Widespread soft-sediment deformation horizons in Lower Silurian strata of the Appalachian basin: distal signature of orogeny

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Abstract: Sedimentology and stratigraphic mapping of soft-sediment deformed beds (ball and pillow and convolute bedding) in the Lower Silurian of eastern North America demonstrate that these event beds are extremely widespread and that their component sediment layers were not deformed during initial deposition, but slightly later, during shallow burial. Successions of laminated arenaceous beds with interbedded shale in regressive (falling stage) systems tracts of third order depositional sequences appear to have been prone to deformation. Deformed zones are likely the result of shear-induced liquefaction of thixotropic muds and foundering of overlying (carbonate and siliciclastic) silts and sands during very large-scale earthquakes. The distribution of deformed beds, together with increased subsidence, clastic influx, and K-bentonite horizons, provides a meter of intensity and timing of pulses of Silurian orogenesis.

Keywords: Appalachian foreland basin, far-field tectonics, seismites, sequence stratigraphy, Lower Silurian.

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Introduction

The Silurian Period may be characterized as the interval between two major tectonic episodes that affected eastern Laurentia, the Late Ordovician Taconic Orogeny reflecting collision with the Amonoosuc island arc, and the Middle-Late Devonian Acadian Orogeny produced by convergence of the Avalonian micro-continent (e.g. Ettensohn 1987, 1991, 1992). The precise tectonic setting of eastern Laurentia during the Silurian is less clearly defined because of strong overprinting by the Acadian Orogeny (Ettensohn & Brett 1998). However, on the basis of recently defined volcanism in the Maritime Provinces (Bevier & Whalen 1990; Van Staal 1992; Cawood et al. 1995; Van Staal & deRoo 1995), together with patterns of foreland basin sedimentation, it is increasingly evident that the Silurian was a time of intermittently active tectonism in eastern Laurentia (Goodman & Brett 1996; Ettensohn & Brett 1998).

Deformed beds have long been recognized in Lower Silurian strata of the Appalachian basin, although the interpretation of their genesis is questionable. Early studies interpreted the deformation of these sediments as a localized phenomenon resulting from irregular sediment loading or changes in sediment volume owing to dolomitization (e.g. Zenger 1965). Recent sequence stratigraphic studies (Brett et al. 1990, 1998) provide a high-resolution framework within which the stratigraphic distribution and lateral extent of these deformed beds may be evaluated (Fig. 1). The widespread nature of these deformed beds suggests a more regional-scale triggering mechanism. The distribution and sedimentological features of Lower Silurian deformed zones in eastern Laurentia closely resemble those attributed to seismically induced deformation of mixed carbonate-siliciclastic Upper Ordovician strata of the same region (Pope et al. 1997; Ettensohn et al. 2002; McLaughlin & Brett 2004). Thus, the Upper Ordovician examples provide a model against which Lower Silurian deformed beds can be compared.

Tectonic Setting

In the earliest Silurian a final tectophase of the Taconic Orogeny may have rejuvenated orogenic areas and led to cannibalization of older Ordovician sediments and their redeposition as the Tuscarora-Medina clastic wedge (Ettensohn & Brett 1998, 2002). In the early Rhuddanian the basin axis appears to have been displaced westward into southern Ontario and Ohio, perhaps as a result of thrust loading and sediment progradation (Goodman & Brett 1994). Much of the Llandovery (late Rhuddanian to mid Telychian) was characterized by tectonic quiescence; during this 5 million year interval the foreland basin and eastern shoreline migrated approximately 400 km eastward (toward the hinterland). This pattern has been related to thrust load relaxation following the cessation of active thrusting. In the latest Telychian abrupt changes in sedimentation patterns indicate a return to active tectonism (Brett et al. 1990, 1998; Goodman & Brett 1994). These changes include: (a) development and erosion of a pronounced arch (forebulge) on the cratonward side of the foreland basin; (b) abrupt reversal of the pattern of eastward basin migration to westward migration; (c) development of a new pattern of basin subsidence; and (d) appearance of K-bentonites. Dating of

