 13346, U.S.A.

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Abstract—Northwest-directed Acadian or Alleghenian overthrusting occurred through décollement along the black, carbonaceous Union Springs Shale in central New York. Detachment was accommodated at: (1) discrete faults marked by striated and polished shale bedding planes and fibrous calcite crystal growths between stepped surfaces; (2) duplex structures defined by upper and lower bounding faults 3–10 m apart with internal faults that developed both early and late in the movement history of the bounding faults; and (3) 5–20-cm wide shear zones also possessing an internal duplex or imbricate structure. Ramps through carbonate units adjacent to the black shale have displacements of less than one meter. Total displacement above the décollement horizon is not well-constrained, but is inferred to be on the order of a few tens or hundreds of meters. Fabric of the undeformed shale has been locally modified by a widely spaced cleavage (average 5-mm intervals) with no apparent shear offsets. This microstructure is most evident near ramps through overlying carbonate and in the vicinity of shear zone terminations. An intensely anastomosing and complex shear fabric is present within the shear zones.

These structures appear to represent the initial stages of overthrust propagation in a region dominated mechanically by the presence of alternating thick, stiff sedimentary layers and weak shale horizons. Further southwest, more interior to the orogen, displacement was accommodated through décollement along deeper salt horizons. Detachment in the stratigraphically higher black shale was generally restricted to an area where the salt is not present, and may represent a regional stepping-up of structure in the Appalachian Foreland.

INTRODUCTION

CENTRAL New York State south of the Mohawk River Valley is underlain by Silurian and Devonian rocks of the Appalachian Plateau structural province (Fig. 1) (Rodgers 1970). The stratigraphic section in this area reaches a maximum thickness of approximately 3000 m and is dominated by alternating shales, sandstones and several thick carbonate units (Rickard 1975). Silurian units rest disconformably to unconformably on Ordovician shales and sandstones, while all post-Devonian rocks have been removed by erosion. Structurally, the Silurian and Devonian sequence appears at first undeformed, and is therefore associated with the most external parts of the Appalachian Orogen. Broad wavelength gentle folds have been traced to west-central New York (Fig. 1) (Wedel 1932, Rodgers 1970) where axial planes strike roughly E–W. In central New York limb dips are generally less than 2° and the location of major structures is difficult to determine.

In addition to the limited large-scale folds of the New York Plateau province, other responses to deformation have been documented by previous workers. Small-scale thrust faults were described by Schneider (1905) and Long (1922) in west-central New York and Prucha (1968) and Chute (1972) have interpreted intense deformation in the Silurian Salina Salt as evidence for décollement on the salt horizons. Frey (1973) emphasized the relationship between areal extent of the salt unit and the location of the overlying, gentle folds mapped by Wedel (Fig. 1). He interpreted those folds to lie above a regional décollement in the Salina Salt. Engelder & Engelder (1977) measured strained fossils indicative of at least 10% layer-parallel shortening normal to fold trends of this décollement-fold system.

