Lower Paleozoic environments of deposition and the discontinuous sedimentary deposits atop the Middle Ordovician unconformity surface in New Jersey

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Abstract

Depositional environments of the Lower Paleozoic rocks of New Jersey indicate an evolving orogenic period. The Kittatinny Supergroup portrays a quiescent period of stable platform sedimentation. Regional uplift, erosion with concomitant broad open folding accompanied the initiation of the Taconic orogeny. On this regional unconformity surface, fluvial and paleokarst sediments were deposited. A lower clastic-argillite sequence characterizes this fluvial deposit. Locally it is capped by an upper carbonate sequence of shallow marine origin. Together these two rock sequences comprise the informally named "Wantage Formation." Paleokarst deposits related to the "Wantage" include infilled sinkholes and dolines along with cave collapse breccias and intraformational breccias.

A marine transgression in Trenton time preserved part of the "Wantage" in depressions as wave action winnowed away other signs of the subaerial erosion. The Jacksonburg Limestone was deposited during this transgressive event. Then as a foreland basin developed and deepened, a change in the type of sediment influx occurred as shown by a variation in the regional lithologic character of the Jacksonburg (crystalline limestone to an argillaceous limestone) and deposition of the overlying Martinsburg Formation. Deposition in the foreland basin culminated in a second regional uplift in Upper Ordovician to Lower Silurian time, producing the Taconic unconformity.

Introduction

Recent mapping of the Lower Paleozoic rocks in the Kittatinny Valley and the Highlands province of New Jersey (fig. 1) has delineated a sequence of localized and discontinuous alluvial and shallow-marine sedimentary rocks resting on the unconformity surface at the top of the Beekmantown Group. This rock sequence is here informally introduced as the "Wantage Formation." Paleokarst deposits beneath the unconformity surface are related to the newly-recognized unit but are not mappable at the 1:24,000 scale. A subsequent manuscript will formalize the "Wantage" for the revised Geologic Map of New Jersey to be published at the 1:100,000 scale in conjunction with the United States Geological Survey.

Field data suggest that the candidate formation was deposited in valleys extending along open synclinal troughs and on the flanks of the related arches. These structures formed in the Cambrian - Ordovician miogeoclinal prism as a result of the Taconic orogeny. The Cambrian - Ordovician tectonic environment of deposition is summarized to describe the sequence of events that led to deposition and subsequent burial of this highly variable unit.

Delineation of the "Wantage Formation" and related paleokarst deposits in New Jersey is important because comparable units from the southern and central Appalachians as well as the midcontinent region and Canada are of economic importance. Some paleokarst units have been hosts for economical, secondary base metal mineralization (Callahan, 1968; Sangster, 1988; De Voto, 1988; Haynes and Kesler, 1989). Mussman and Read (1986) note that deposits along the Knox unconformity are possible hydrocarbon reservoirs in the Eastern Overthrust Belt in the Appalachians. Haynes and Kesler (1989) show that hydrocarbons can accumulate in erosional highs which can be outlined by valley deposits. Paleovalley fills have already been exploited for hydrocarbons in the midcontinent (Howard and Whitaker, 1988).

Lower Paleozoic Rocks and Environments of Deposition

Lower Paleozoic rocks of New Jersey crop out in the Kittatinny Valley and as outliers in the Highlands province (fig. 1). The Kittatinny Valley comprises the southeastern part of the Valley and Ridge province, also known as the Great Valley. The northwestern part of the Valley and Ridge province contains Silurian molasse and younger marine-trangressive rocks of Silurian through Devonian age, which are described in detail by Epstein and Epstein (1969) and Epstein and Lyttle (1987). The Highlands province borders the Kittatinny Valley on the southeast and includes the New Jersey part of the Middle and Upper Proterozoic rocks of the Reading Prong (Drake, 1969). Cambrian and Ordovician carbonates within the Highlands are generally restricted to infolded and faulted intermontaine valleys in the southwest Highlands area (Kummel, 1940; Herman

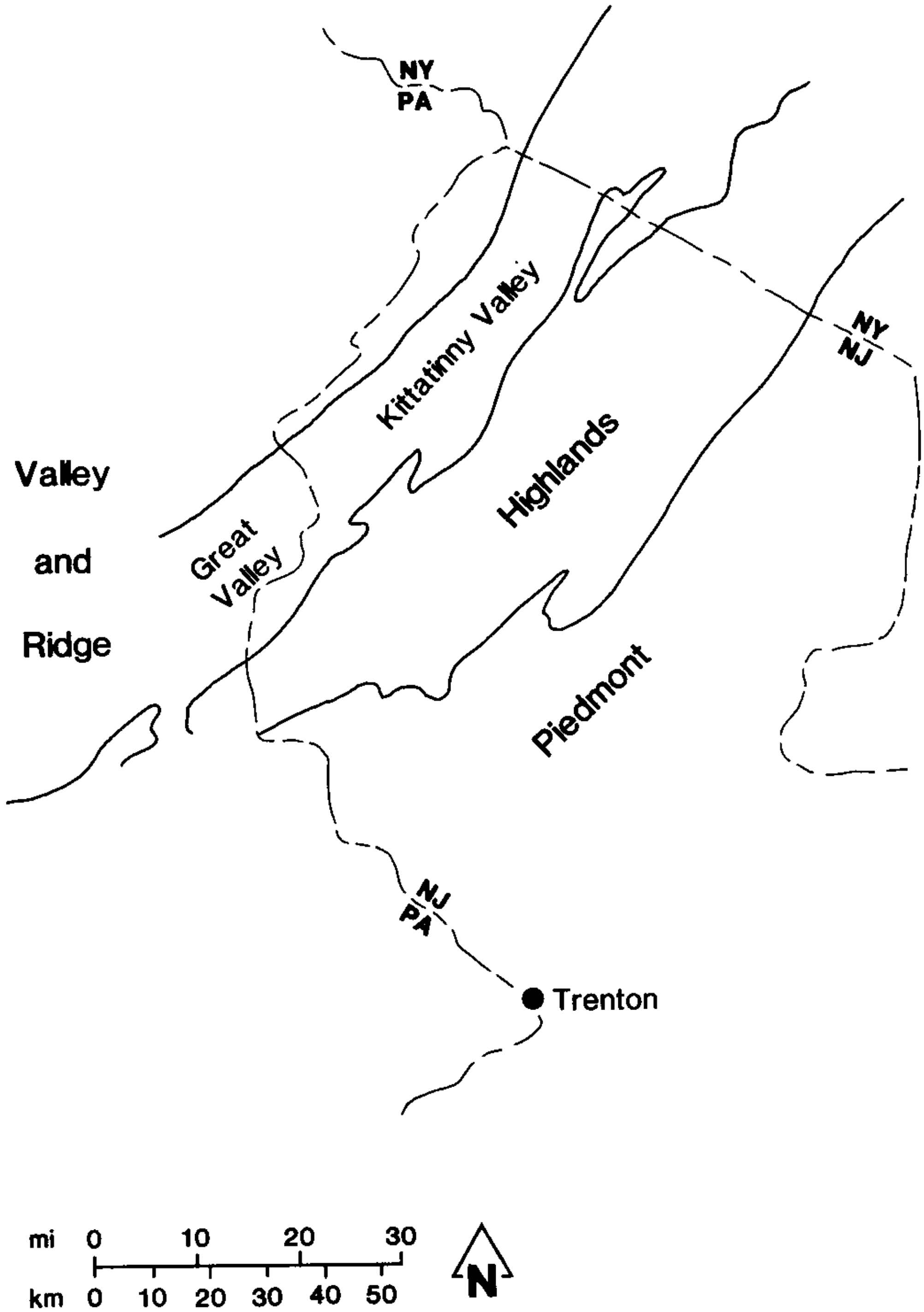

Figure 1. Kittatinny Valley and its setting among the provinces of northern New Jersey.

and Monteverde, this volume, pl. 2a). These carbonate valleys pinch out along strike to the northeast, and also farther to the southeast along the Newark Basin Border Fault System.