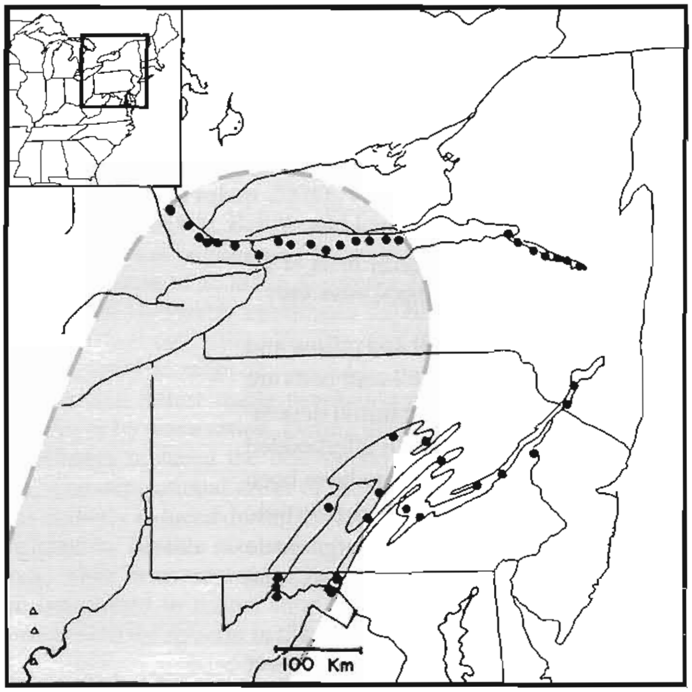

Fig. 1. Location map showing the distribution of Silurian outcrops in the northern Appalachian Basin and eastern Cincinnati Arch region (modified from Goodman & Brett 1994). Area on inset map marks the study area. Dots show positions of outcrops examined for this study. Large shaded area indicates areal extent of DeCew deformed beds.

volcanics and metamorphism in the northern Appalachians indicates a latest Llandovery (430 Ma) date for the onset of tectonism associated with the Salinic Orogeny (or "disturbance"; Boucot 1962), probably resulting from incipient transpressional collision of Avalonia with the St. Lawrence promontory of Laurentia (Cawood et al. 1995). Ettensohn and Brett (1998) postulate two tectophases of the Salinic Orogeny based on the development of successive shale prone basins in the latest Llandovery to earliest Wenlock (Williamson-Willowvale Shale tectophase) and mid Wenlock (Rochester Shale tectophase). The second and stronger tectophase may have persisted through much of later Silurian time.

Stratigraphic Distribution of Deformed Beds

Lower Silurian strata of eastern North America contain multiple discrete intervals of soft-sediment deformation separated by successions of tens of meters of strata that show little to no evidence of disruption. Lower Silurian strata that display deformed beds in west-central New York State and southern Ontario include *peritidal to shoreface red mudstones and fine-grained sandstones* of the early Llandovery (Rhuddanian) Grimsby Formation (Fig. 2A), upper to middle shoreface cross-bedded sands of the overlying Thorold Sandstone (Fig. 2B); lower shoreface silty cross-bedded dolostones of the latest Llandovery to early Wenlock Dawes Formation and equivalent uppermost Keefer Sandstone *in Pennsylvania; and lower shoreface laminated arenaceous do*lostones of the middle Wenlock DeCew Dolostone (Fig. 2C).

These deformed beds are preferentially clustered within the regressive (Brett et al. 1990; 1998) or falling stage systems tracts (FSSTs) of 3rd-order depositional sequences. That these thin (2–5

Fig. 2. Deformation structures in the Lower Silurian of the Appalachian Basin. **A.** Deformed bedding of the Llandovery Grimsby Formation at Niagara Gorge, New York. Note stretched and deformed sole marks on the bottom of siltstone pillow below hammer. **B.** Deformed sandstones and shales of the Thorold Formation at Hamilton, Ontario, displaying ball and pillow structures (adjacent to hammer marked by arrow) overlain by a deformation fabric of silty mudstone with sandstone pseudonodules. **C.** Convolute bedding in the Wenlock DeCew Dolostone at Niagara Gorge, New York. Note that only the lower half of the DeCew is deformed; this is a signature of the DeCew across central New York and eastern Ontario.