The Salina Salt does not extend to the present eastern

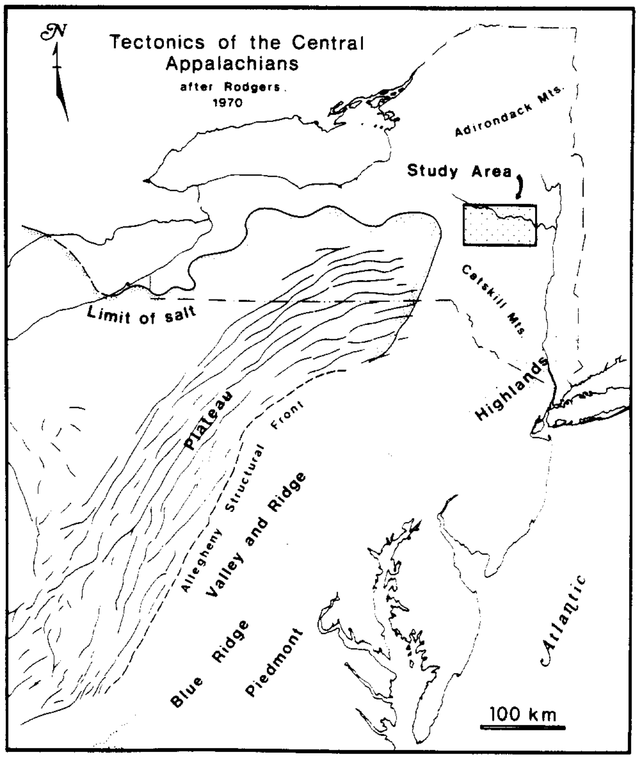

Fig. 1. Structural provinces of the central Appalachians, after Rodgers (1970). The study area is located in east-central New York State (New York is outlined by a dot–dash symbol) in a region not underlain by the Silurian Salina Salt (limits of salt deposits from Frey 1973). This area is a portion of the Appalachian Plateau, a structural province that has undergone limited folding and overthrusting to the northwest. Thin lines in the Plateau locate anticlinal hinges.

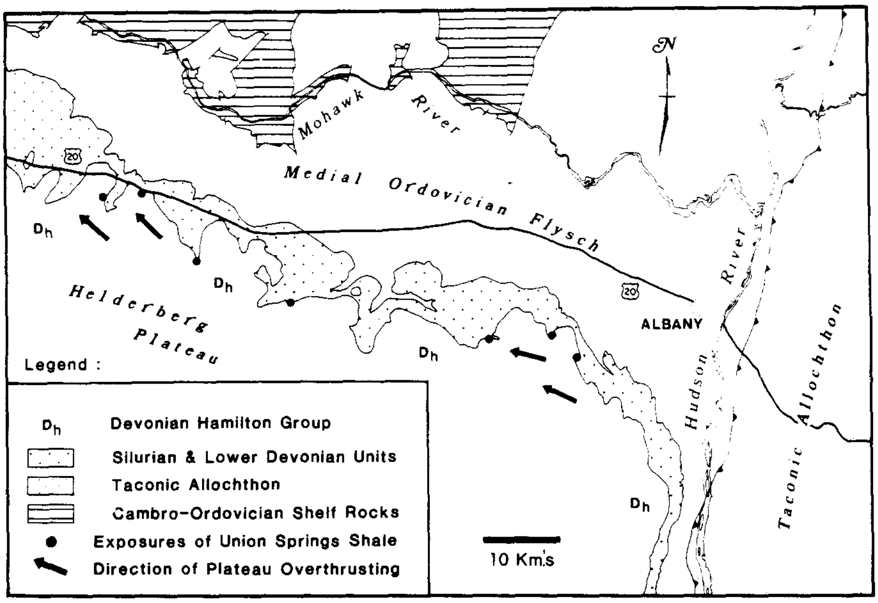

Fig. 2. Locations of good exposures of Union Springs Shale (see also Rickard 1952) and inferred directions of overthrusting (black arrows). Westernmost dot is Cox's Ravine, next dot to the east is the Cherry Valley outcrop illustrated in Fig. 6. Easternmost dot is Clarksville.

limits of Silurian rocks in New York (Frey 1973). Rickard (1952), however, described zones of deformation in the Middle Devonian Union Springs Shale (Marcellus Formation; Cooper 1930) as far east as Clarksville, New York, about 16 km west of Albany (Fig. 2). The Union Springs Shale is a particularly black, carbonaceous interval of the Siluro-Devonian section. These 'disturbed zones' are found at least as far west as Cherry Valley (Fig. 2), a total east to west distance of 65 km. This suggested the possibility that a continuous detachment surface exists within the Union Springs Shale of east-central New York, possibly accommodating overthrusting in the New York Appalachian Plateau where the stratigraphically lower Salina Salt horizons are not present. This paper describes the results of field work conducted in the study area of Fig. 1. The principal goals of the work have been to document the geometry of small-scale structures accompanying the initiation of detachment in shale horizons of overthrust belts and where possible, to develop kinematic models for their evolution.

Description will begin with geometrically simple structures and associated fabric changes, and lead to a discussion of more complex features that have been interpreted as narrow shear zones (Bosworth 1982a,b). The localities studied are indicated in Fig. 2 and have been described in detailed stratigraphic terms by Rickard (1952).