The Lower Paleozoic stratigraphy of New Jersey reflects the tectonic evolution from a drift facies, passive margin contintental edge to a convergent foreland margin of the Taconic orogeny. The environments of deposition reflect the tectonic evolution of an initial supratidal and shallow marine environment to a deeper neritic-flysch basin at the foreland of a convergent margin (Epstein and Epstein, 1969). This change included uplift and subaerial erosion of parts of the passive margin sequence caused by foreland migration of a peripheral bulge in front of an eastward dipping subduction zone (Jacobi, 1981; Shanmugam and Lash, 1982, 1983). A subsequent marine submergence of the eroded shelf in a foreland basin setting resulted in the mantling of limestone and flysch sediments over the Cambrian and Lower Ordovician rocks. A later uplift of the filled foreland basin caused subaerial erosion of the Middle and Upper Ordovician flysch deposits before blanketing by a Silurian molasse sequence. The uppermost Lower Ordovician through Upper Ordovician rocks record a continuous deformational event with synchronous sedimentation that culminated in the folding and faulting of all pre-Silurian rocks. A generalized stratigraphic column can be seen in figure 2.

The Hardyston Quartzite and the Kittatinny Supergroup of Drake and Lyttle (1980) represent the passive-margin stratigraphy. The Lower Cambrian Hardyston Quartzite is composed of arkosic sandstone, quartz sandstone and conglomerate resting nonconformably on Middle and Upper Proterozoic granites and gneisses of the Reading Prong (Aaron, 1969). This basal transgressive clastic sequence provides the base upon which the predominently dolomite of the Kittatinny Supergroup was deposited. The Kittatinny Supergroup includes in ascending order, the Lower Cambrian Leithsville Formation, the Middle Cambrian to Lowest Ordovician Allentown Dolomite and the Lower Ordovician Beekmantown Group. The Beekmantown Group is divided into a lower and an upper part.

The Leithsville Formation and Allentown Dolomite are predominantly dolomite with minor interbeds of quartz sandstone and shale. Sedimentary structures include mudcracks, hardgrounds, stromatolites, graded beds, cross-bedded clastics and dolomites, oolites and flat-pebble conglomerate. These features indicate minor eustatic flucuations in an environment varing from supratidal to intertidal (Drake, 1969). The lower part of the Beekmantown Group is also dominantly dolomitic, but contains minor limestone and quartz sand lenses. These lithologies and features indicate a continued subtidal-neritic depositional environment extending into the Lower Ordovician. However, water circulation was restricted during deposition of the fetid dolomite in the basal sequences of

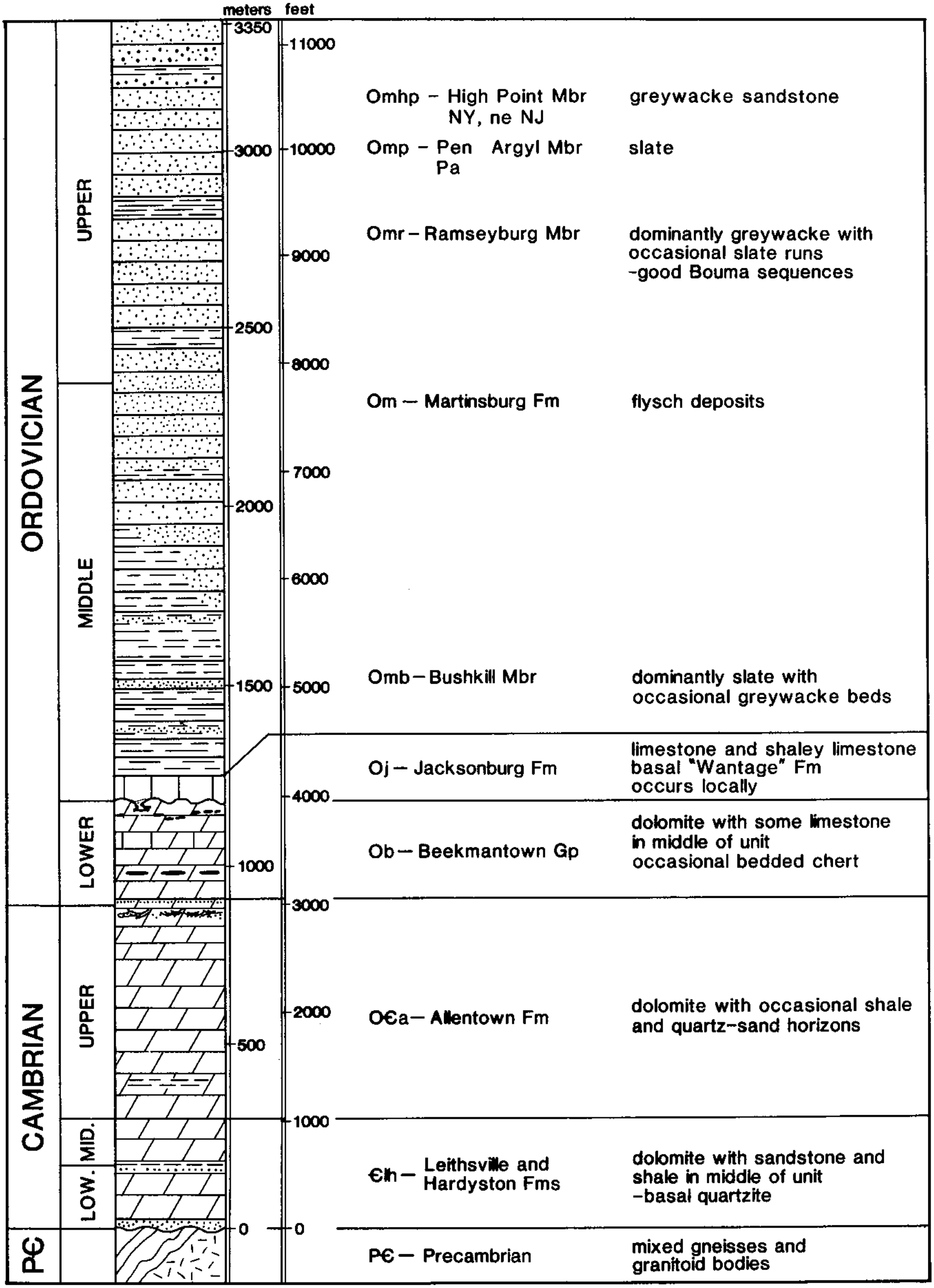

Figure 2. Generalized stratigraphic column for the Kittatinny Valley and southwest Highlands area

the upper part of the Beekmantown Group (Hobson, 1963). The overlying sequence of non- fetid dolomite suggests a subsequent return to a more open circulation. A few local beds of limestone also occur in the uppermost part of the Beekmantown Group in places where erosion was minimal before subsequent mantling by the Jacksonburg Limestone. No noticeable carbonate-platform tilting can be seen between beds in the Kittatinny Supergroup (Kummel 1940).

