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Tectonic, foreland-basin origins of Upper Ordovician black gas shales in the Appalachian Basin of eastern United States

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ABSTRACT

Black gas shales are major parts of many foreland-basin sequences and comprise important components of unconformity-bound tectophase cycles, which reflect sedimentary/stratigraphic, flexural responses to deformational loading and relaxation in an orogen. Using as examples Upper Ordovician black gas shales, deposited during the Taconian orogeny in the Appalachian Basin of the eastern United States, black-shale origins and their importance in understanding the tectonic framework are discussed. Foreland-basin black shales are clearly the product of distinctive tectonic frameworks and histories, and aside from economic value, may provide important controls on the timing and location of tectonic events.

Introduction

In the Appalachian Basin, gas-prone black shales are major parts of most flexural, foreland-basin sequences and reflect the timing of major loading-related, foreland subsidence. The Upper Ordovician Utica black shales, for example, are some of the most productive gas shales in the United States, and they represent early foreland-basin deposits during the Taconic tectophase of the Taconian orogeny (Ettensohn 1991). In fact, black shales are among the earliest deposits in foreland basins (Fig. 1A) and are parts of cycles showing a consistent sequence of lithologies, called tectophase cycles (Fig. 2). Overlying a bulge-related unconformity, marine black

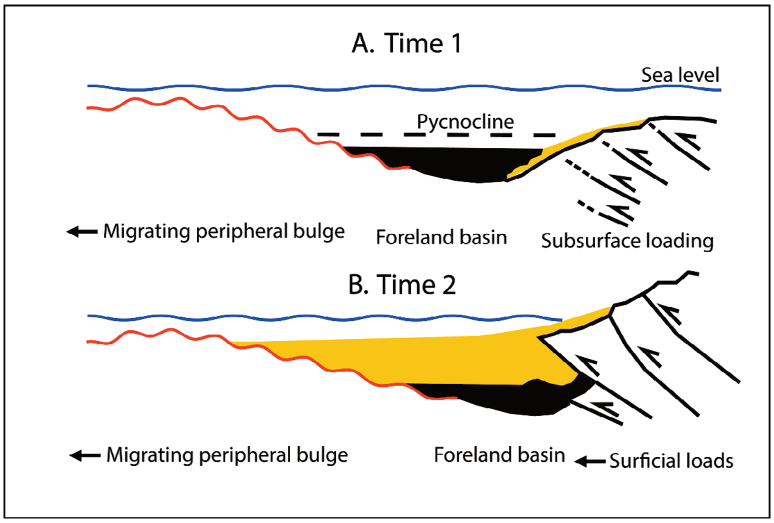

Fig. 1. Schematic diagrams showing the timing and relationships between foreland-basin generation, bulge moveout, sediment infill and deformational loading in the orogen. **A** – basin-bulge formation during early, subsurface, subaqueous deformational loading with little sediment influx during the first three phases of a typical tectophase cycle (Fig. 2). With major subsidence and little clastic input, organic-rich muds accumulate in the deep, stratified basin. **B** – "loading-type relaxation" (Fig. 2, phase 4), during which a now-static surficial load and drainage net develops, supplying coarser clastic sediments to the subsiding foreland basin. A pycnocline is a zone of thermohaline density stratification in a deepening basin with decreasing O_2 content (adapted from Ettensohn 1997). Orange color – coarser clastic sediments, black color – black, organic-rich muds.