SIMPLE DETACHMENT AND DUPLEX STRUCTURES

The simplest structures encountered within the Union Springs Shale consist of two or three bedding-parallel horizontal faults, bounded above and below by undeformed shale and enclosing between them crumpled shale or alternating zones of folded and unfolded shale (Fig. 3). The fabric that is folded in these exposures is a finely-spaced fissility defined in thin section by aligned chlorite and illite grains. It is present throughout the Union Springs Shale, and is interpreted to represent either a bedding or compaction feature. The fault surfaces are generally marked with NW-trending grooves or fibrous quartz and calcite crystals (Fig. 4). Steps between the fibrous crystals indicate a NW-directed sense of overthrusting. The internal microstructure of the fibrous fault surfaces includes small-scale ramp-like features and pull-aparts, and these accord with the sense of shear inferred from the steps. The faults are generally spaced a few meters apart, and are typically found within the black shale rather than at a shale/carbonate contact.

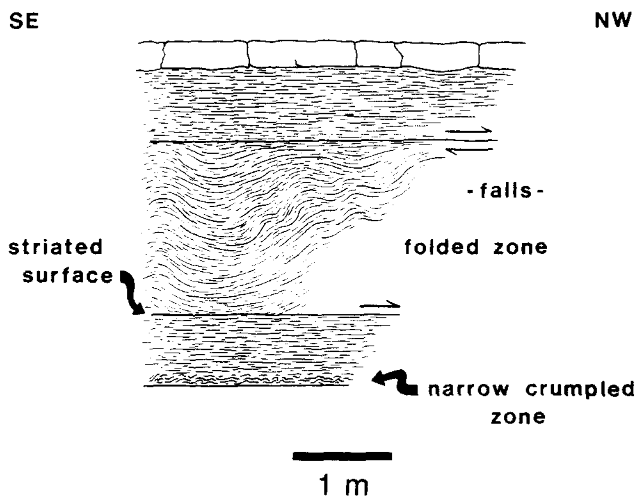

Fig. 3. Simple detachment structures at an eastern exposure of the study area (south-southeast of Thompson's Lake, in a small creek bed near the intersection of Long Road and Elm Drive; second outcrop from the east shown in Fig. 2). Deformation is limited to crumpling and folding in a section bounded by striated fault surfaces.

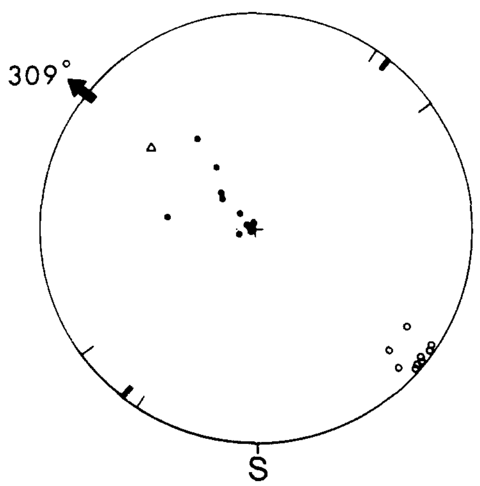

Fig. 4. Stereogram of structural measurements taken from detachment features in the Union Springs Shale of east-central New York State. Schmidt net, lower-hemisphere projection; S, geographic south. Solid circles are poles to fault surfaces, open circles give orientations of slickenside striations or fibrous crystals (not all faults are striated). Triangle is pole to weak 'spaced' cleavage at Cherry Valley. Heavy line on perimeter of stereogram gives average strike of phacoidal cleavage in shear zones at Cherry Valley (Chestnut Street) and Cox's Ravine. Thin lines on perimeter give range of average strike measurements for stylolitic cleavage in overlying Cherry Valley Limestone. 309° is the inferred direction of overthrusting, the age of which is unknown (Acadian? Alleghenian?).

The orientation of grooves and fibers is constant over the entire field area, trending within a few degrees of 129° (Fig. 4). No cleavage is recognizable in the field in these shale sections, although a widely spaced, sub-vertical weak stylolitic cleavage is present in some of the adjacent carbonate units. The average strike of this cleavage is 038°, approximately perpendicular to the movement direction inferred from the grooves and fibrous crystals.

It is possible that the parallel fault geometry could have evolved simply as multiple surfaces of slip within the weak shale interval, but other exposures suggest otherwise. In some cases the upper and lower fault surfaces bound a package of imbricated shale defining a duplex structure (Dahlstrom 1970). Two geometrical relationships between the bounding and internal faults can be recognized (Fig. 5). Some of the internal faults are truncated by the upper detachment surface, whereas others merge with it. All intersections with lower bounding surfaces are smooth junctions. The relationship between shale fissility and fault orientation is similarly complicated. Some of the internal packages within the duplexes contain shale with fissility parallel to the internal faults, while others contain shale with fissility parallel to the main bounding faults (Fig. 5).