Savoy (1981) suggests that deposition of the carbonate platform continued at least into the Whiterock Stage before it was disturbed by a regional uplift and concomitant erosion forming the unconformity surface at the top of the Beekmantown. The Whiterockian age is based on faunas obtained from dolomite cobbles originating from the eroded Beekmantown and deposited in the Jacksonburg Limestone. The pebbles are from outcrops near Hope, New Jersey (Savoy, 1981). The unconformity at the top of the Beekmantown thus records the first major sign of the Taconic orogeny. Kummel (1915) suggests that at least 800 feet of the Beekmantown was locally eroded. Erosion generally decreases along strike from the northeast, just over the state boundary into New York, to the southwest into Pennsylvania (Savoy, 1981; Savoy and others, 1981). Savoy and others (1981) suggest that the Beekmantown unconformity in the Great Valley of New Jersey requires stratigraphic relief of 900 feet, near the Pennsylvania border, to 1300 feet, near New York and that a minor regional tilting can account for this relief. However, in southeastern New York, local structural complexities need to be invoked (Savoy, 1981; Savoy and others, 1981). This study shows that a simple platform tilt with paleokarstification cannot account for the degree of local erosion into the Beekmantown Group. Nor can it explain the diversity and distribution of sediments of pre- Trenton and Trenton age deposited on the unconformity surface. Rather, it is suggested that a more undulose carbonate platform surface, marked by broad, low amplitude, longitudinal folds eaxisted during subaerial ersosion and karstification during the uppermost Lower to Middle Ordovician (Herman and Monteverde, this volume).

A strong cross-strike variation in the degree of pre-Silurian erosion of the Kittatinny Supergroup was first recorded by Kummel and Weller (1902). They noted that the unconformity in the Green Pond outlier represents much deeper erosion into lower parts of the Kittatinny dolomite and locally extends to basement, in contrast to the Beekmantown unconformity in the northwest Highlands and Kittatinny Valley. They also suggested that erosion of the Beekmantown Group in the Green Pond area could have continued until deposition of the Silurian Green Pond Conglomerate, with only local deposition of parts of the Middle Ordovician Martinsburg Formation. However, field relations suggest that erosion of the Kittatinny Supergroup in the Green Pond Outlier stems from an Upper Ordovician - Lower Silurian regional unconformity of Taconic time (Rodgers, 1971). This erosional event probably beveled low enough to remove all signs of the older Beekmantown unconformity in areas hindward of the Kittatinny Valley.

The first post-Beekantown unconformity deposit in New Jersey is the "Wantage Formation". The lower "Wantage" is a clastic-to- argillaceous sequence which grades upward into a shallow marine carbonate sequence that is suggested as conformable with the overlying Jacksonburg Limestone. Markewicz and Dalton (1977) described several occurrences of this unit and interpreted them as paleokarst infillings. They noted that the contact between the "Wantage Formation" and the Beekmantown Group varied from an angular unconformity to a disconformity, depending on its position in the karst valley. The clastic-argillaceous and carbonate sequences need not occur together in any single outcrop. The discontinous character and compositional variability of the unit is affected by structural relief and variable source rocks as described in the "Wantage Formation" section below.

The Jacksonburg Limestone consists of a lower, fossiliferious, fine to coarsely crystalline limestone with some dolomite, chert and limestone cobble conglomerate (Cement Limestone Member) that grades upward into a more argillaceous limestone (Cement Rock Member) (Drake, 1969). The formation represents a major marine- transgressive event in the early development of a foreland basin. The Cement Limestone Member contains some cobble-conglomerate beds both on the unconformity surface and higher in the sequence (Kummel, 1901; Miller, 1937). The conglomerate beds have rounded to subrounded cobbles which are eroded pieces of the underlying Beekmantown Group (Markewicz and Dalton, 1977; Savoy, 1981). Kummel (1901) suggests moderate transport of these cobbles. Savoy (1981) differentiates rounded cobbles associated with stream deposits from angular clasts of paleokarst infill deposits. Elsewhere in the central Appalachians, angular blocks of weathered rocks of the Beekmantown Group occur as surface deposits on erosional highs (Mussman and Read, 1986). They are not sinkhole deposits but are composed of the eroded and bisected surface rubble related to overlying soil profiles which were reworked and mantled during subsequent marine transgression. Stream-deposited cobbles that occur above the base of the limestone sequence suggest that initial deposition of this unit occurred in restricted lows, and that as the depositional basin became more submerged due to continuing compression, erosional highs were inundated and their loose rubble was either covered in situ, or susequently reworked and deposited into lows over earlier laid Jacksonburg limestone beds.

Weller (1903) and Miller (1937) report a hiatus in sedimentation towards the base of the Jacksonburg Limestone at the type section in Warren County, NJ. This feature records a fluctuating shoreline before final submergence of the irregular terrane and subsequent deposition of the remaining portions of the Jacksonburg. The Cement Rock Member increases in thickness and volume compared to the Cement Limestone Member in both the Highlands and Kittatinny Valley towards southwestern New Jersey and eastern Pennsylvania (Miller, 1937; Sherwood, 1964; Drake, 1967; Davis and others, 1967; Drake and others, 1969). This implies that regional basin subsidence was more pronounced southwest and southeast of the present-day Kittatinny Valley during the Middle Ordovician. Regionally, the Jacksonburg Limestone grades upward into the basal claystone shale/slate of the Martinsburg Formation (Kummel, 1940; Drake and Epstein, 1967; Drake, 1969).

The Martinsburg Formation in eastern Pennsylvania and western New Jersey has been subdivided into three members. In ascending order they are the Bushkill, Ramseyburg and Pen Argyl Members (Drake and Epstein, 1967). The lithology of the Bushkill and Ramseyburg Members is indicative of flysch sedimentation (Drake, 1969). The Bushkill Member is mostly claystone slate with lesser amounts of graywacke siltstone and carbonaceous slate; its mean grain size increases upward. The Ramseyburg Member is mostly graywacke sandstone and siltstone with a calcareous matrix, but it contains some interbedded shale sequences. Drake (1969) suggests that the Ramseyburg Member was deposited during the peak of Taconic tectonism. The Pen Argyl Member crops out almost entirely in Pennsylvania. It extends eastward across the Delaware River into Warren County, N.J. and pinches out at the surface along Kittatinny Mountain (Drake and others 1969). This upper member contains thick-bedded slate and is thought to represents post-peak-stage Taconic tectonism (Drake, 1969). Drake also proposes that the restriction of the Pen Argyl largely to this area in Pennsylvania is related to the Martinsburg basin morphology.