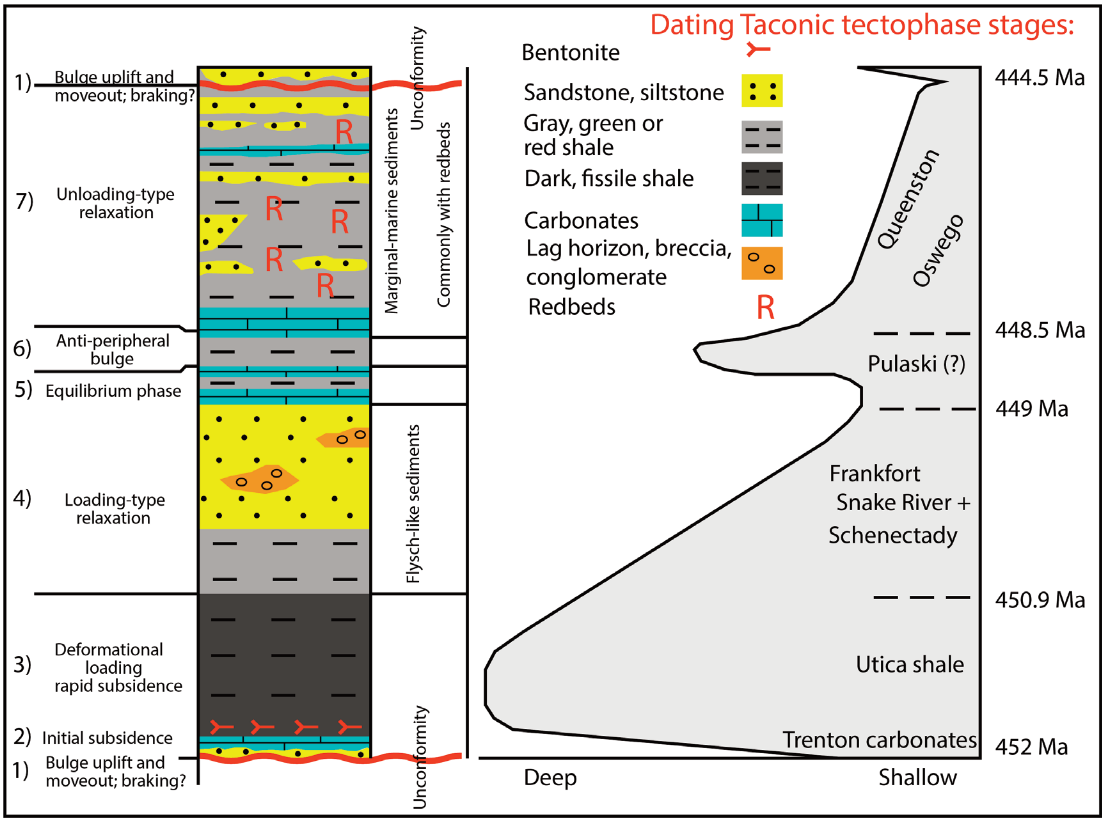

Fig. 2. A typical unconformity-bound tectophase cycle from the northern Appalachian Basin. Unit names are examples from the Late Ordovician Taconic tectophase of the Taconian orogeny (see Figs 3b, 4) in New York State. Dates are derived from the radiometric dating of bentonites and biostratigraphy. The Upper Ordovician Utica Shale Group and its equivalents at the base of the tectophase sequence are major sources of unconventional gas in the eastern United States (Kirschbaum et al. 2012) (adapted from Ettensohn et al. 2019).

shales initiate most cycles and mark the time of maximum deformational loading and flexural subsidence. However, they are deposited when most deformation is subaqueous and produces little clastic influx (Fig. 1A). In the absence of major clastic input, organic matter with suspended clay and silt comprises most of the sedimentation in the early foreland basins. With rapid subsidence and low sedimentation rates, the basins quickly became stratified, facilitating the preservation of the organic-rich sediments (Fig. 1A). The shales in each cycle are overlain by a series of relaxational clastics, including deeper-water, flysch-like clastics followed by more shallow, marginal-marine, molasse-like clastics. These thick clastic deposits may preserve underlying organic-rich sediments from weathering and erosion and provide potential reservoirs for conventional hydrocarbons derived from the underlying organic-rich muds.

Tectonic implications

Moreover, because of the distinctive character of black shales in the surface and subsurface, mapping their distribution (Fig. 3A) supports the role of tectonism in their origin and may even help track the progression of orogeny in space and time. In the Appalachian area of the United States, the distribution of Middle to Upper Ordovician black shales suggests that the Taconian orogeny proceeded in a diachronous fashion from south to north along the eastern Laurentian margin, and that tectophases were mediated by convergence at successive continental promontories. Hence, based on black-shale distribution, the Taconian orogeny was apparently a “transgressive” orogeny in that the locus of convergence shifted northeastwardly parallel to the strike of the Appalachian Basin during Mohawkian (Sandbian–Katian, Blackriverian–Chatfieldian) time. By the end of Blackriverian time, the Blountian tectophase of the Taconian orogeny largely focussed on the Virginia promontory, had expended itself, while by the Blackriverian–Chatfieldian (early Katian) transition, the focus of orogeny had shifted to the New York promontory in what has been called the Taconic tectophase. This transition between tectophases and black-shale foreland basins is illustrated along section line A-B-C-D in Figs 3A and 4 and was mediated by successive southwest-northeast collisions at continental promontories (Fig. 3A).

