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Foreland-basin sequence response to collisional tectonism

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ABSTRACT

As structural salients and recesses evolved from reentrants and promontories along the collisional continental margin associated with the Taconic orogeny, cross-strike structural features provided a mechanism for transferring zones of relative subsidence and uplift across the Appalachian foreland basin. The regional distribution of Lower Silurian clastic sequences reflects this tectonic influence. Thick, aggradational sequences formed in areas corresponding to salients in response to high rates of sediment supply and creation of sediment accommodation. As the rate of sediment supply exceeded the rate of accommodation added, shoreline progradation onto the distal foreland ramp produced upward-coarsening sequences. In areas of structural recesses, accommodation was created by erosion during sea-level fall and lowstand. Upward-fining sequences formed as the topographic lows were filled during subsequent sea-level rise.

Results from this investigation indicate that predictable variations in foreland-basin deposition and in the resulting stratigraphic pattern occur along regional tectonic strike as well as in the dip direction. The thickness of foreland-ramp sequences is greater in areas of salients than in recesses, whereas the ratio of sandstone to total thickness is greater in the recesses. Aggradational sequences grading laterally into upward-coarsening progradational sequences of the distal ramp characterize areas of relative subsidence, which provides a mechanism for creating sediment accommodation. In contrast, deep erosion, common unconformities, and incised valley fills are present in areas corresponding to recesses, where the rate of eustatic fall commonly exceeds the subsidence rate. These along-strike stratigraphic variations in response to collisional tectonism should be considered in the interpretation of other foreland-basin successions.

Keywords: Appalachian basin, foreland basins, sequence stratigraphy, structural geology, Taconic orogeny, tectonism.

INTRODUCTION

Objectives and Significance

The purpose of this investigation is to examine the application of existing sequence-stratigraphic models for foreland basins in an area of along-strike tectonic variability and to propose new concepts to account for the stratigraphic response to tectonism. Because of the very broad scale of tectonism that influences regional variations in foreland-basin stratigraphic patterns, a large regional database is needed for this type of analysis. In this investigation, sequence-stratigraphic models are applied and tectonic influence is interpreted for Lower Silurian strata of the Appalachian basin. The results provide an example of how tectonism influences foreland-basin stratigraphy and may serve as a useful model in the study of other foreland-basin successions.

The specific effects and degree of tectonic influence on sedimentation patterns in foreland basins are commonly difficult to determine. In particular, along-strike stratigraphic variability in response to tectonism is not widely documented in studies of foreland-basin stratigraphy. In this investigation, interpretations of stratigraphic patterns and the influence of collisional tectonism are based on an extensive subsurface database of more than 370 wells (Fig. 1). Core descriptions from 49 wells[1] are integrated with geophysical log data and with new and previous outcrop observations. Regional maps, including interval isopach and percent sand, were constructed using the cores and geophysical logs. From cores, outcrops, and geophysical log patterns calibrated to cores, a single type of sequence is identified for each location. Regional stratigraphic patterns are interpreted in terms of eustatic and tectonic processes. A complementary study by Castle (1998) focused on interpretations of depositional environments and criteria for identifying regionally correlative surfaces.

Geologic Setting

Lower Silurian strata form a large, northwest-thinning wedge on the foreland ramp of the northern and central Appalachian basin (e.g., Piotrowski, 1981; Brett et al., 1998; Castle, 1998). This thick succession of interbedded sandstone and shale grades cratonward into carbonate rock. The Appalachian foreland basin began to assume its present shape during Middle Ordovician time with plate margin subduction associated with the Taconic orogeny (Rodgers, 1970; Hatcher, 1972, 1989). Basin-modeling studies (Quinlan and Beaumont, 1984; Beaumont et al., 1988) and stratigraphic investigations (Dorsch et al., 1990, 1994; Ettensohn, 1994; Goodman and Brett, 1994; Ettensohn and Brett, 1998) indicate that the Appalachian basin during Early Silurian time was tectonically active, undergoing episodes of local differential subsidence. During this time, the actively subsiding foreland consisted of a deep, sediment-filled basement depression adjacent to and parallel with the uplifted belt of the Taconic orogen and a shallower, more distal ramp dipping gently southeast toward the orogen and away from the craton.

Depositional environments interpreted for the Lower Silurian succession, which includes the Medina Group and the Tuscarora Sandstone (Fig. 2), are fluvial, estuarine, shoreface, deltaic, tidal channel, tidal flat, and shelf

[1]GSA Data Repository item 2001073, facies characteristics and core descriptions, is available on the Web at http://www.geosociety.org/pubs/ft2001.htm. Requests may also be sent to Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301; e-mail: editing@geosociety.org.

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(Folk, 1960; Yeakel, 1962; Knight, 1969; Smith, 1970; Martini, 1971; Cotter, 1983; Laughrey, 1984; Keltch et al., 1990; Duke et al., 1991; Castle, 1998; Brett et al., 1998). A regional unconformity at the base of the Lower Silurian succession has been interpreted as forming in response to eustatic fall in latest Ordovician time (Dennison, 1976; Bambach, 1987; Goodman and Brett, 1994; Pope and Read, 1997). However, regional stratigraphic relationships indicate that tectonism also influenced the development of this unconformity (Dorsch et al., 1994; Ettensohn, 1994; Ettensohn and Brett, 1998). The Medina Group and Tuscarora Sandstone are capped by an Aeronian age unconformity, which is overlain by hematitic shale, limestone, dolostone, and phosphate of the Clinton Group (Goodman and Brett, 1994; Brett et al., 1998).

SEQUENCE TYPES

Upward-Coarsening Sequence Type A

Sequence type A, characterized by thick, coarse-grained deposits, is present in the Tuscarora Sandstone of the proximal foreland basin (Fig. 3). Sandstone grain size, sandstone bed thickness, and the proportion of sandstone to shale increase upward in the lower part of the sequence. Very fine to fine-grained sandstone overlies a basal sequence-bounding unconformity (Fig. 4A) and grades upward to trough cross-bedded, medium- to very coarse grained sandstone. Bidirectional cross-bedding, shale drapes on foreset beds (Fig. 5A), and burrows occur in sandstones in the lower part of the sequence. Shale rip-up clasts and quartz pebbles become more common upward. Bases of most sandstone beds throughout this type of sequence are erosional. In the upper part of the succession, cross-bedded medium- to very coarse grained sandstone (Fig. 5B) is overlain by hematitic, argillaceous, and bioturbated sandstone (Fig. 5C).