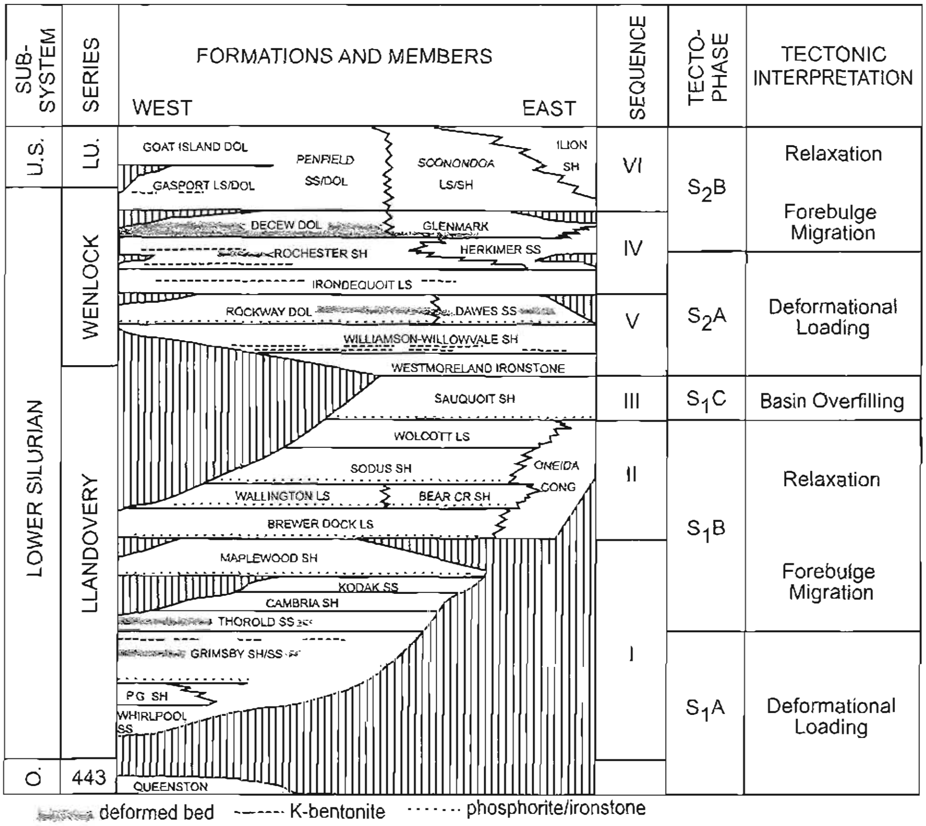

Fig. 3. Tectophases and sequences of the lower Silurian across New York State showing the position of widespread deformed beds, K-bentonites, and condensed beds (modified from Goodman & Brett 1994). Note that the stratigraphic positions of widespread deformed beds are generally coincident with interpretations of late stage deformational loading and transition into forebulge migration from studies of shifting basin geometry.

m) intervals record a response to forced regressions is indicated by (a) their sharply erosional bases, (b) evidence of abrupt facies dislocations and (c) abrupt increase in siliciclastic sediment grain size, and (d) their location below major regionally angular sequence bounding unconformities. McLaughlin and Brett (2004) inferred a strong facies control on the distribution of deformed beds from comparable regressive facies in the Upper Ordovician of the Cincinnati Arch region. Silurian deformed beds discussed herein occur in very comparable facies and may reflect similar controls. Periods of regression are marked by locally increased sedimentation rates in offshore areas. The rapid deposition of fine sandy beds and mud layers may have provided the appropriate deformation prone sediments.

Sedimentology of Silurian deformed beds

Lower Silurian deformed beds display a range of sedimentary features that supply information about the environment and timing of deformation. The deformed strata are typically composed of thin shales, overlain by laminated silt- to fine sand-sized sediments (both carbonate and siliciclastic). The shales typically show little evidence of bioturbation. The overlying fine-grained carbonates/sands commonly contain hummocky to swaly cross-bedding (lower shoreface deposition) and sharply defined sole marks (e.g., scratches, prod marks, and flutes). The latter suggest deposition on firm, over-compacted mud substrates that were stable, even during rapid deposition of sediments. The sharp contacts between the mud and the overlying silt-sandstone beds formed an interface poised at instability given the thixotropic properties of the mud. Truncation of the upper surface of some deformed beds indicates that deformation occurred at a shallow depth below the sediment-water interface. Thus, detailed sedimentology suggests that these sediment layers were not deformed during initial deposition, but later, during shallow burial.