Abrupt changes in the distribution of black shales in time and space, as noted at the arrow in Fig. 3B, may also indicate major changes in the nature of the orogeny. For example, during the Late Ordovician (Mohawkian-Cincinnatian, Katian–Hirnantian) Taconic tectophase, changes in the distribution of the Martinsburg and Utica black shales (Figs 3A, 4) support a reversal of subduction polarity that effected the reactivation of basement structures and basin migration (Fig. 5). Shale distribution suggests that early Chatfieldian (early Katian), east-verging subduction early in the tectophase generated a cratonic extensional regime that resulted in a relatively narrow foreland basin along reactivated Iapetan basement structures (Fig. 5A). Abruptly, however, in late

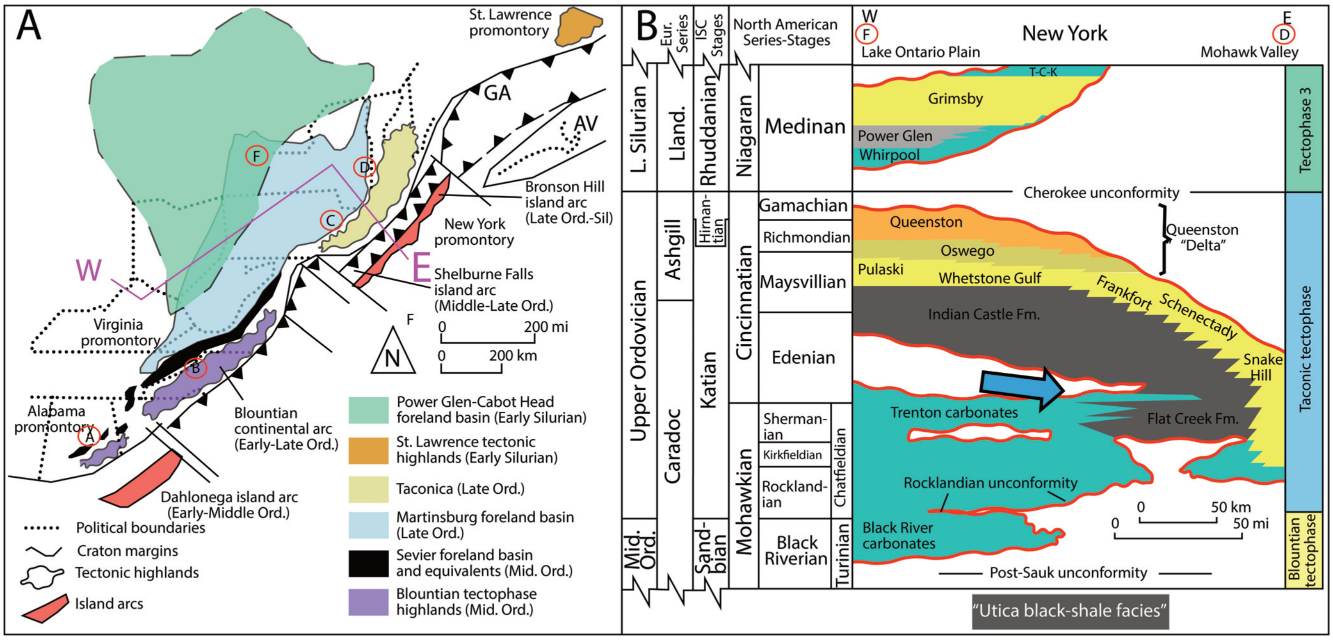

Fig. 3. A – tectonic framework for tectophases of the Middle–Late Ordovician Taconian orogeny along the southeastern margin of Laurentia. The mapped, blue, black-shale basin is the Late Ordovician Martinsburg-Utica foreland basin, representing collision at the New York promontory. Cross section A-B-C-D is shown in Fig. 4 and schematic section W-E in Fig. 5. **B** – cross section F-D in Fig. 3A, showing an abrupt change in the nature and development of black shales at the arrow. At the arrow, foreland-basin black shales and an underlying unconformity migrate westward in space and time into the Michigan Basin (not shown). This abrupt change probably represents a change in subduction polarity near the Chatfieldian–Edenian (mid-Katian) transition (see Fig. 5) (adapted from Ettensohn et al. 2019).