The faults defining duplex structures are usually finely striated or grooved, and less frequently are marked by fibrous crystal growths. Sense of shear is difficult to determine from these features, but small-scale asymmetric folds associated with internal faults (Fig. 5) give a consistent southeast-over-northwest overthrust movement. Axial planes of these small folds and larger open folds within shale imbricates (Fig. 5), as well as the internal faults themselves all strike NE–SW. Other interesting features found within the duplex structures are asymmetric kink bands. When found as an isolated feature, the kinks indicate a southeast-over-northwest rotation of shale fissility, but they are also associated with folding within duplex structures as at the northwest end of the section illustrated in Fig. 5. In these cases their geometry is related to the development of the fold itself. Tectonic foliations are generally not recognized within the shale duplex structures.

CHERRY VALLEY ROADCUT

An interesting exposure of the Union Springs Shale is present just northeast of Cherry Valley, New York, near the intersection of U.S. Rt. 20 and a small country road known as 'Chestnut Street' (Fig. 2). The outcrop is capped by several thick limestone and shaly limestone beds, the Cherry Valley Limestone (Clarke 1903, Rickard 1952). A weak but easily discernible vertical stylolitic cleavage is present in these beds, with the usual NE–SW strike. A ramp structure is visible in the carbonates above Stake C (Fig. 6). Offset is approximately 2/3 m, with well-defined slickenside striations and fibrous crystals trending 124°. An unusual footwall syncline is associated with this ramp, and this appears to be geometrically associated with the upper zone of cleavage development that runs from above Stake C to midway between Stakes E and F (Fig. 6).

The eastern end of the section shown in Fig. 6, between Stakes A and B, is marked by a general tilting of shale fissility to the southeast. Locally a cleavage is

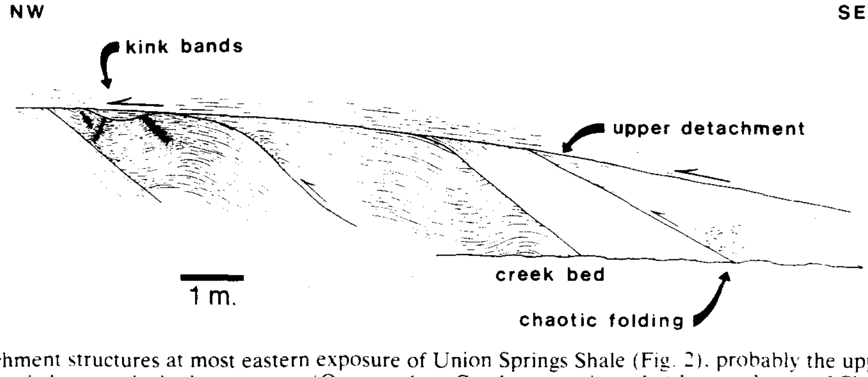

Fig. 5. Detachment structures at most eastern exposure of Union Springs Shale (Fig. 2), probably the upper portion of a moderately large-scale duplex structure (Onesquethaw Creek, approximately 6 km northwest of Clarksville).