Another upper member of the Martinsburg Formation which has recently been identified in the northeast part of the Kittatinny Valley continues northeastward into New York. It consists of a thick-bedded graywacke sandstone with a siliceous matrix. Thinner-bedded, planar-laminated to massive shales are interbedded with the coarse clastics, which also contain ellipsoidal rip-up clasts of shale. Drake (in press) has designated this sequence the High Point Member. In this area, the Ramseyburg Member is also coarser and more siliceous than it is to the southwest. These facies relations indicate more proximal deposits to the northeast and more distal, finer- grained flysch concentrations to the southwest.

Taconic tectonism continued with flysch deposition into a foreland basin centering in the current Valley and Ridge province and extending hindward into the Highlands province. The foreland basin was subsequently uplifted in Late Ordovician to Early Silurian time (Rodgers, 1971; Epstein and Epstein, 1969; Epstein and Lyttle, 1987) which locally resulted in a regional unconformity of Taconic age. The angular discordance between the Ordovician Martinsburg and the Silurian Shawangunk Formation varies along strike. Epstein and Lyttle (1987) describe the Taconic unconformity along a 120 mile strike length from eastern

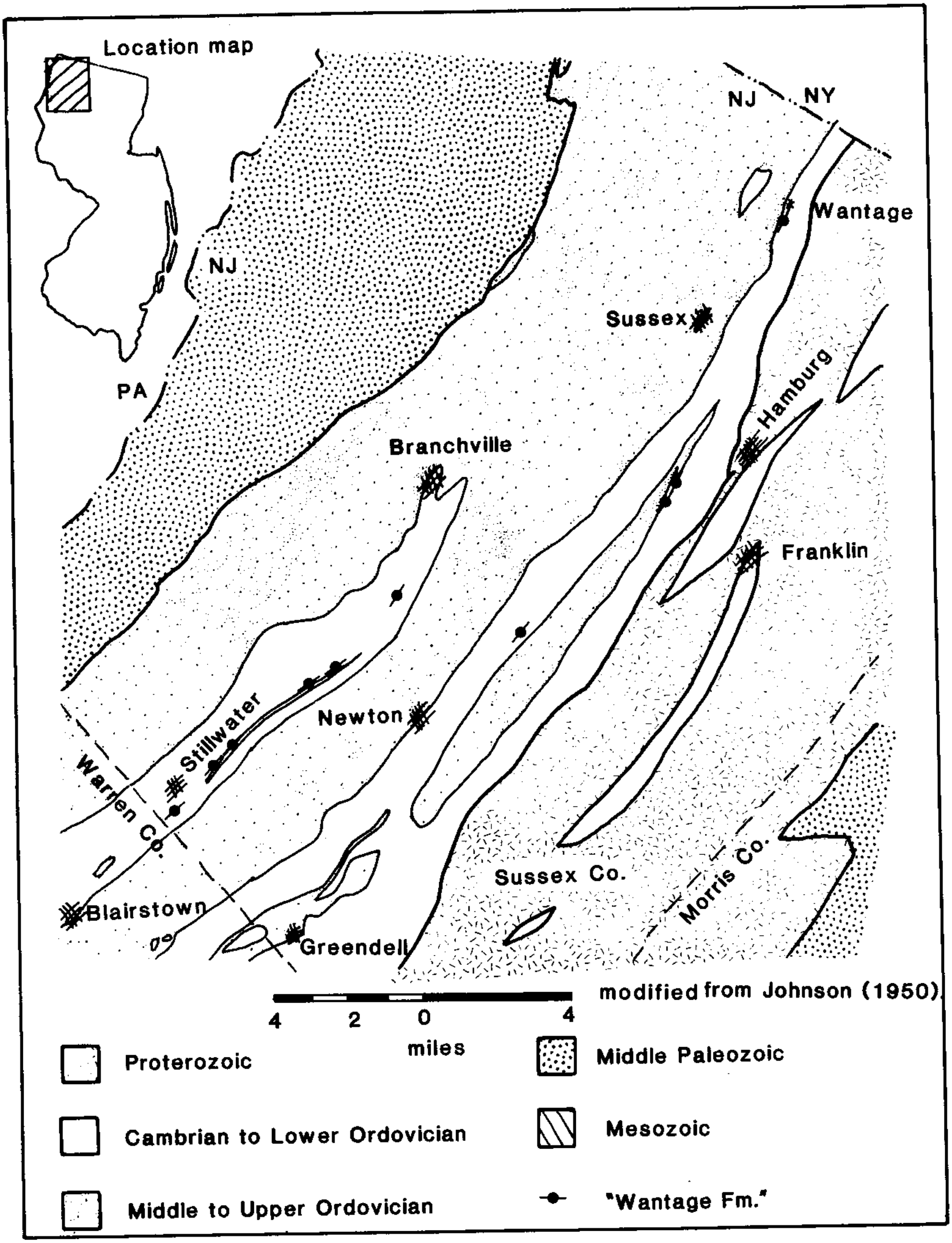

Figure 3. Outcrop locations of the "Wantage Formation" in northeastern Kittatinny Valley.

Pennsylvania through New Jersey and into southern New York where the angular discordance ranges from negligible to a maximum of 15 degrees. In eastern Pennsylvania both an angular unconformity and disharmonic folding occur in the units at the unconformity surface (Epstein and Lyttle, 1987; Herman and Monteverde, this volume). At these locations a detachment surface along the unconformity surface is necessary to explain the disjunctive fold patterns. This detachment has been named the Blue Mountain decollement by Drake and others (1969), and Epstein (1973). Taconic folds in the Martinsburg Formation are described by Epstein and Lyttle (1987) as mostly broad and open except north of Ellenville, New York where deformation and the angular unconformity are intense. Epstein and Lyttle (1987) describe a dimictite on the unconformity surface in southwestern New York State that is generally 1 foot (31 cm) thick. They suggest that this 'weird unit' is colluvium from a totally eroded source rock which could relate to rocks currently cropping out to the east of the exposed unconformity. Subsequent shearing masked much of the original fabric of this unusual diamictite. The folding and faulting related to the Taconic orogenic event are described by Herman and Monteverde (this volume).

The "Wantage Formation"

Recognition of the areal extent of the "Wantage Formation" has been greatly increased since several exposures were first described by Markewicz and Dalton (1977). They did not map these rocks as a separate unit or delineate their regional extent. Recent mapping shows that the "Wantage Formation" is widely distributed thoughout the northwestern Highlands and Kittatinny Valley in each of the major Paleozoic belts containing Ordovician carbonate rocks (figures 1, 3 and 4). Except where modified by structural complexities, the formation rests in depressions on the unconformity surface at the top of the Beekmantown Group and, where the carbonate sequence is present, grades upward into the Jacksonburg Limestone. It commonly occurs as isolated, elongated, lense shaped bodies having a maximum estimated thickness of 150 feet (46 m) and a maximum length of 20,000 feet (6.1 km). A semicircular outcrop pattern occurs where sediments infill doline-like depressions on the unconformity. The longer, narrow outcrop patterns suggest alluvial deposition in paleovalleys. Similar types of deposits have been described in the central and southern Appalachians (Cooper and Prouty, 1943; Cooper, 1944; Miller and Brosge, 1954; Harris, 1960, 1969; Lowry and others, 1972; Mussman and Read, 1986; Haynes and Kesler, 1989; Mussman and others, 1988) and in Canada (Johnson and Rong, 1989; Kerans and Donaldson, 1988; Desrochers and James, 1988).