The upward increase in grain size and bed thickness, along with sedimentary structures that suggest an upward increase in energy, indicates that the lower part of this sequence type represents progradation. Shale drapes on foreset beds and bidirectional cross-beds suggest tidal influence. Erosive bases of beds and fining-upward grain-size patterns are consistent with deposition in channels, which are interpreted as predominantly estuarine in the lower, burrowed interval and fluvial in the upper part of the sandstone succession. Progradation and associated upward decrease in marine influence are interpreted as a response to local sedimentation rate exceeding the rate of

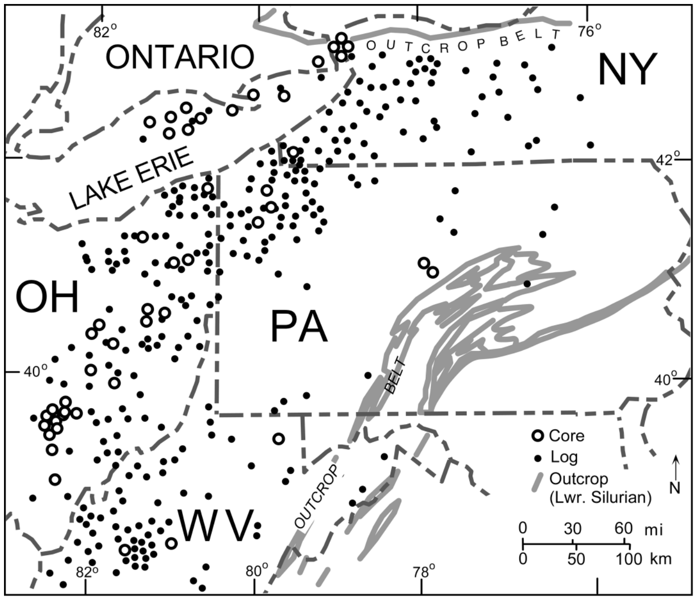

Figure 1. Map of the study area showing locations of wells with data used in this investigation.

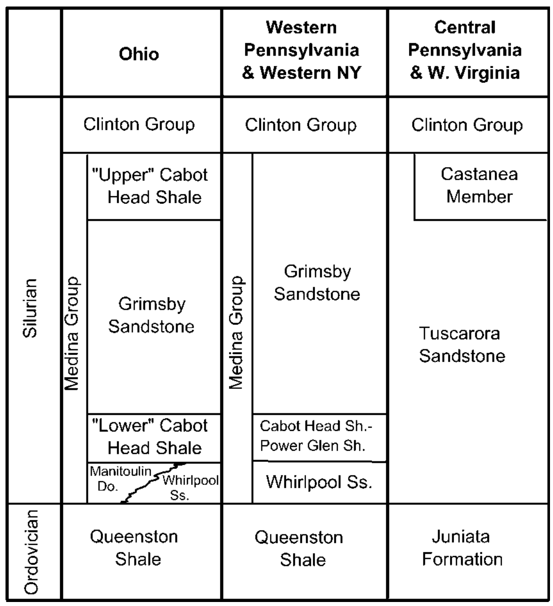

Figure 2. Stratigraphic column (after Patchen et al., 1984; Avary, 1996; McCormac et al., 1996). Do.—Dolomite; Ss.—Sandstone; Sh.—Shale.

relative sea-level rise. Progradation was followed by aggradation of thick fluvial and estuarine deposits as sedimentation kept pace with relative rise in sea level. Outcrops and cores suggest that depositional facies of upward-coarsening type A sequences grade from predominantly fluvial to predominantly estuarine along strike from West Virginia to southern Pennsylvania. Above a regionally correlative surface interpreted as a sequence boundary, retrogradational deposits overlie the upward-coarsening type A sequences (Fig. 3).

Upward-Coarsening Sequence Type B

Sequence type B, the most common type in the Medina Group, consists predominantly of shale grading upward to sandstone (Fig. 6A). In some areas, the thin basal Whirlpool Sandstone is present. Grain size in this basal sand-

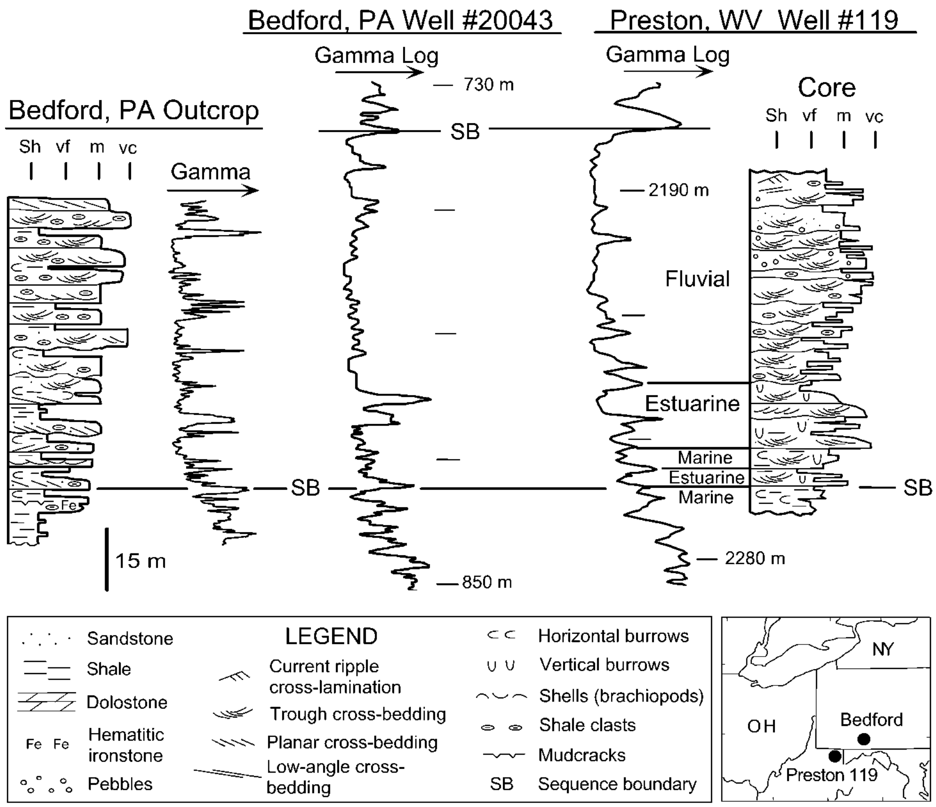

Figure 3. Outcrop and subsurface examples of predominantly aggradational, upward-coarsening sequence type A. Sandstones in the Bedford outcrop are interpreted as predominantly estuarine on the basis of biogenic structures and sedimentary features, including bidirectional cross-bedding and shale drapes on foresets. Retrogradational deposits overlie the upper sequence boundary. Sh—shale; vf—very fine-grained sandstone; m—medium-grained sandstone; vc—very coarse-grained sandstone.

stone, which unconformably overlies Ordovician shale (Fig. 4B), decreases upward from fine to medium sand at the base to very fine sand near the top. The basal sandstone unit can be separated into a lower trough cross-bedded interval and an upper interval containing common wave-ripple cross-lamination. The upper interval grades into the overlying Cabot Head Shale (Fig. 4C), which exceeds 12 m in thickness on the distal part of the foreland ramp and thins southeastward to a pinch out. Interbedded sandstone and shale of the Grimsby Sandstone gradationally overlie the Cabot Head Shale; rarely, the basal contact of the Grimsby Sandstone is sharp. In this interval, very fine to medium sand contains common planar-tabular and trough cross-bedding. Bidirectional cross-bedding and shale drapes on foresets (Fig. 4D) indicate tidal influence in some cores, whereas wave-produced low-angle cross-stratification is common in other cores. Burrows and phosphatic brachiopods are commonly present. The degree of bioturbation increases, grain size decreases, and hematite content increases near the top of the formation.

Above the basal transgressive deposits of the Whirlpool Sandstone and the Cabot Head Shale, interpreted depositional facies in the Grimsby Sandstone become more proximal upward, suggesting progradation. Toward the northwest, the proportion of sandstone to shale generally decreases, reflecting increasing distance from the source area. The progradational pattern probably represents a relative highstand of sea level, although deposition during transgression is possible with a sufficiently high rate of sediment supply. Retrogradational, shallow-marine deposits overlie this sequence type (Fig. 6A). The top of the Medina Group is marked by a regionally correlative surface (Fig. 4E) interpreted as a third-order sequence boundary by Brett et al. (1990, 1995, 1998).