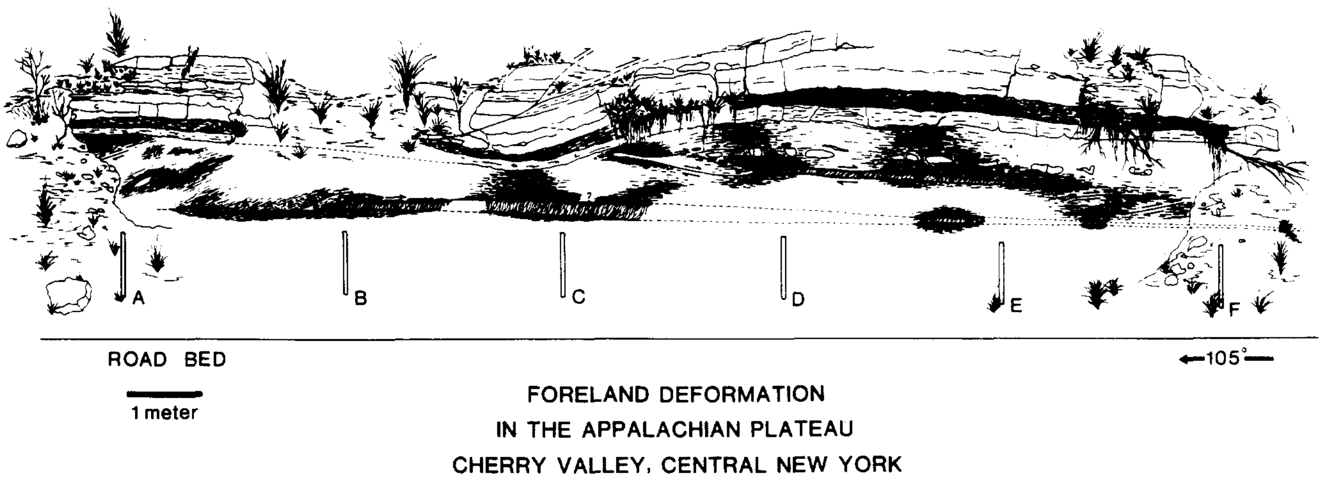

Fig. 6. Tracing from photographic mural of the Cherry Valley roadcut (Chestnut Street near intersection with U.S. Rt. 20). Stakes A–F are for reference purposes. Facing approximately south.

present in this tilted shale, dipping roughly 50° southeast. The cleavage is defined by clay–carbon partings (Nickelsen 1972) spaced at approximately 5-mm intervals. No consistent offsets along cleavage lamellae have been recognized, but it cannot be definitively stated that these surfaces did not originate as shear fractures or joints, that subsequently facilitated preferential transport of mobile phases. Several small-scale thrust faults are present here parallel to the shale fissility, and these are also associated with asymmetric kink bands that indicate southeast-over-northwest movement.

Beneath the lowermost shaly limestone of the Cherry Valley Limestone, within the upper section of the Union Springs Shale, is a horizon of carbonate concretions lying in a generally limy interval of the shale (Fig. 6). This layer of concretions is truncated at the footwall syncline above the position of Stake C. A few concretions are present in the tilted shale section, with their long axes parallel to the shale fissility. It is important to note that no cleavage occurs around the peripheries of these concretions, which might conceivably have acted as strain 'concentrators' for the adjacent shales.

Shear zones

Two zones of intense cleavage development are present at the Cherry Valley outcrop. The lower zone starts above Stake B and continues beneath deep rubble west of the end of the section shown in Fig. 6. The upper zone begins west of the footwall syncline (discussed above) and terminates between Stakes E and F. The upper and lower surfaces of the cleavage zones are discrete faults, with striations and fibrous crystals parallel to the regional overthrust direction inferred from the faults described in the previous section. The cleavage zones therefore represent sites of intense deformation, across which significant displacements have occurred, and therefore have been referred to as shear zones (Bosworth 1982a,b). This term is used in the broad sense advocated by Ramsay (1980), and should not be misconstrued as a statement suggesting that these zones have experienced a progressive 'simple shear' strain history.

The internal fabric of the shear zones consists of a complexly anastomosing, in part sigmoidal, 'phacoidal' cleavage (Figs. 7, 9 and 10). Individual surfaces are polished or glazed, and in some cases bear subtle grooves or striations. In thin section the cleavage lamellae are defined by discrete fractures surrounded by concentrations of clay and carbon. They cut through asymmetric microfolds, and there are bent clay flakes and offset microstructures adjacent to many lamellae. This indicates that shear has taken place parallel to the phacoidal cleavage surfaces at some point in their deformation history. Scanning electron microscopy studies of cleavage lamellae surfaces reveal the presence of microstriations that support this conclusion (Bosworth in prep.). The sense of shear on surfaces within the shear zones is again generally southeast-over-northwest, but the details of the movement history are more complicated. The average strike of the phacoidal cleavage is approximately perpendicular to the inferred overthrust direction (Fig. 4). All the structural evidence therefore suggests that the shear zones represent another aspect of the same deformational sequence as that responsible for the simpler detachment structures described above. The maximum thickness of the shear zones is about 20 cm.