Regionally, the "Wantage Formation" consists of a lower clastic-argillite sequence which grades upward into an upper carbonate sequence. The argillite's color varies between grayish olive (10Y 4/2), grayish red (5R 4/2 - 10R 4/2) and medium gray (N5). It contains disseminated, subangular to subrounded sand- to

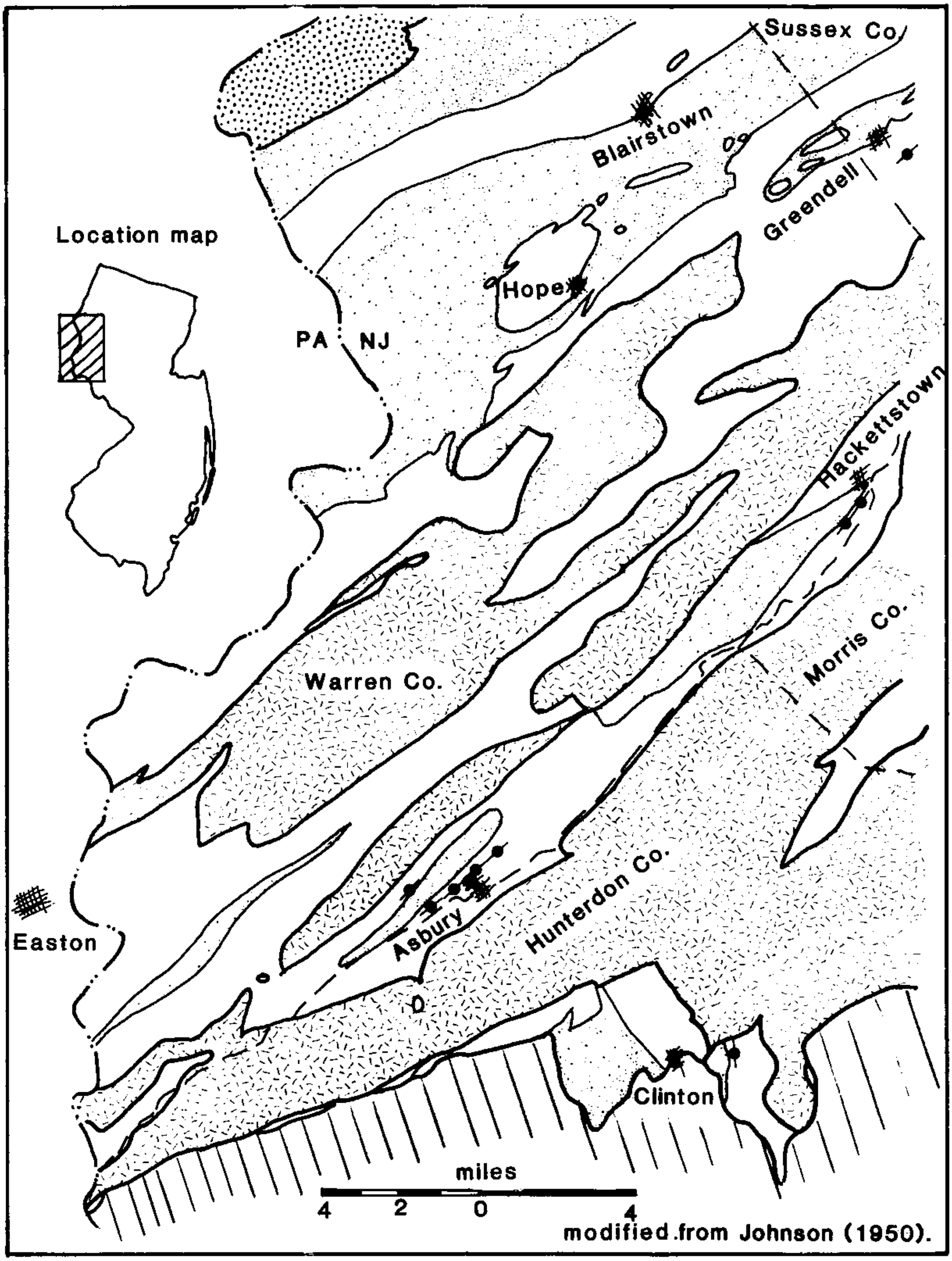

Figure 4. Outcrop locations of the "Wantage Formation" in southwestern Kittatinny Valley and the southwest Highlands area. Note symbols same as in figure 3.

pebble-sized chert clasts. At most outcrops interbeds and lenses of subangular quartz sand are evenly distributed throughout the argillite. Trough cross-bedding, edgewise conglomerate and convolute bedding are common. Near the base, subrounded dolomite and chert cobble-to-pebble conglomerates can recur; they commonly lense out and vary from matrix- to clast-supported. The conglomerate beds have a scoured basal contact and the cobbles are generally aligned along bedding or are slightly imbricated. As suggested by Harms and others (1982), imbrication of conglomerate clasts and trough cross-bedding suggest a fluvial environment of deposition. Matrix material consists of fine quartz sand, chert gravel, argillite and dolomite; the quartz sand and chert gravel are mainly in the lower conglomerate beds. The argillaceous material, along with the subangular chert fragments suggests a reworked soil material (Markewicz and Dalton, 1977) deposited in a fluvial environment. A similar unit has been reported by Harris (1960) in the southern Appalachian region. In New Jersey the chert fragments and frosted quartz sand grains are the relatively insoluble material which would resist weathering in a soil profile to a greater extent than the host dolomite or limestone. The lack of well developed roundness of the chert gravel supports limited transport and a local source terrain. Further evidence for limited transport and reworking is that the chert does not commonly occur concentrated into a lag deposits but is usually "floating" in argillite. Preliminary anaylsis of the argillite shows the presence of kaolinite with lesser amounts of illite. This chemistry may indicate a well- weathered source terrain or could solely be inherited from the parental carbonate. Clearly more work is needed to decipher this.

A generalized carbonate sequence contains interbedded medium light- to medium dark-gray, fine- to medium-bedded, fine-grained limestone and dolomite. The beds are massive to locally laminated. The upper contact with the basal calcarenite of the Jacksonburg Limestone is thought to be conformable. The carbonates were deposited in a shallow marine environment which marks the first evidence of a post-unconformity marine transgression. Generally the lower clastic-argillite sequence is thicker than the upper carbonate sequence.

The ratio between the clastic-argillite and carbonate components varies considerably between different occurrences of the "Wantage Formation" (fig. 5). The type section just south of Beaver Run Road, 1.7 miles west of the town of Hamburg, best represents the generalized regional sequence; it has both the lower clastic- argillite and upper carbonate sequences. The lower clastic- argillite section is dominated by a grayish olive (10Y 4/2) fine- to medium-bedded argillite with disseminated subangular chert sand and chert pebbles. Small (less than 2 inches (5 centimeters) long) lenticular pods of limestone occur within quartz sand lenses in the lower part of the sequence along with several very thin to thin interbeds of rounded to subrounded quartz and chert sand having basal scour and fill structures. The carbonate sequence contains medium light to medium dark-gray (N4 to N6), thin-bedded dolomite, limey dolomite and limestone. These fine-grained carbonates are massive to wavy-laminated. Both the upper and lower contacts are covered. Markewicz and Dalton (1977) describe a contact between the "Wantage Formation" and the Beekmantown Group at this type section. They suggest that a small soil-like zone between the two is apparently a disconformable contact.