Observation of the deformation structures (e.g., ball-and-pillows, mudstone diapirs) suggests that mobilization of thixotropic mud caused deformation of the surrounding sediments during gel to sol transitions (see discussions of thixotropy by Boggs 2001; Collinson 2003; and Altaner 2003). Compact thixotropic muds will not deform unless subject to shear by some external agent, such as earthquake waves (Brenchley & Newall 1977; Collinson 2003). Thus, in the undisturbed state, the muds were cohesive enough to record sole marks and to support the load of overlying silts/sands. During episodes of seismic shaking muds flowed upward as diapirs and evacuated from the lower part of a deforming interval of strata to be redeposited on top (Fig. 2B).

Lateral extent of deformation: case study of the DeCew Dolostone

The deformed beds within the DeCew Dolostone are the most widespread and consistently disrupted of any unit within the Lower Silurian of eastern North America. Careful tracing of these deformed strata reveals that they are continuous from the DeCew type area in central New York State, westward into eastern Ontario and southward into central Pennsylvania (Brett et al. 1990) and southern Ohio (Brett & Ray 2005). This would suggest an areal extent of approximately 200 000 km^2. If these correlations are accurate the DeCew deformed beds represent one of the most widespread seismites yet recorded in the geologic record. Deformed zones with similar areal distributions have been described from the Upper Ordovician of eastern North America (Pope & Read 1997; McLaughlin & Brett 2004) and from the Triassic of Britain (Simms 2003). Very large earthquakes (>7 M) and bolide impacts are implicated in those areas as triggering deformation (see Ettensohn et al. 2002).

Triggering mechanisms

At present it is not clear that activation along only a single fault produced the seismic energy to cause the deformation of the Lower Silurian sediments. Thrust-induced loading of the cratonic margin may have resulted in reactivation of an entire network of basement faults well in to the cratonic interior, providing the triggering mechanisms to produce widespread soft-sediment deformation.

Lower Silurian deformed beds correspond with formation of shale basins and occurrence of K-bentonites (Fig. 3). The timing and degree of tectonic loading of the Laurentian cratonic margin during the Silurian has been established by analyzing the distribution of dark shale basins marking areas of increased subsidence and truncation of strata indicating forebulge migration and/or isostatic rebound (Goodman & Brett 1994). Ettensohn & Brett (2002) used these sedimentary indicators in the early Llandovery to recognize a late tectophase of the Taconic orogeny. Recent fieldwork has recovered a thin altered volcanic ash deposit (K-bentonites) from this interval as well. It is significant that the only deformed beds of the Llandovery (Grimsby and Thorold formations), for that matter since the Upper Ordovician early Maysvillian stage (~5 million years previous; McLaughlin & Brett 2004), are coincident with this indicator of resumed tectonism. Similarly, Wenlock strata were deposited during the first and second tectophases of the Salinic orogeny (Ettensohn & Brett 1998), a period noted for widespread formation of dark shale basins, though with different geometries than Taconic basins. Again, recent fieldwork has recovered a series of thin K-bentonites from early to mid-Wenlock age strata in eastern North America (Brett & Ray 2005; C.E. Brett, unpublished data). These ash beds further corroborate evidence for a Salinic orogeny during this time.

Conclusions

The facies-specific nature and widespread distribution of deformed beds within the Lower Silurian strata of eastern North America suggest a common response to a regional triggering mechanism, i.e. activation of fault networks in response to loading of the craton margin. We suggest, as in the case of Upper Ordovician deformed beds distributed over much the same area, that the primary factor in the widespread nature of the deformation was not necessarily an enormous singular earthquake/bolide impact as much as it was the distribution of a critical sedimentary architecture (silt–sand layer over mud with little to no mixing via bioturbation). The regular distribution of this deformation-prone facies within many Silurian depositional sequences (FSSTs) was regulated by eustatic fluctuations. The record of deformed intervals within Silurian strata of the Appalachian Basin, together with evidence of periods of increased siliciclastic influx, K-bentonite horizons, and shifting basin geometry provides a meter of intensity and timing of pulses of tectonism marking the final (late) tectophase of the Taconic orogeny in the early Llandovery and the short-lived Salinic orogeny during the late Llandovery to late Wenlock.

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