The internal geometry of the shear zones is complicated by the presence of cross-cutting, small-scale thrust faults (Fig. 8). These faults appear to merge with the upper and lower bounding faults of the shear zones. As illustrated in Fig. 8, they frequently connect calcite-filled pull-apart structures, that confirm their thrust geometry.

The terminations of the shear zones have been examined in some detail. The eastern termination of the lower shear zone is located above Stake B shown in Fig. 6. This area is depicted in detail in Fig. 9. The lower bounding fault of this shear zone appears to be a major detachment surface for the entire section, as it runs the total length of the exposure and is defined by laminations of fibrous quartz and calcite separated by thin sheets of

Fig. 7. Photograph of the lower shear zone illustrated in Fig. 6, taken above Stake C. A small ramp and pocket of deformed shale is visible above the shear zone. This reverts to undeformed, fissile shale to the right of center. Length of the hammer handle is about 0.6 m.

polished and striated shale, the total thickness of which measures more than 2 cm in some places. As is illustrated in Fig. 9, the lower shear zone is preceded (spatially) by numerous risers off this detachment surface. In this area the shale is kinked or contorted in places, and begins to take on a sigmoidal appearance. The eastern termination of the upper shear zone is perhaps even more complicated (located above Stake D). Here the risers flatten out at about the level of the upper bounding fault of the shear zone (Fig. 10). Between these risers is a 'spaced' cleavage very similar to that found at the far eastern end of the outcrop (see above). Immediately adjacent to the lower bounding fault is a narrow (2–3 cm) zone of broken calcite veins that merges with a zone of sigmoidal cleavage of similar thickness, below the risers shown in Fig. 10. The initial portion of the shear zone contains several complexities, including a strongly contorted zone and an isolated packet of undeformed shale beneath the pre-shear zone ramp of the upper bounding fault. The lower bounding fault continues east to the footwall syncline in the Cherry Valley Limestone, where it appears to merge with the shale/carbonate contact (Fig. 6).

Although the western termination of the lower shear zone could not be excavated, the upper shear zone disappears between Stakes E and F. The details of the structure are much simpler here than at the eastern terminations. The lower bounding surface rises up gently, and merges with the upper surface (Fig. 11). The mutual surface continues a meter further west, parallel to shale fissility, where it becomes difficult to recognize. A number of gently SE-dipping thrust faults cut across the shale fissility at this point.

The only other example of a shear zone found in the Union Springs Shale is located in Cox's Ravine, just over 1 km northwest of the village of Cherry Valley itself. Here a very narrow shear zone, a few centimeters wide, is found at the base of the lowest bed of the Cherry Valley Limestone. Orientation of the internal phacoidal cleavage and fault striations are similar to those at the Chestnut Street exposure. Structures similar to these shear zones have also been documented by R. P. Nickelsen in the Valley and Ridge Province of central Pennsylvania (pers. comm. 1982).

INTERPRETATION OF SHEAR ZONE DEFORMATION HISTORIES

The observations made at Cherry Valley suggest a possible model for the evolution of the narrow shear zones. The through-going nature of the lower bounding faults suggests that these surfaces predate development of the shear zones, and are analogous to the detachment surfaces observed elsewhere in the Union Springs Shale (Figs. 3 and 5). The relatively simple structure of the western termination or 'leading edge' of the upper shear zone (Fig. 11) indicates that this is perhaps a stable configuration, that is displacement would have occurred on the upper and lower bounding faults at this point, but

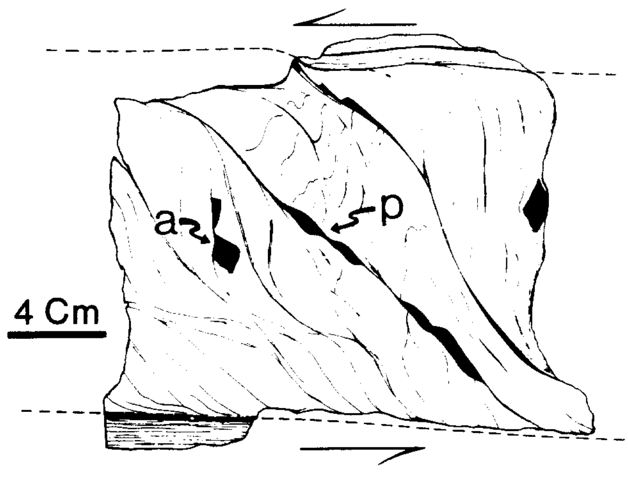

Fig. 8. Detailed sketch of a slabbed sample from the lower shear zone illustrated in Fig. 6. The shale was first coated with epoxy at the outcrop, and further impregnated in the laboratory before cutting. Several late, through-going thrust faults are visible cutting across finer cleavage surfaces in the shear zone. These faults developed quartz and calcite filled pull-aparts, labeled 'p'. Angular argillite chips ('a') probably represent the remains of a thin, boudinaged bed, now completely disrupted within the shear zone. (West is to the left.)