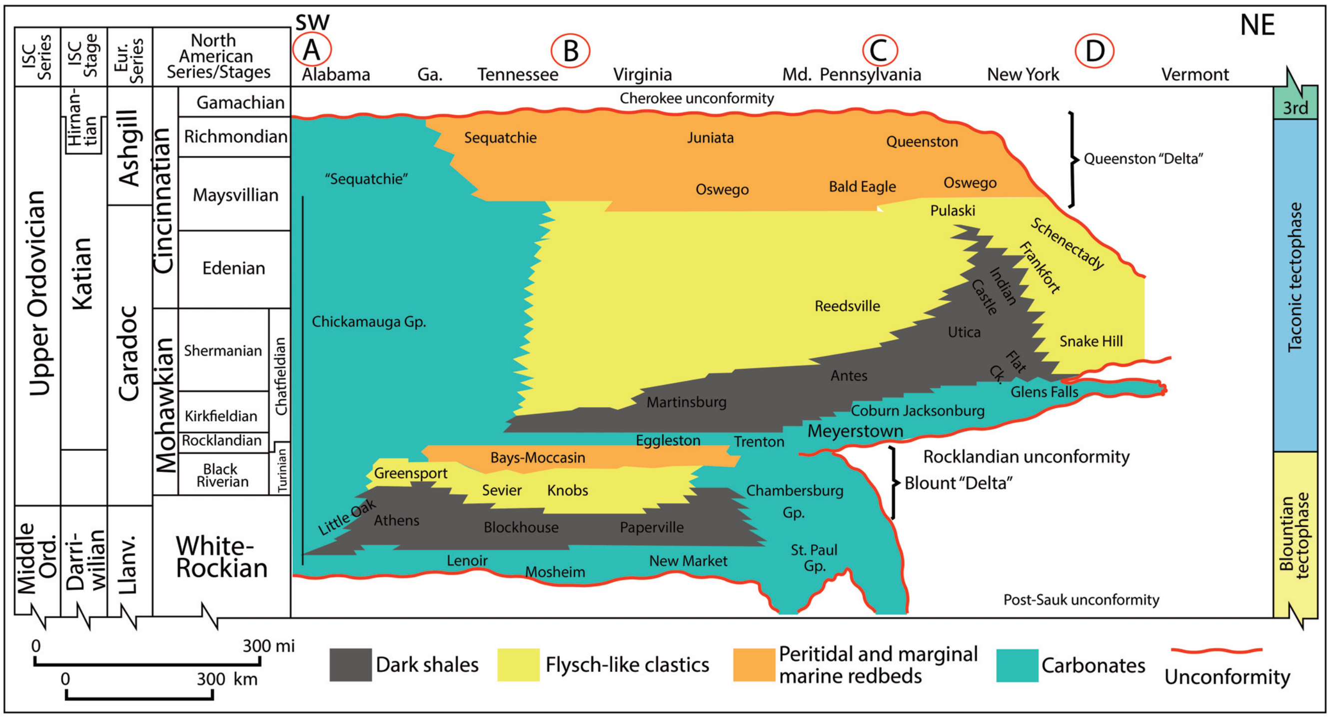

Fig. 4. SW-NE cross section A-B-C-D in Fig. 3A. Note the presence of two, complete, unconformity-bound, tectophase sequences (Blountian and Taconic) and how the sequences migrate northeastward in time, indicating the diachronous nature of the Taconian orogeny. In the Taconic tectophase, northeastward migration of the foreland basin is shown by the migration and "younging" of dark shales in that direction (adapted from Ettensohn et al. 2019).