In the section near Stillwater, Sussex County, the clastic- argillite sequence is repeatedly interbedded with the carbonate sequence (fig. 5). The sequence contains interbedded sequences of silty to shaley dolomite, suggested as detrital in origin, a few very thin beds of quartz sand, and thick-bedded chert cobble conglomerate with mostly a dolomite matrix. The cobbles range from dolomite to chert with a higher proportion of chert cobbles in the lower conglomerate beds than the upper conglomerate beds. The matrix also appears to have a higher quartz sand content in the lower conglomerates. A basal scour marks the lower contact with the detrital silt-sized dolomites. Fine laminations can be seen in the dolomite interbeds. No argillite is seen. However along strike, there are outcrops of a thin bed of medium light- gray, silty argillite which contains trough cross-bedding and convoluted bedding. Several other longitudinal lenses of the cobble conglomerate also occur along strike. The elongated character of these different outcrops, their compositions, and their sedimentary structure suggest that a fluvial environment existed during "Wantage" emplacement before deposition of the Jacksonburg Limestone.

In the Asbury, Warren County section no carbonate has been noted. This could simply be a structural complication inasmuch as a fault apparently cuts the upper contact of the "Wantage" with the unexposed Jacksonburg Limestone. Grayish olive, argillite to silty argillite with dissemenated pebbles of subrounded to subangular chert and quartz are common here. Fine laminations occur in the siltier beds. A dolomite-and-chert pebble conglomerate and a medium-grained quartz sandstone overlie the argillaceous beds. Dolomite pebbles are subrounded and highly weathered. The chert pebbles are subangular to subrounded and mostly white. The source rock for the chert can be seen along strike where the Beekmantown Group has not been extensively eroded. Matrix material contains green argillite, frosted quartz-sand grains and detrital dolomite. The sandstone resembles the conglomerate matrix in composition. Cross- and planar-bedding can be seen in the sandstone.

In the Hackettstown section in Morris and Warren Counties, there is an abrupt contact between the grayish-olive argillite and the basal Jacksonburg, with no apparent change in strike and dip between units. Immediately along strike to the northeast, the entire sequence thins and the argillite grades upwards into a siltstone. Sedimentary structures include trough and planar cross-bedding, graded bedding, and edgewise conglomerate with shale rip-up clasts. Farther along strike

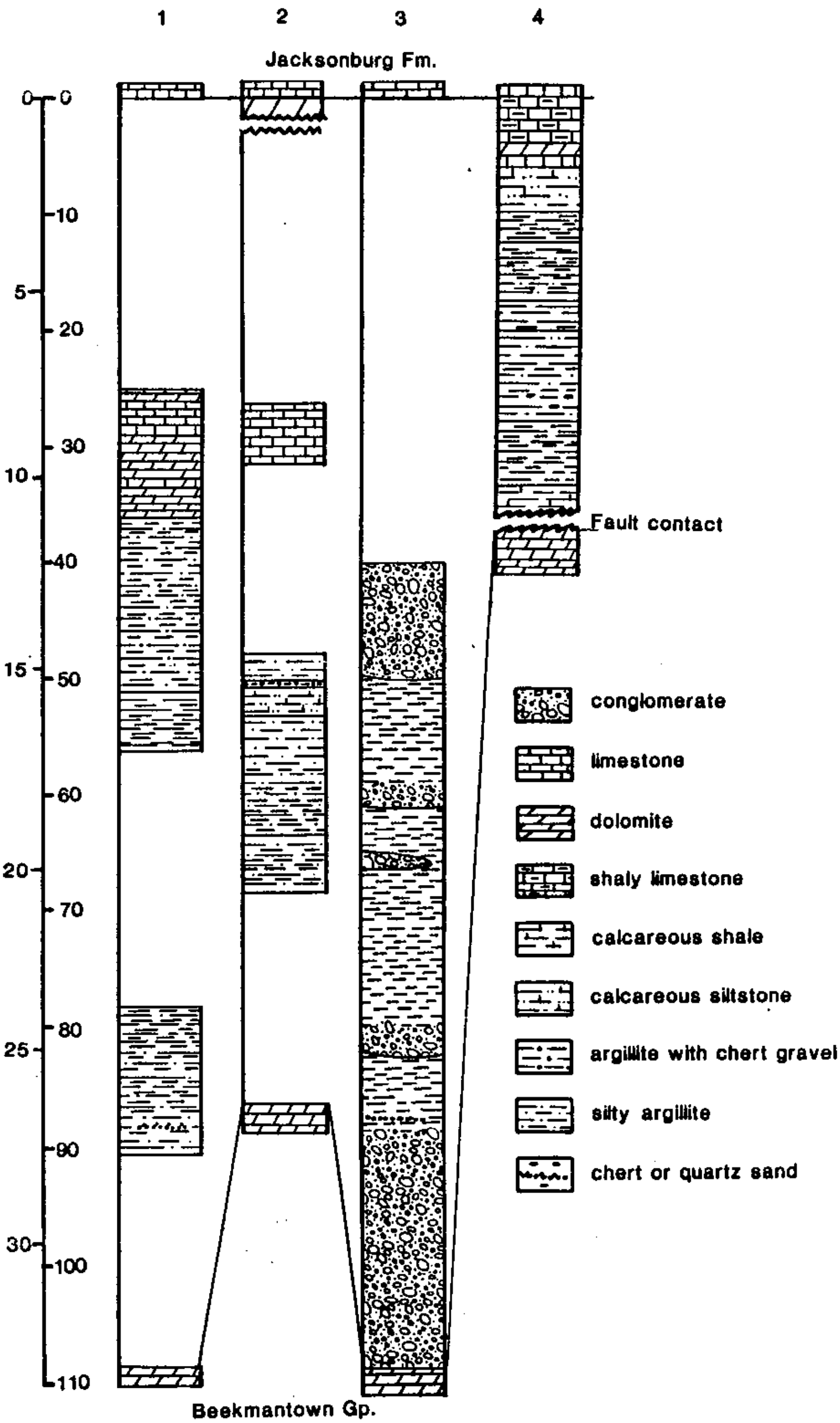

Figure 5. Lithology and correlation of four measured sections of the "Wantage Formation". (1),(2) west of Hamburg, (3) Stillwater, (4) Wantage.

a sequence of a grayish-olive argillaceous siltstone and a thin black shale grades into a limestone. All the beds are thought to belong to the "Wantage Formation" although the limestone could be the basal Jacksonburg Limestone.