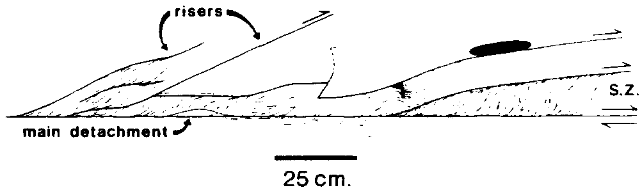

Fig. 9. Small-scale structures at the eastern termination or trailing edge of the lower shear zone shown in Fig. 6. Sketch is from just east of Stake B. Black elliptical object is a small carbonate concretion. Structure is very complicated, with the fabric above the main detachment resembling that within the shear zone, but not bounded by a discrete, continuous upper fault surface. Rotation of pre-deformation fissility appears to be an important process here in defining the final fabric. (West is to the right.)

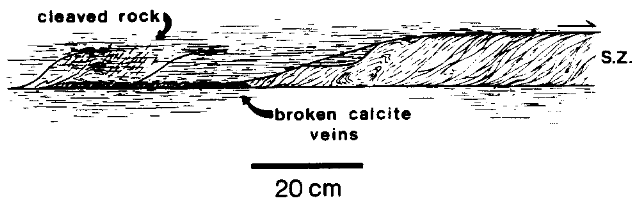

Fig. 10. Trailing edge of the upper shear zone shown in Fig. 6. Sketch is from above Stake D. Several faults can be seen rising off the main detachment and leveling out at about the same level as that of the upper shear zone bounding surface. Cleaving of the undeformed shale contributes to the final fabric of the rock above the detachment. (West is to the right.)

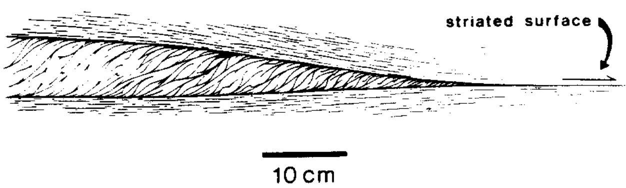

Fig. 11. Western termination or leading edge of the upper shear zone shown in Fig. 6. Sketch is from above and west of Stake E. Structure appears to be very straightforward, with the upper and lower fault-surfaces of the shear zone merging into one detachment that runs parallel to fissility in the shale. (West is to the right.)

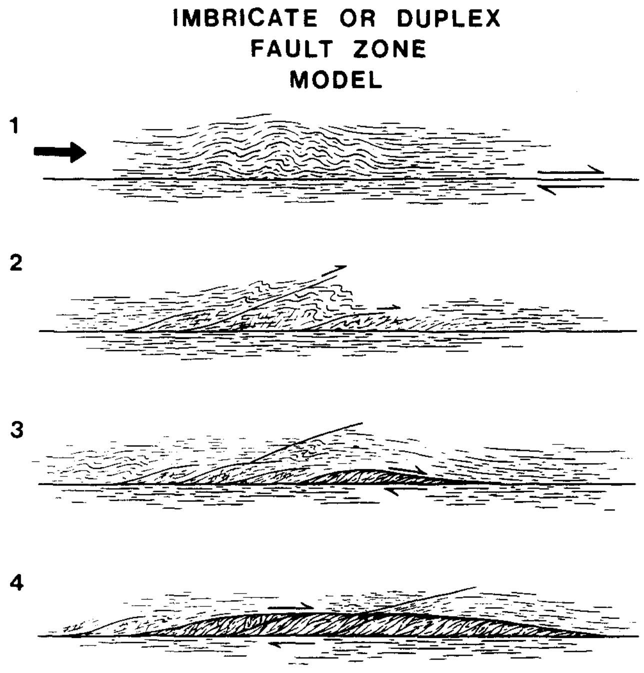

Fig. 12. An evolutionary model for the Cherry Valley shear zones. The final geometry of the shear zones is similar to a duplex fault zone, with early internal thrusts bounded above and below by through-going faults. These small-scale duplexes may have some evolutionary analogies with large-scale duplexes or imbricate fault zones, and as they can be observed in their entirety in a single outcrop, should prove useful in understanding thrust fault geometries at all scales of observation.