Upward-Fining Sequence

The third type of sequence, characterized by a thick sandstone interval directly overlying a basal erosion surface (Fig. 4F), is thinner than the other sequence types and shows an upward-fining trend from sandstone to shale (Fig. 6B). Subsurface cross sections indicate that the basal surface is correlative with the uppermost Ordovician unconformity in New York (Kearney, 1983) and West Virginia (Avary, 1996). The grain size of sandstones in this sequence type ranges from very coarse to very fine sand; size decreases upward within the sequences. In proximal regions, quartz granules to pebbles and shale rip-up clasts are dispersed in the sandstones and concentrated locally in thin to medium beds (Fig. 4G). These beds have sharp and irregular bases, and are commonly trough cross-bedded. Truncation of underlying beds indicates scour. In cores of this sequence type recovered from the distal foreland, horizontal and low-angle cross-bedding are common in very fine to medium-grained sandstone (Fig. 4H). Wave-ripple cross-lamination becomes more common upward as grain size decreases. The occurrence of phosphatic brachiopods and small, horizontal and vertical burrows in the distal foreland indicates marine influence. Interbedded shale and very fine grained sandstone (Fig. 4I) grade upward to shale above the sandstone-dominated part of the sequence.

The upward decrease in grain size and the change in dominant internal structure from cross-bedding to ripple bedding suggest an overall upward decrease in depositional energy. Trough cross-bedded, medium- to very coarse grained sandstone beds with scoured bases are interpreted to have accumulated in channels. These beds are considered nonmarine (fluvial) in intervals that lack any indication of marine or tidal influence. Sharp-based, trough cross-bedded sandstones that contain burrows, bidirectional cross-bedding, and shale drapes on foreset beds are interpreted as estuarine. Horizontally laminated, low-angle cross-bedded, and wave-rippled sandstones are considered shoreface deposits because of the presence of these wave-produced structures and the absence of tidal indicators. The overlying interval of interbedded shale and very fine grained sandstone, which contains common burrows and brachiopod shell fragments, is interpreted as lower shoreface transitional to offshore marine (e.g., Fig. 6B, 652–656 m). The fluvial and estuarine beds of this sequence type occur in proximal areas of the foreland, whereas the shoreface sandstones predominate in the distal areas.

The pattern of upward fining and upward increase in marine influence above a sharp, irregular base suggests that topographic lows on the underlying erosion surface (unconformity)

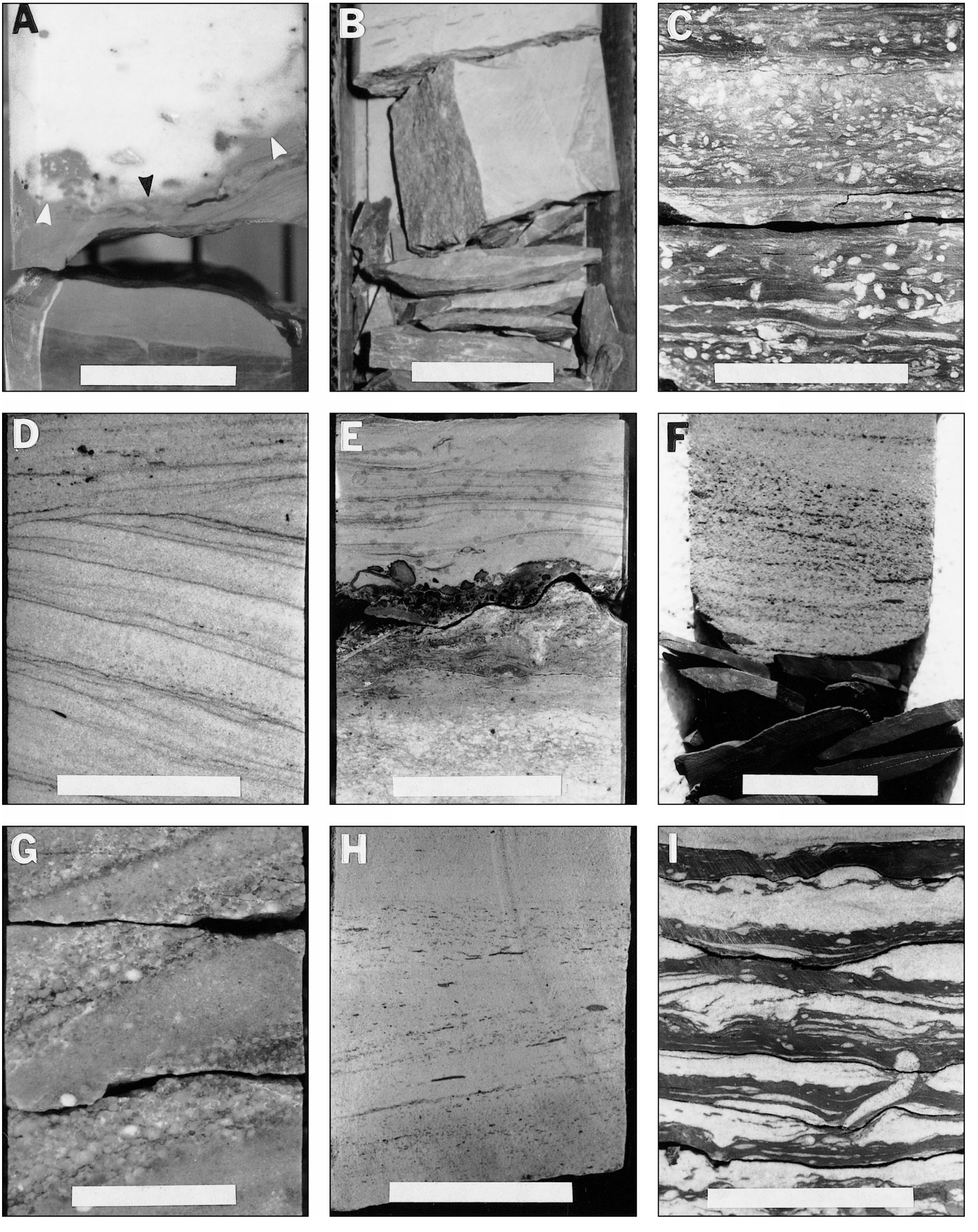
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Figure 4. Core photographs. Scale bars = 5 cm. (A) Sequence boundary between gray shale of the Ordovician Juniata Formation and overlying, white, very fine grained Tuscarora Sandstone; the contact (indicated by arrows) marks the base of an upward-coarsening type A sequence (Preston County, West Virginia, #119, 2262.4 m). (B) Cross-bedded, fine-grained Whirlpool Sandstone (light gray, blocky) unconformably overlying medium-gray shale of the Queenston Formation (Crawford County, Pennsylvania, #20665, 1462.2 m). (C) Interlaminated shale and very fine grained sandstone with abundant burrows; interpreted as shallow marine; Cabot Head Shale (Carroll County, Ohio, #256, 1514.5 m). (D) Bidirectional cross-bedding and shale drapes in medium-grained Grimsby Sandstone; interpreted as tidal channel (Venango County, Pennsylvania, #36455, 1612.0 m). (E) Contact between the Medina Group and the overlying Neahga Shale of the Clinton Group; the surface is marked by a physical break and by the overlying black, phosphatic granules, which are correlative with the Densmore Creek Phosphate Bed of New York (Carroll County, Ohio, #256, 1490.2 m). (F) Sequence boundary at the base of a transgressive, upward-fining sequence in the Grimsby Sandstone (Hocking County, Ohio, #12358, 775.4 m). (G) Cross-bedded, very coarse grained sandstone from the lower fluvial interval of a transgressive, upward-fining sequence, in the Tuscarora Sandstone (Clay County, West Virginia, #513, 2274.5 m). (H) Horizontally laminated and cross-bedded, medium-grained sandstone from the lower part of a transgressive, upward-fining sequence, Grimsby Sandstone; burrows and phosphatic brachiopods indicate marine or brackish-water influence; interpreted as shoreface (Fairfield County, Ohio, #12273, 669.2 m). (I) Burrowed interlaminated shale and very fine grained sandstone; from the upper part of a transgressive, upward-fining sequence, Grimsby Sandstone; interpreted as lower shoreface to shallow marine (Hocking County, Ohio, #12338, 749.7 m).