Fossils have been ineffective in dating the "Wantage Formation". A slightly abraded conodont assemblage of Canadian age has been reported by Karlins and Repetski (1989) from the Stillwater section. This fauna yielded a spurious age because it represents a reworked fauna liberated from rocks of the Beekmantown Group. Repetski (1985) reports similar relations from northeastern Tennessee where abraded, slightly weathered conodont assemblages were obtained from reworked chert gravel and clay material representing eroded carbonate deposits on the Knox unconformity. Like the fauna recovered in New Jersey, the Tennessee conodont assemblage is much older than the basal unconformity deposits can be. The most reliable estimate of the age of the "Wantage" is bracketed by the youngest dolomite or limestone cobble in the Jacksonburg Limestone as identified by Savoy (1981)(early Whiterockian) and the oldest age represented in the Jacksonburg Limestone, which is either latest Blackriverian (Weller, 1903) or earliest Trenton (Miller, 1937). Therefore the age of the "Wantage" is Whiterockian to early Trenton. Further work is necessary to more closely date the "Wantage". Patchen and others (1985) correlates the "Wantage" with the "Pamelia Formation, green unit" of New York, thereby assigning a lower Blackriver age. This leaves a major time span of nondeposition or deposition and subsequent erosion between the "Wantage" and the Jacksonburg Limestone. As the Pamelia only outcrops in northcentral New York and has not been traced into New Jersey, a direct correlation seems inappropiate. Therefore introduction of a new formation is warranted.

The "Wantage Formation" commonly crops out in narrow, longitudinal bodies. Lithologic composition and sedimentary structures point to a fluvial depositional environment for the clastic-argillite components. The carbonate sequence is probably a shallow marine deposit. An interesting question relating to the shape of these bodies is: how did fold forms of Taconic age affect the deposition of the "Wantage" components. In order to reconstruct the Taconic geomorphology, the structural complexities of younger deformation events must first be removed from the encompassing rock bodies. These procedures are presented in detail by Herman and Monteverde (this volume). However restoration of the original fold and stratigraphic relations, is hampered by the common occurrence of shearing associated with Alleghanian thrust faulting along the contact between the "Wantage Formation" and the surrounding, more competent rocks. This is due to the competency contrast between the dolomites of the Kittatinny Supergroup and the argillites and limestones of the "Wantage Formation" and Jacksonburg Limestone. With the deformation effects of the Alleghanian orogeny removed, the "Wantage Formation" commonly retrodeforms to keels in synclinal troughs of Taconic age and as wedge-shaped deposits shed on the flanks of related arches. It is therefore assumed that open, broad folds on the platform shelf formed at an early time during the Taconic orogeny and coincided with the regional arching associated with the unconformity above the Beekmantown Group. During this erosional period karstification and a well developed soil profile formed on the subaerially exposed carbonates. Erosional lows formed along the flanks of arches and in the keels of synforms. With further erosion, longitudinal alluvial channels were cut into these troughs, and the "Wantage Formation" was deposited. As the seas of Blackriver to Trenton age rose, transgressive wave action may have winnowed away some fluvial beds before laying down the upper Wantage carbonate sequence or the basal beds of the Jacksonburg Limestone. This same wave action would have eroded the soil material from the weathered carbonates. This could explain the limited distribution of the preserved bodies of the "Wantage Formation". The "Wantage" also occurs as depression (doline) and sinkhole infills. Here the outcrop pattern is smaller and more wedge-shaped with more draping of beds on the depressions. A block diagram depicting the proposed depositional environment for the "Wantage Formation" is shown in figure 6.

Related Paleokarst Deposits

Paleokarst deposits both on the unconformity surface and those within the Beekmantown Group which are found in New Jersey are similar to those described elsewhere in the central and southern Appalachians by Callahan (1968), Fagan (1969), Harris (1969), Smith (1980), Mussman and Read (1986), and Mussman and others (1988). Similar deposits are also reported in Canada by Desrochers and James (1988), Kearns and Donaldson (1988), and in the Leadville district of Colorado by De Voto (1988). These deposits are mostly paleosolution breccias in sinkholes and caves, and intraformational breccias (fig. 7).

Sinkholes and dolines are characterized by sharp and irregular contacts between the infilled material and the host rock although gradational contacts can be seen. The solution breccia may grade laterally through rotated block breccia, into open-network breccia and fitted "crackle" breccia until competent rock is reached (Choquette and James, 1988). Markewicz and Dalton (1977) describe an occurrence of a solution breccia 300 to 400 feet (91-122 m) wide and several hundred feet deep with this type of gradational wall rock contact. Angular to subangular blocks from the host beds and from collapsed overlying units are the major clast constituents. Matrix material ranges from a medium- to dark-gray, fine- to medium-grained dolomite, and the cement can range from a white, medium- to coarse-grained calcite to a green argillite depending on the location. The green argillaceous material is considered an infilling of a collapsed soil horizon. Sorting is extremely poor. The contacts are generally perpendicular to bedding but can branch out and become horizontal at depth. When contacts are