Chatfieldian–early Edenian (early Katian) time, subduction vergence apparently changed to the west (Fig. 5B), generating a regionally compressional regime that was accompanied by subsidence and change in regional dip, such that black shales and an underlying unconformity migrated westwardly (Figs 3B, 5B). By Maysvillian (late Katian) time, the distribution of Utica and Utica-equivalent black shales shows that the Appalachian and Michigan basins merged into one large, fully yoked basin. The coincidence of changes in basin shape and migration with the shift in subduction polarity suggests a causal relationship (Figs 3B, 5). The approximate time of polarity change is well-known from other sources but is also

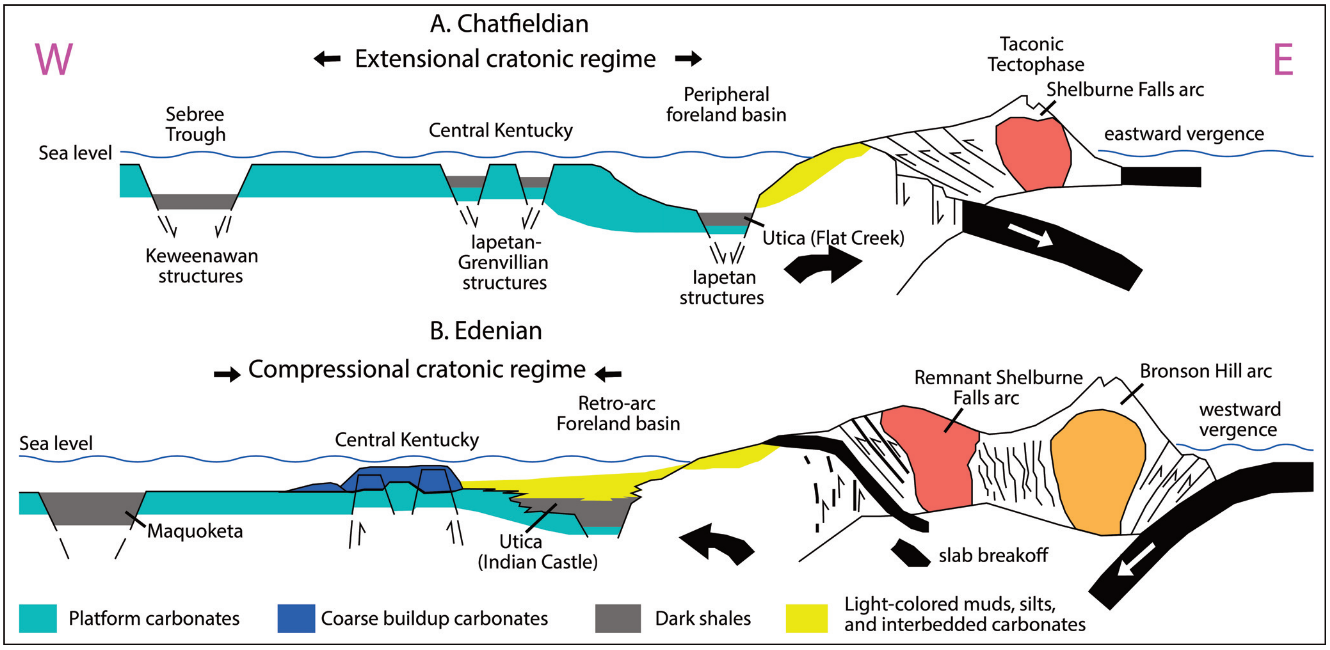

Fig. 5. Schematic diagrams showing craton-wide consequences of change in subduction polarity in the orogen, along section line W-E in Fig. 3A. **A** – Chatfieldian extensional regime with eastward subduction and Utica black shales (Flat Creek) filling an extension-related foreland basin. **B** – Edenian compressional regime with westward subduction and westwardly migrating Utica black shales (Indian Castle; see Fig. 3B) (adapted from Ettensohn and Lierman 2015).

well-constrained by the biostratigraphic ages of and changes in the distribution of the related black shales (Figs 2, 3B).

Conclusions

Black, organic-rich, unconventional gas shales are common in many foreland basins and owe their origin there to flexural tectonic mechanisms related to deformational loading in the adjacent orogen. Ordovician black-shale units in the Appalachian Basin of the eastern United States demonstrate that black shales are early parts of unconformity-bound tectophase cycles and are responses to active deformational loading, which is the shortest part of an orogeny.

Subsequent coarser clastic deposition, in contrast, is a relaxational response to earlier deformation and reflects the greater part of an orogeny. These cycles suggest that black shales as hydrocarbon source and reservoir rocks are clearly the product of distinctive tectonic frameworks and histories, and aside from economic value, may provide important controls on the timing and location of tectonic events.

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