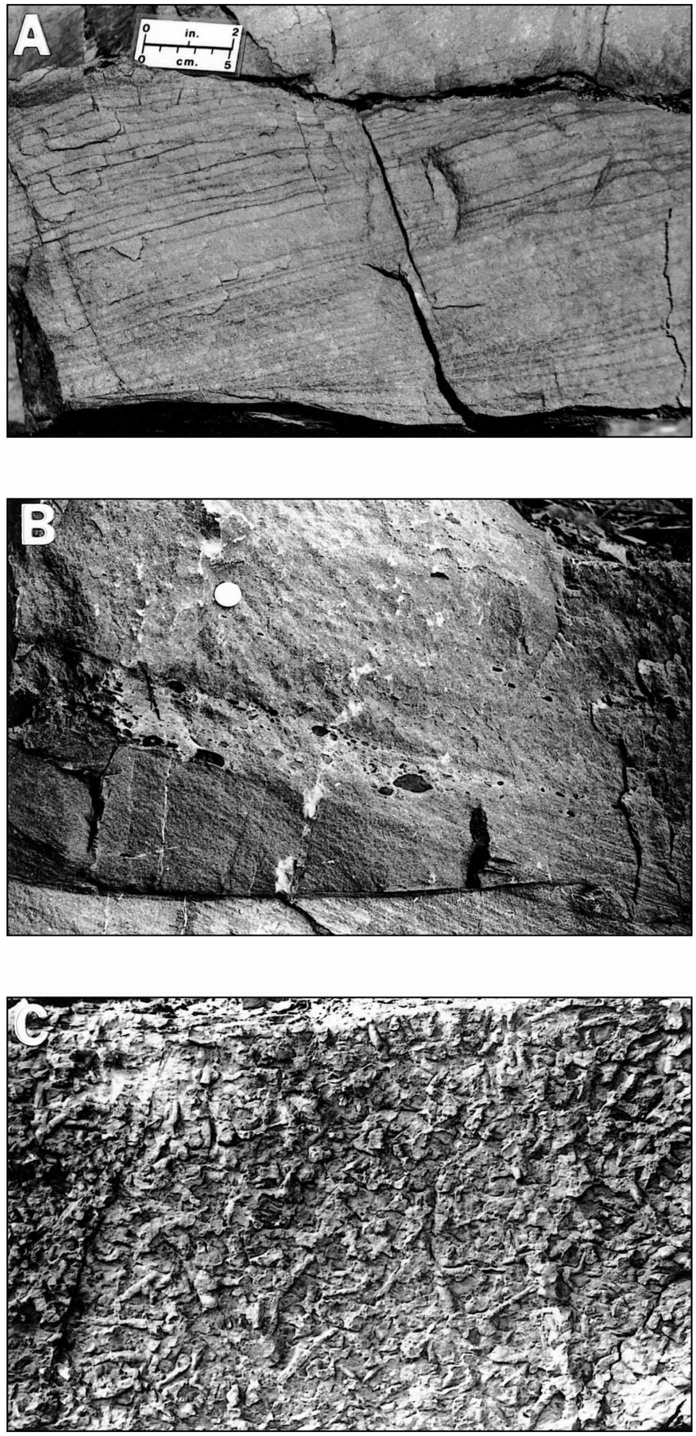

Figure 5. Outcrop photographs. (A) Shale drapes on foreset beds in medium-grained sandstone, interpreted as estuarine (Tuscarora Sandstone, Mill Hall, Clinton County, Pennsylvania). (B) Foreset beds in medium- to coarse-grained sandstone in the lower part of the photograph are truncated by a scoured contact and overlain by very coarse grained sandstone containing common shale rip-up clasts (dark pebbles); interpreted as fluvial (Tuscarora Sandstone, Jacks Mountain, Mifflin County, Pennsylvania). Width of outcrop shown is 0.62 m. (C) Intense bioturbation on underside of hematitic, argillaceous sandstone bed (Castanea Member, Mill Hall, Clinton County, Pennsylvania). Width of outcrop shown is 0.50 m.

were filled during transgression. The overall upward increase in marine influence indicates that relative rise in sea level continued during deposition of the sequence. This style of deposition is analogous to similar patterns observed in other successions that are interpreted as transgressive fills of valleys incised during base-level fall (e.g., Posamentier and Vail, 1988; Baum and Vail, 1988; Allen and Posamentier, 1993; Bowen et al., 1993; Zaitlin et al., 1994; Cotter and Driese, 1998).

REGIONAL DEPOSITIONAL TRENDS

Interval isopach contours of the Lower Silurian interval studied are broadly convex to the northwest (Fig. 7A). The southeastward increase in thickness generally corresponds to the increase in tectonic subsidence of the foreland basin toward the Taconic orogen. Such asymmetric subsidence is caused by lithospheric downwarping in response to thrust loading associated with plate subduction (Quinlan and Beaumont, 1984). Although the major phase of the Taconic orogeny occurred during Ordovician time, tectonic modeling by Quinlan and Beaumont (1984) indicates that some degree of downwarping in the Appalachian basin continued through Early Silurian time. Sand percent within the interval studied increases southeastward toward the supply of siliciclastic sediment (Fig. 7B), but shows a pattern that is different from that of the total interval thickness (Fig. 7A). Sand percent contours in western Pennsylvania are convex toward the southeast, indicating a general decrease in sand percent along regional strike toward western Pennsylvania.

The upward-fining sequences, interpreted as transgressive fills of incised valleys, are present in two major areas: one in western New York and the other in West Virginia and southeastern Ohio (Fig. 7C). The upward-coarsening type A sequences occur between the two areas of upward-fining sequences and proximal to the orogen, where aggradation occurred in response to high rates of sediment supply and subsidence. The upward-coarsening type B sequences are present on the distal foreland ramp and formed in response to northwestward progradation of the shoreline. Sequences dominated by lowstand deposits are absent because a shelf-slope break was not present on the foreland ramp.