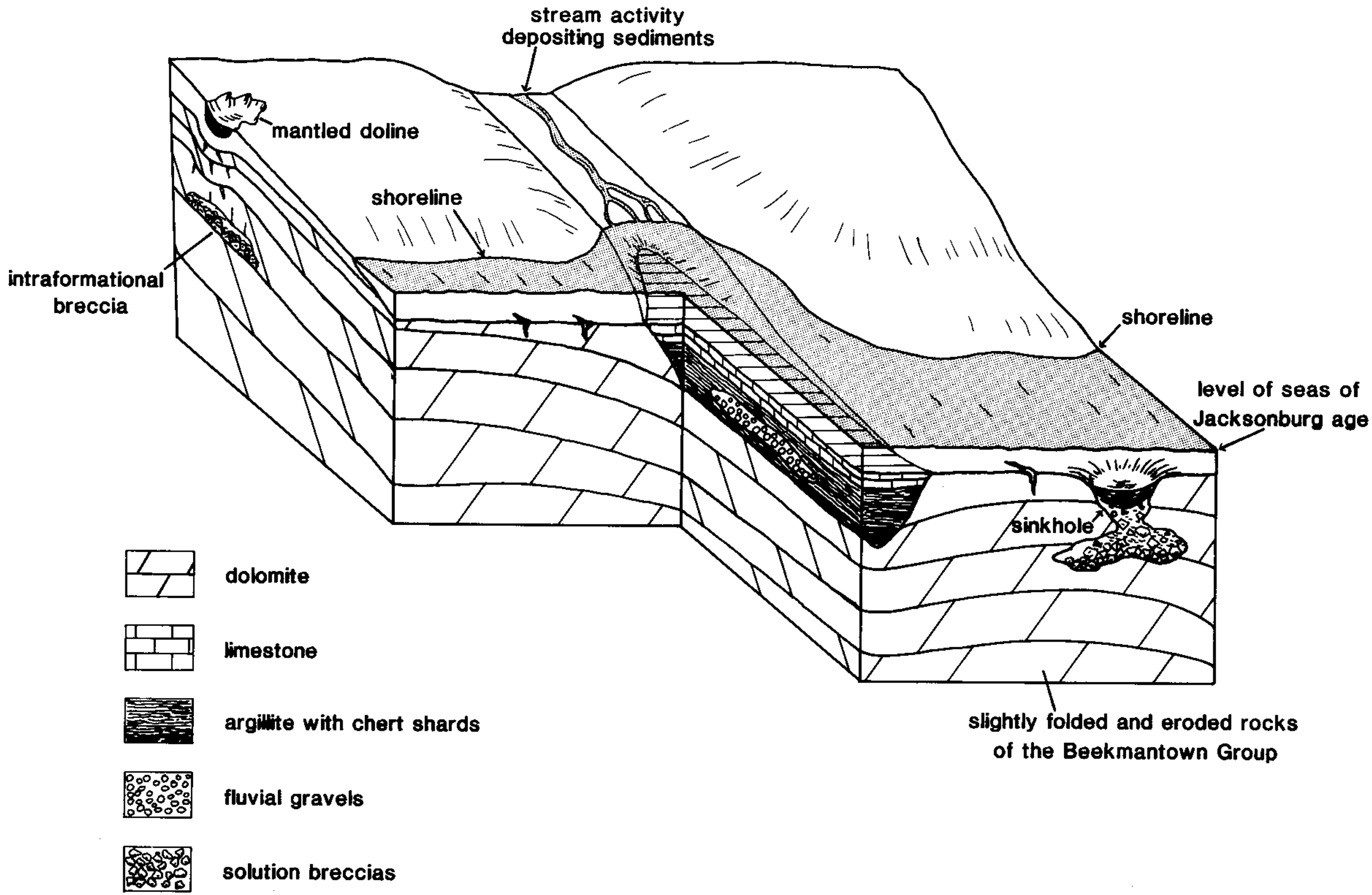

Figure 6. Block diagram showing proposed environment of deposition for the "Wantage Formation".

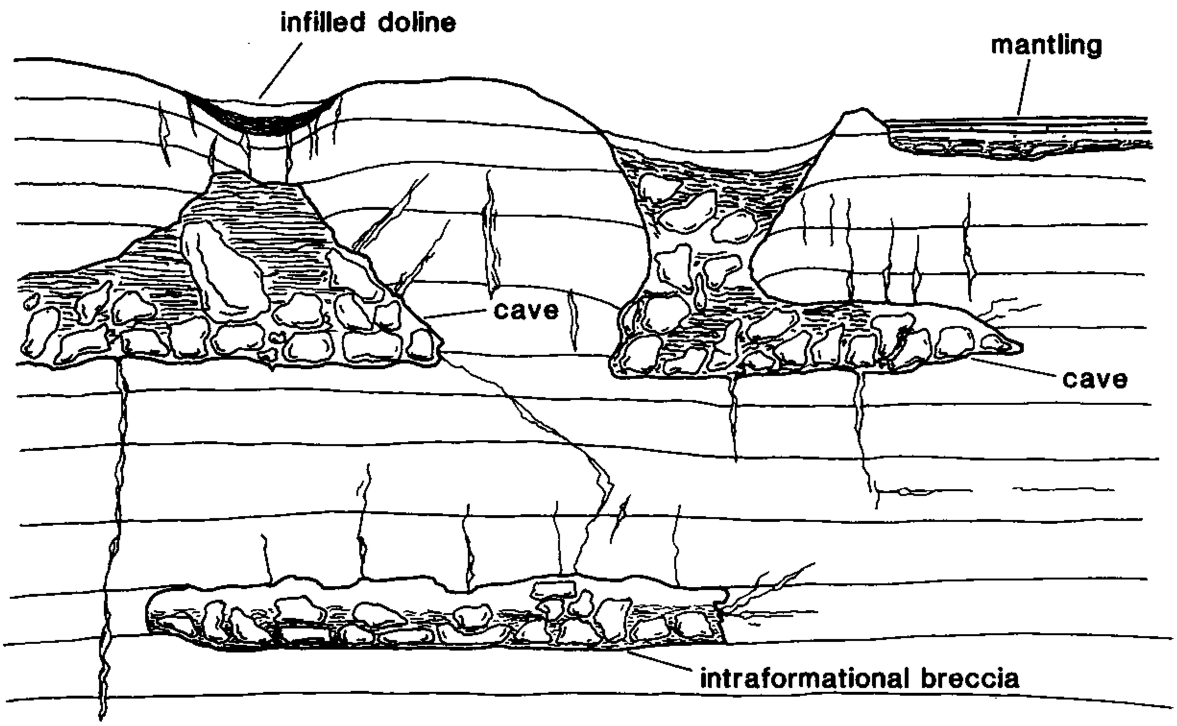

Figure 7. Generalized sketch of types of paleokarst deposits.

Figure 8. Line drawing (from photograph) showing paleosinkhole in Alpha, NJ. Infilling of eroded area interrupts bedding dipping from upper left to lower right.

horizontal a roof commonly occurs and the body is classified a cave. Figure 8 shows a small infilled sinkhole of Lower Paleozoic age exposed in a railroad cut in the town of Alpha, Warren County.

Caves described by Mussman and Read (1986) for the central Appalachians are thin, sheet-like to irregular bodies, both perpendicular and parallel to bedding. They have sharp and irregular contacts with the host rock. In New Jersey, caves contain angular blocks of the host unit in a clast- to matrix-supported breccia. The matrix can range from a fine- grained detrital dolomite to a white, medium- to coarse-grained calcite or dolomite cement. Matrix material may be well sorted as seen elsewhere in the central Appalachians (Mussman and Read, 1986). Caves are usually not visibly connected to the unconformity surface.

Intraformational breccias are the host horizons of some common secondary ore deposits in the central Appalachains. Mussman and Read (1986) suggest that this type of breccia has a regular basal contact and irregular lateral and upper contacts. The main breccia can grade into a rubble breccia, into a crackle breccia, and finally into the host rock (Keating, 1983). All breccia clasts are angular and unsorted. Matrix material is dominated by medium- to coarsely-crystalline calcite and dolomite. Frequently the cement can be mineralized as in the Friedensville zinc deposit in Friedensville, Pennsylvania where a honey-colored sphalerite occurs (Callahan, 1968). Markewicz and Dalton (1977) describe a breccia of this type with a light-gray crystalline calcite and/or dolomite cement as common in the middle of the lower part of the Beekmantown Group.

Conclusions

In summary, the "Wantage Formation" is a paleokarst deposit as described by Choquette and James (1988). As suggested by Markewicz and Dalton (1977) it can directly fill sinkholes and dolines which occurred as lows on the erosion surface. Field data also suggests that the "Wantage" occurs as a fluvial deposit in erosional valleys related to the unconformity surface on top of rocks of the Beekmantown Group. It is suggested that these valleys formed in synclinal troughs and are on the flanks of neighboring arches, both consequences of Taconic orogenesis. Other paleokarst features related to the "Wantage Formation" include sinkholes, caves and intraformational breccias, all of Middle Ordovician age. These other features occur as isolated wedge-shaped lenses and as elongated bodies. Generally the "Wantage Formation" consists of a thicker, lower, clastic- argillite sequence which locally grades upward into a carbonate sequence. Both components can however be interbedded throughout the formation. Locally the carbonate sequence is absent, due to either nondeposition or structural complexities. Source rocks for the "Wantage Formation" are local and contain carbonate soil material, resistant quartz sand and chert fragments;

locally subrounded dolomite cobbles and pebbles are preserved. The upper carbonate component is shallow marine in origin.

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