the shear zone would not have grown in size in this direction. At the eastern terminations or 'trailing edges' of the shear zones, however, the structure is quite complicated (Figs. 9 and 10). The material above the lower detachment surface in both cases was undergoing a great deal of deformation just east of each shear zone. A cleavage developed in some areas (Fig. 10), other sections underwent rotations, folding and kinking (Fig. 9), and numerous risers developed above the main detachment. There is a strong tendency for these ramp-like structures, particularly in front of the upper shear zone, to shallow out at the level of the upper bounding fault of the shear zone itself. The striations, offsets and pull-aparts associated with the anastomosing internal cleavage of the shear zones suggest that although these surfaces may not have originated as shear fractures, shearing certainly played an important role in their evolution.

A model interpreting these structural relationships is presented in Fig. 12. Detachment was initiated as a through-going fault, with localized folding of overlying shale sections (Fig. 12-1). As much of the Union Springs Shale contains discrete fault-detachment surfaces without any obvious crumpling of adjacent shale, folding does not appear to be a necessary percursor to the formation of the throughgoing faults. The stylolitic cleavage probably began to develop in the carbonate beds of the section at this time. Following some slip on the main detachment surface, risers and ramp-like features broke off the main fault, perhaps at sites where asperities were present or temporary lock-ups occurred (Fig. 12-2). In some areas this process led to the development of a duplex structure in the shale, with upper and lower detachment surfaces separated by several meters of folded or imbricated shale. Ramps also developed in the carbonate section, with offsets on the order of a few meters or less. A similar process also occurred on a smaller scale to produce the shear zones. At some point a small ramp merged back with the main detachment, surrounding a 'wedge' of deformed material that traveled along, above the main fault (Fig. 12-3). The new 'shear zone' continued to grow at its trailing edge by further imbrication and merging with other risers (Fig. 12-4). Each of the sigmoidal cleavage surfaces within the shear zones may represent one such imbrication event. These surfaces then underwent rotation to steeply dipping orientations as the shear zone experienced internal horizontal shortening in conjunction with continued shearing, their ends being dragged into parallelism with the bounding faults. This history should probably not be viewed as a series of discrete events, but rather as a continuum, with shortening of older portions of the shear zones occurring while new imbricates were still being added. Shortening in the adjacent shale and stiff limestone struts would be accomplished by the local folding, ramping and development of stylolitic cleavage described above. Although the kinematics of these shear zones may not precisely correspond with those interpreted for large-scale duplex structures, their geometries appear very similar.

REGIONAL SIGNIFICANCE OF DETACHMENT STRUCTURES

The thrust faults and duplex structures in the Union Springs Shale occur in an area of east-central New York previously believed to have escaped the effects of Appalachian detachment and overthrusting. The orientations of these structures indicate that this entire region has undergone a consistent upper-sheet movement to the northwest (average = 309°; Figs. 2 and 4). The Union Springs Shale has apparently acted as a décollement horizon in an area where the stratigraphically lower Salina Salt was not deposited. This area is the most external portion of the Appalachian Orogen, and the décollement horizon would therefore have stepped-up stratigraphically as it propagated away from more internal parts of the orogen, if the salt and shale detachment events are in fact related. Unfortunately, no age constraints can be placed on the timing of this deformation, except that it is post-medial Devonian. The detachment structures in the Union Springs Shale could therefore be either Acadian or Alleghenian in age.

CONCLUSIONS

Décollement in the Appalachian Plateau structural province of central New York occurred at through-going fault surfaces and more complex duplex structures in the Middle Devonian Union Springs Shale. In some areas these structures were accompanied by the development of narrow shear zones possessing an internal imbricate or small-scale duplex geometry. These shear zones are interpreted to have evolved through growth at their trailing edges, while the entire structure was transported above a main detachment surface. The shear zones, detachment surfaces and larger duplexes represent the initial stages of deformation in the décollement history of the Appalachian foreland.

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