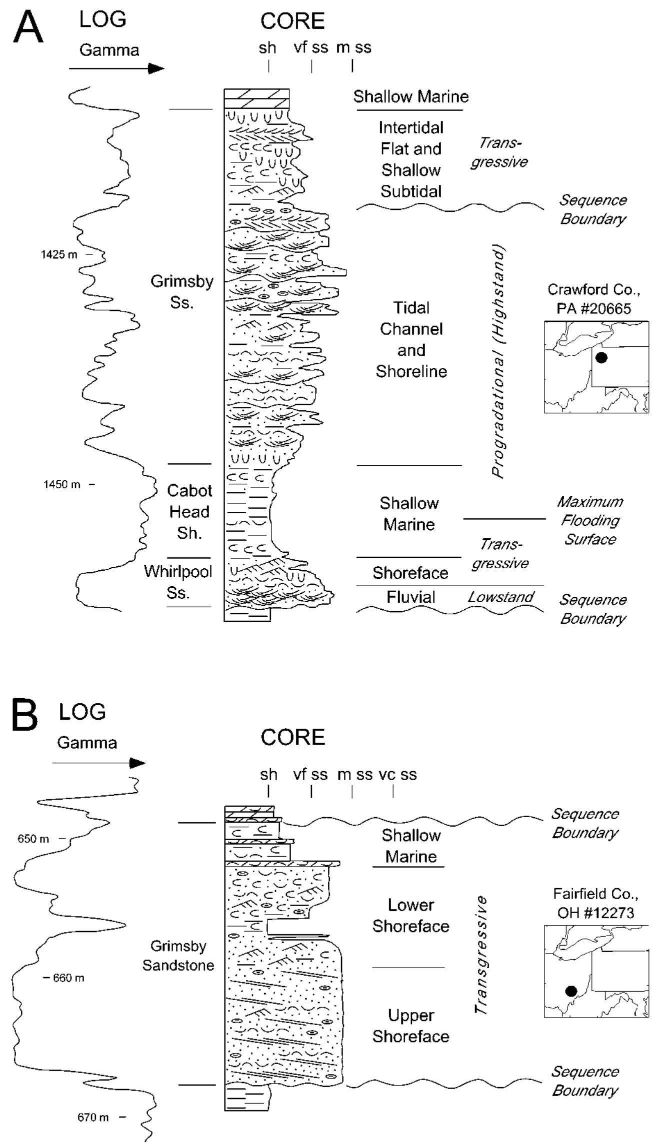

Figure 6. Gamma-ray geophysical logs and core descriptions. See Figure 3 for legend. (A) Upward-coarsening sequence type B interpreted as representing shoreline progradation. The sequence boundary at ~1420 m was recognized previously as an unconformity overlain by marine shale (Laughrey, 1999). Evidence for tidal processes was discussed by Castle (1998). Tidal energy may have been focused by shoreline irregularities and channel incision. (B) Upward-fining sequence interpreted as transgressive incised-valley fill. In sequences of this type nearer the orogen, fluvial sands grade upward to estuarine and shallow-marine deposits. sh—shale; vf ss—very fine grained sandstone; m ss—medium-grained sandstone; vc ss—very coarse grained sandstone.

STRATIGRAPHIC PATTERNS AND TECTONIC INFLUENCE

Application of Sequence-Stratigraphic Models Based on Asymmetric Subsidence

During the past 25 yr, concepts of sequence stratigraphy have evolved from general models applicable to passive continental margins (e.g., Vail et al., 1977; Posamentier and Vail, 1988; Posamentier et al., 1988; Van Wagoner et al., 1990) to models for other settings, including foreland basins (e.g., Heller et al., 1988; Posamentier and Allen, 1993a, 1993b; Van Wagoner and Bertram, 1995). Existing models of foreland-basin stratigraphic architecture reflect the broad subdivision of an asymmetric ramp into two zones: a rapidly subsiding area adjacent to the orogen and a distal zone of lower subsidence rate. This two-part division follows foreland-basin tectonic models postulated by Beaumont (1981), Quinlan and Beaumont (1984), and Beaumont et al. (1988).

According to the foreland-basin stratigraphic model of Heller et al. (1988), rapid subsidence associated with thrust-load emplacement results in the accumulation of coarse

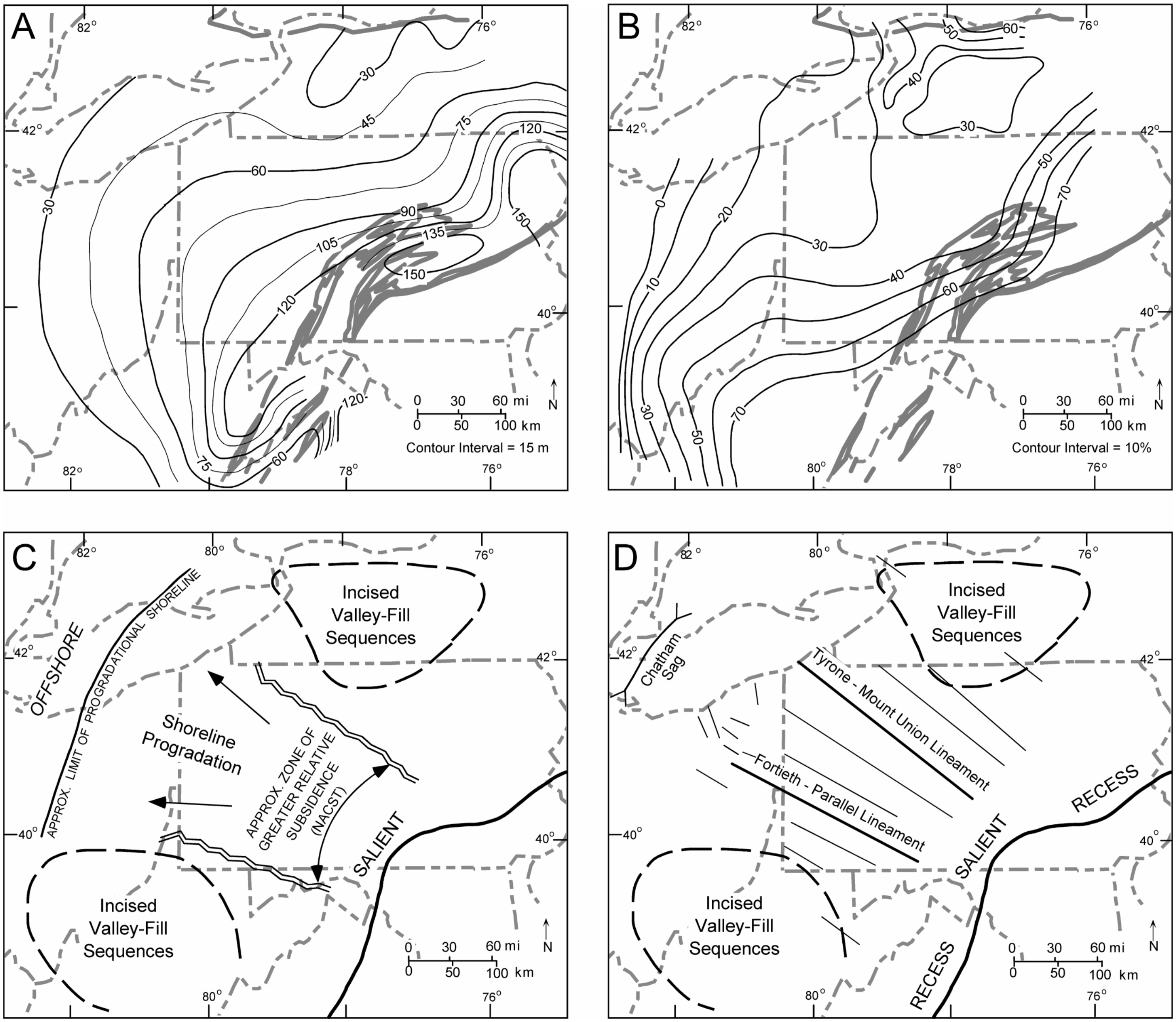

Figure 7. (A) Interval isopach map of the Lower Silurian interval studied. Thicknesses are based on well control used in this investigation (Fig. 1); additional control is incorporated from published maps (Smosna and Patchen, 1978; Finley, 1984; Coogan, 1991). (B) Percent sand contour map of the interval studied. Sand percent in outcrops increases above 70% toward the southeast (Swartz, 1934; Cotter, 1983), which is in the direction of the sand source. Values for the subsurface are determined from core descriptions and from gamma-ray geophysical logs using a 66% normalized cutoff. (C) Map showing zone of greater relative subsidence, termed the north-central Appalachian cross-strike trough (NACST), interpreted from distribution of sequence types, interval thickness, and sand percent. Within the NACST, predominantly aggradational, upward-coarsening type A sequences grade distally (northwest) to progradational, upward-coarsening type B sequences. To the north and south, where relative subsidence was less, valleys were incised during relative lowstand and then filled during subsequent transgression. The location of the salient is from Rankin (1976) and Rankin et al. (1989). (D) Map of tectonic lineaments, which provide a mechanism for extending subsidence onto the foreland ramp. Locations of lineaments are from Parrish and Lavin (1982), Rodgers and Anderson (1984), Shumaker (1986, 1996), Wilson and Shumaker (1988), Harper (1989), and Coogan (1991).

siliciclastic deposits adjacent to the uplift. In Lower Silurian strata of the Appalachian basin, aggradational fluvial deposits of the Tuscarora Sandstone may correspond to this phase of high rates of sediment supply and accommodation creation. Heller et al. (1988) argued that a second phase of sedimentation takes place after thrust-belt emplacement as rebound causes uplift and erosion in the most proximal part of the basin. During this phase of flexural uplift, extensive progradation onto the distal foreland ramp occurs, which may account for the progradational pattern represented by the upward-coarsening type B sequences.

In the area from Ontario to central Pennsylvania, the sequence-stratigraphic pattern of the Medina Group across the foreland ramp to the Tuscarora Sandstone generally fits the predictions of Posamentier and Allen's (1993a) model for foreland ramps. They divided foreland-basin deposition into two zones: zone A, a proximal wedge of mainly fluvial deposits that thickens toward the orogen; and zone B, a thinner interval of more distal facies. Consistent with the overall thickness of the strata and position near the orogen, upward-coarsening type A sequences of the Tuscarora Sandstone correspond to deposition in Posamentier and Allen's (1993a) zone A, where sediment accommodation was created by backward-rotational subsidence caused by thrust loading at the orogen (Fig. 8). As accommodation in the proximal foreland became filled, the rate of sediment supply to the distal foreland increased, which led to shoreline progradation northwestward across the foreland into zone B, where subsidence rates were lower due to greater distance from the orogen. The presence of overlying finer grained, shallow-marine strata, including the Castanea Member (Castle and Goodman, 1997), indicates retrogradation subsequent to shoreline progradation.

Sequence-Stratigraphic Evidence for Cross-Strike Zone of Differential Subsidence

Although existing sequence-stratigraphic models are useful in predicting stratigraphic patterns in the dip direction, subsurface and outcrop information from the Lower Silurian succession indicates that these models do not account for stratigraphic variations observed along strike. Regional variations in interval thickness, sand percent, and sequence distribution indicate that a dip-parallel area of relatively greater subsidence in the Appalachian foreland influenced Early Silurian sedimentation. This broad, northwest-southeast–trending zone is termed the north-central Appalachian cross-strike trough (NACST, Fig. 7C). In comparison to adjacent areas north and south, a greater thickness of strata within this zone is a response to a higher rate of sediment accommodation created. On the distal foreland ramp, the marine Cabot Head Shale is thicker, and within the north-central Appalachian cross-strike trough extends farther toward the orogen than to the north or south. Marine influence in this zone is consistent with the presence of marine and estuarine facies in the Tuscarora Sandstone in central Pennsylvania. In this area, the Tuscarora Sandstone is finer grained and shows greater marine influence than is evident in sandier, coarser grained strata along strike to the south. In the Lower Silurian sandstones, erosional and nondepositional features, including hiatal breaks and incised valley fills, occur more commonly in areas north and south of the north-central Appalachian cross-strike trough than within the trough. Valley erosion in these areas occurred when the rate of relative sea-level fall exceeded the rate of basin subsidence. During subsequent sea-level rise, filling of incised valleys produced upward-fining sequences. Within the north-central Appalachian cross-strike trough, the rate of sea-level fall remained less than or equal to the rate of basin subsidence, which generally precluded substantial valley incision. Fluvial deposits within the north-central Appalachian cross-strike trough are likely to be broader and more widespread laterally compared to the incised fluvial strata deposited in areas to the north and south.

Mechanism for Differential Subsidence

Data and interpretations from previous investigations, as well as from this study, support the presence of a cross-strike tectonic feature that influenced foreland-basin sedimentation and offer a mechanism for its origin. A series of structural elements, traditionally called salients and recesses, has been interpreted as affecting Paleozoic sedimentation along the Appalachian orogen (e.g., Rankin, 1976; Thomas, 1977; Lash, 1987, 1988; Rankin et al., 1989; Macedo and Marshak, 1999). Thomas (1977) interpreted the structural salients and recesses as evolving from reentrants and promontories, respectively, along the Laurentian continental margin. The promontories were oceanward extensions of the craton, and the reentrants represented embayments along the colliding passive margin. One of the structural salients, the South Mountain salient of Rankin (1976), coincides with the proximal part of the cross-strike tectonic zone of accommodation (NACST, Fig. 7C). The location of this salient generally corresponds to the Pennsylvania reentrant (Lash, 1988) and the Pennsylvania depocenter (Rankin et al., 1989). By studying Ordovician shelf unconformities, Lash (1988) recognized that the Pennsylvania reentrant is characterized by an uninterrupted Ordovician succession lacking major unconformities, and interpreted this region as having remained a foreland-basin depocenter during uplift of the adjacent continental margin. Based on the presence of thinner deposits (Rankin, 1976; Thomas, 1977; Lash, 1989) that contain platform successions interrupted by unconformities (Lash, 1988), a lower rate of subsidence is interpreted for the Virginia and New York promontories, which are located directly north and south of the Pennsylvania reentrant. Consistent with observations from the Ordovician succession, the areas dominated by the Lower Silurian upward-fining sequences generally correspond to the promontories.

Interpretations by Dorsch and Driese (1995) for Virginia and eastern Tennessee provide support for relatively less subsidence in that area, which is adjacent to the area of upward-fining sequences south of the north-central Appalachian cross-strike trough. They cited outcrop evidence for a large amount of erosion at the Ordovician-Silurian unconformity, which they attributed to flexural uplift due to isostatic rebound following active thrusting. Dorsch and Driese (1995) suggested that the underlying sandstones, which are correlative with the Ordovician Juniata Formation and which they call lower Tuscarora Sandstone, accumulated during active thrusting and associated foredeep subsidence. They referred to strata above the unconformity as upper Tuscarora Sandstone, and interpreted these sandstones as having formed during eustatic rise in early Llandoverian time. According to their interpretation, detritus reworked during the transgression was derived from the Taconic orogen during a new phase of compressional tectonism. Dorsch and Driese's (1995) observations of the stratigraphic pattern are consistent with the interpretation of transgressive filling of incised topography at the Ordovician-Silurian boundary.

Rodgers and Anderson (1984) and Harper (1989) suggested that early Paleozoic sedimentation in the Appalachian foreland was influenced by lineaments acting as basement faults separating downdropping blocks. In the Lower Silurian succession studied, interval thickness is greater and sand percent is less in the region that is located between the Ty-

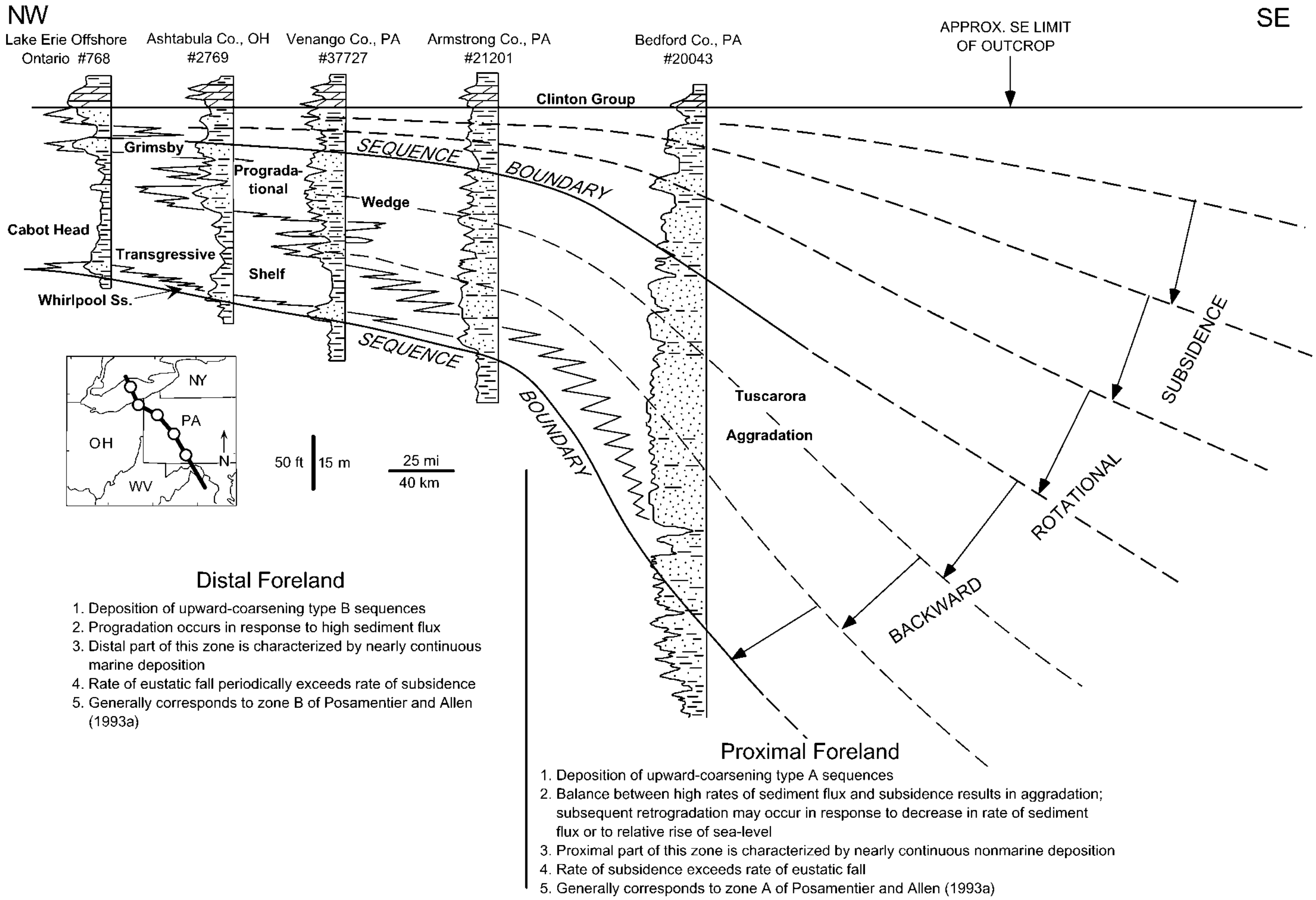

Figure 8. Regional cross section integrating the two-phase stratigraphic model of Heller et al. (1988) with the foreland ramp-type basin model of Posamentier and Allen (1993a). Increase in subsidence toward the orogen created accommodation for aggradation of thick, predominantly fluvial sands. Shoreline progradation onto the distal ramp occurred as the rate of sediment supply exceeded the rate of accommodation in the proximal foreland. The schematic dashed lines represent backward rotational subsidence, which is interpreted based on the southeastward increase in total thickness of the succession and on foreland-basin flexural models proposed by Beaumont (1981), Quinlan and Beaumont (1984), and Beaumont et al. (1988). The upper sequence boundary, which is regionally correlative with the sequence-bounding unconformity in the upper part of the Grimsby Sandstone, corresponds with the sequence boundary shown in Figure 3 (742 m in Well #20043) and in Figure 6A (1420 m). A maximum-flooding surface occurs within the Cabot Head transgressive shelf interval, but its precise position is difficult to identify on the gamma-ray geophysical logs shown.

rone−Mount Union and Fortieth Parallel lineaments (Fig. 7D). Rodgers and Anderson (1984) suggested that the block southwest of the Tyrone−Mount Union lineament has dropped down relative to the northeast block, which is consistent with structural influence of the lineaments on deposition of the Lower Silurian clastic deposits. Vertical displacement along the cross-strike lineaments may have provided a mechanism to extend subsidence associated with evolution of the structural salient onto the distal foreland, thus producing the north-central Appalachian cross-strike trough. Consistent with this interpretation, the area between the Tyrone−Mount Union and Fortieth Parallel lineaments lines up approximately with the Chatham sag, a structural low to the northwest between the Findlay arch and the Algonquin arch (Fig. 7D).

IMPLICATIONS TO PREDICTING FORELAND-BASIN STRATIGRAPHY

Variations in foreland-basin stratigraphic architecture form in response to the relative influences of subsidence, eustasy, and sediment supply. The transgressive, upward-fining sequences are favored by low subsidence rate, large-amplitude relative changes in sea level, and low rate of sediment supply. In this setting, lowstand deposition may be represented by fluvial strata within the lower part of incised valley fills or by sediment bypass into more distal areas. The predominantly aggradational, upward-coarsening type A sequences are deposited in areas of high subsidence rate, minor eustatic influence relative to tectonic influence, and high rate of sediment supply. In these areas, the rate of eustatic fall is less than or equal to the rate of subsidence, which results in a general absence of subaerial erosion and stream incision. The upward-coarsening type B sequences form under conditions of subsidence and sea-level change that are intermediate between those represented by the upward-fining sequences and the upward-coarsening type A sequences. Sequence boundaries are commonly expressed as unconformities on the distal foreland ramp, where upward-coarsening type B sequences form. In contrast, sequence boundaries more commonly occur as conformable surfaces in proximal foreland areas of higher rates of subsidence and sediment supply.

Strike-parallel stratigraphic variability and the effects of cross-strike tectonic features are likely to be more common than recognized previously in foreland-basin stratigraphic studies. An exception is the work of Ricci Lucchi (1986a, 1986b, 1990), who interpreted the effect of transverse (cross strike) tectonic lineaments on Cenozoic clastic fill in foreland basins of the northern Apennines. Relative uplift and subsidence across these lineaments, the origin of which is uncertain, is reflected in along-strike variations in sediment type and thickness. In a study of the Venetian foreland basin in the Southern Alps, Massari et al. (1986) attributed along-strike differential subsidence and localized angular unconformities to the interplay of thrust faults and transverse strike-slip faults. In the northern part of the Appalachian basin, Hiscott et al. (1986) recognized a higher rate of sedimentation of Middle Ordovician basin-plain and submarine-fan facies within the Quebec reentrant, which they suggested was formed by reactivation of basement faults or by uneven distribution of structural loads associated with thrusting.

Results of this investigation demonstrate the importance of incorporating the effects of along-strike structural variations in foreland-basin stratigraphic models (Fig. 9). Structural salients occur in most fold-thrust belts, where they evolve from basins of varying geometry and tectonic environment (Macedo and Marshak, 1999). In areas of salients, the stratigraphic pattern reflects filling by abundant sediment supplied from uplift along the orogen. Progradational to aggradational stacking patterns characterize these areas of subsidence, and eustatic falls are represented typically by subtle facies changes and correlative conformities rather than by unconformities. In contrast, areas corresponding to recesses are dominated by deep erosion, extensive unconformities, and transgressive infilling. Incised valley fills occur commonly as erosional lows are filled during relative sea-level rise. Near the orogen, areas of recesses may remain emergent during transgression.

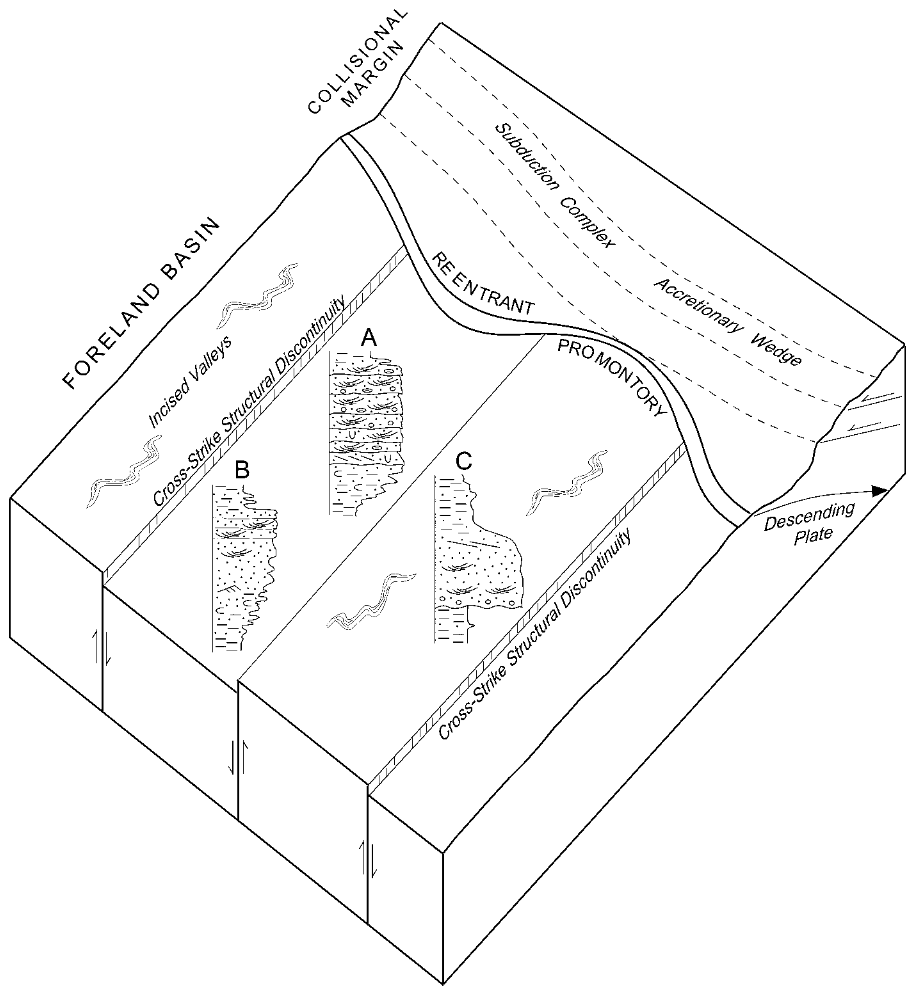

Figure 9. Block model illustrating the effect of collisional tectonism on stratigraphic variability in foreland basins. During collision, structural salients and recesses evolve from reentrants and promontories along the continental margin. Boundaries between these regions of differential subsidence are extended toward the distal foreland by displacement along cross-strike structural discontinuities (lineaments). In areas corresponding to salients (reentrants), high rates of sediment supply and accommodation creation produce thick, predominantly aggradational, upward-coarsening type A sequences (labeled A). As accommodation in the proximal foreland fills, the shoreline progrades toward the distal part of the basin, producing upward-coarsening type B sequences (B). In areas of recesses (promontories), erosion and stream incision occur as the rate of relative sea-level fall exceeds the rate of subsidence. During subsequent relative rise in sea level, topographic lows become filled with upward-fining sequences (C).

CONCLUSIONS

Regional trends of interval thickness and sand percent, combined with the spatial distribution of sequence types, indicate that along-strike tectonic variability influenced Lower Silurian stratigraphic architecture in the Appalachian foreland basin. A cross-strike–trending zone of relatively greater subsidence (north-central Appalachian cross-strike trough) was an area of sediment transport and deposition. Thick, aggradational sequences of the Tuscarora Sandstone developed in response to a high rate of subsidence combined with high sediment flux adjacent to actively eroding areas of the Taconic orogen. The relative subsidence rate slowed eventually, probably as the intensity of the orogeny diminished, resulting in filling of accommodation and progradation of the shoreline across the foreland ramp. To the north and south of the north-central Appalachian cross-strike trough, sediment accommodation was generated by erosion and incision when the rate of sea-level fall exceeded the rate of subsidence. Topographic lows were filled by upward-fining sequences deposited during subsequent relative rise in sea level.

The along-strike tectonic variability that influenced stratigraphic patterns in the Appalachian foreland basin is attributed to the occurrence of salients and recesses that evolved from reentrants and promontories along an irregular, colliding continental margin. The north-central Appalachian cross-strike trough coincides with a reentrant, whereas adjacent areas to the north and south coincide with promontories. The influence of the north-central Appalachian cross-strike trough on sedimentation is not restricted to the proximal foreland, but extends onto the distal ramp. Downdropping of crustal blocks along cross-strike structural lineaments offers a mechanism for extending differential subsidence onto the distal foreland.

Successful application of sequence-stratigraphic models to deciphering and predicting the complex stratigraphy of foreland basins depends upon understanding the responses to tectonism. By influencing the fundamental processes of sediment dispersal and sedimentation, along-strike variations in the rate and extent of uplift and subsidence affect stratigraphic patterns in foreland basins. Existing sequence-stratigraphic models for foreland-ramp settings do not predict these patterns, which can be explained in terms of a colliding margin. Because cross-strike structural features may occur commonly on active foreland ramps, the importance of along-strike tectonic variation as a significant control on stratigraphic architecture of foreland basins may have been underestimated in prior studies. Results of the current investigation demonstrate that tectonically induced variations in deposition and the resulting stratigraphy occur along strike, as well as in the dip direction, and are important to consider in the interpretation of foreland-basin successions.

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