Palaeogeography, Palaeoclimatology, Palaeoecology xxx (2011) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Genesis of unusual lithologies associated with the Late Middle Devonian Taghanic biocrisis in the type Taghanic succession of New York State and Pennsylvania

G.C. Baird [a,*], J.J. Zambito IV [b], C.E. Brett [b]

[a] Department of Geosciences, S.U.N.Y. Fredonia, Fredonia, New York 14063, USA
[b] Department of Geology, University of Cincinnati, 500 Geology/Physics Bldg., Cincinnati, Ohio 45221-0013, USA

ARTICLE INFO

Article history:
Received 23 February 2011
Received in revised form 10 August 2011
Accepted 12 November 2011
Available online xxxx

Keywords:
Devonian
Taghanic
Carbonate
Chamosite
Depositional
Models

ABSTRACT

The Middle Devonian (late middle Givetian) Tully Formation in New York State is the type regional expression of the global Taghanic Biocrisis. It is marked by anomalous development of massive to rhythmically bedded, micritic limestone deposits within a vastly thicker Acadian foreland basin clastic succession. Lower-medial Tully carbonates record the incursion of tropical Old World Realm (OWR) taxa (Tully Fauna) and the outage of the long-standing, higher diversity, cooler-water, endemic Eastern Americas Realm (EAR) biota (Hamilton Fauna). Succeeding Tully strata record a return of the Hamilton Fauna followed by its demise due, both to replacement by the lower diversity, cosmopolitan Genesee Fauna and by the overspread of widespread anoxic bottom conditions coupled with the onset of drastically increased sediment input following Tully Group deposition.

Massive, micritic limestones, yielding modest diversity Tully Fauna assemblages are particularly characteristic of the lower-medial Tully succession on the western New York Tully platform; these are coeval with nearly barren ribbon limestone and siltstone deposits in the adjacent New Berlin (east-central New York) and central Pennsylvania basins. These depocenters trapped terrigenous sediment and helped to create sediment-starved conditions on the platform. Anomalous Tully carbonate deposition is believed to be coincident with strong super estuarine water mass stratification in offshore Tully shelf and basin settings where a warmer, denser, more saline water mass flowed northward (shoreward) across the study area beneath a counter flow of oxygenated, river-influenced surface water. Dysoxic conditions would have developed below the pycnocline, favoring the Tully Fauna incursion, precipitation of carbonate mud, and possibly promoting the formation of ooidal chamosite.

At least five thin (1–30 cm-thick) mappable beds of black, ooidal, chamosite, are observed in Taghanic shelf margin, slope, and basin deposits. These beds are typically intensely bioturbated, variably rich in associated siderite, contain corroded low-diversity fossil assemblages, and are regionally associated with condensed lag deposits above unconformities. Work by others suggests that chamosite formation occurs under minimally reducing, post-oxic, interstitial conditions which are followed, in turn, by more strongly reducing conditions which allow for variable siderite and pyrite formation. Terrestrial pedogenic alteration of silicates by evolving land plant communities under warm, humid conditions led to an increased supply of kaolinite as well as Iron oxides and hydroxides that served as precursors to chamosite formation. In the New Berlin Basin, the transgressive, top-Hamilton-base-Taghanic succession is marked by a succession of diastems associated with basin deepening and upward-increasing chamosite occurrence in dysoxic facies. Occurrence of ooidal chamosite in upper medial Tully platform deposits (Smyrna Bed) may reflect water mass stratification and extreme sediment-starvation at the shelf margin. Eastward spectral transformation of sparsely fossiliferous Smyrna ooidal chamosite in the western New Berlin Basin into richly fossiliferous, non-chamositic, equivalent neritic deposits east of that basin, suggests that the counter-flow of oxygen and nutrient-rich, lower salinity water had blocked the denser, restricted water layer from advancing over the eastern Tully clastic shelf closer to shore.

1. Introduction

The Taghanic Biocrisis was a time of enhanced biotic turnover (faunal extinctions and incursions) associated with inferred global-scale, paleoclimatic changes (House, 2002; Aboussalam, 2003). This disturbance, which may have been comparable in scale to the better

* Corresponding author. Tel.: +1 716 673 3840; fax: +1 716 673 3347.
E-mail address: gordon.baird@fredonia.edu (G.C. Baird).

0031-0182/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.palaeo.2011.11.010

documented Frasnian–Famennian extinction, marked the start of a stepwise drop in global faunal diversity and a long-term trend towards faunal cosmopolitanism in marine biotas generally (Johnson, 1970; Boucot, 1988). As is increasingly becoming apparent, the "Taghanic Biocrisis" is represented by several closely-spaced, discrete bioevents; in the type Taghanic interval within the Tully Formation succession in New York State (Figs. 1 and 2), the Taghanic interval was initially characterized by stepwise incursions of exotic marine taxa ("Tully Fauna") from the tropical "Old World Realm" (OWR) with a concurrent regional "extinction" (outage) of large portions of the endemic, cooler water, Eastern Americas Realm (EAR) Hamilton Fauna as that biota was being replaced (Brett and Baird, 1995; Brett et al., 1996; Baird and Brett, 2003a, 2008; Zambito et al., in press; Fig. 2).

Various models for the Taghanic Biocrisis have been proposed. Bridge and Willis (1994); Algeo et al. (1995) and Algeo and Scheckler (1998) have argued that mid-Late Givetian expansion of multistory forests led to an increase of chemical leaching in terrestrial settings with consequent increases in nutrient supply to coastal waters which caused major eutrophication events in marine settings. Day (1996), Witzke and Bunker (1996) and Marshall et al. (2010) envision a period of cool arid climatic episodes alternating with hot pluvial events occurring within the Taghanic time-slice. Traditionally, the Givetian, with its diverse faunas and stromatoporoid reefs, was thought to have been an interval of warmer seas, followed by a "hot" Taghanic interval, which was succeeded, in turn, by cooler conditions during the Late Devonian. However, recent geochemical studies have called this interpretation into question. Van Geldern et al. (2006) and Joachimski et al. (2009) have assembled isotopic paleotemperature curves respectively from brachiopod calcite and conodont apatite, respectively. Although their paleotemperature curves vary in certain details, both studies indicate that the Taghanic time-slice records a pattern of increasing global sea surface paleotemperatures which were intermediate between relatively cool paleoclimates during the Eifelian–Middle Givetian time slice and distinctly warmer sea surface conditions during the Frasnian. Given that neither of these studies had brachiopod or conodont samples from the type Taghanic succession, it is possible that this "nondistinctive" transitional isotopic signature for this interval may reflect incompleteness of sections in these other areas. Hence, ongoing work by us (Zambito et al., 2011) is being directed to the isotopic assessment of conodont apatite to establish a detailed ^{18}O paleotemperature curve for a relatively complete section in the type Taghanic area of western New York.

This event is recorded in the lower and middle parts of the Tully Formation, an anomalous, carbonate-dominated unit which caps the Hamilton Group, a much thicker siliciclastic succession yielding biofacies of the Hamilton Fauna (Fig. 2). The Hamilton Fauna is interpreted as recording an extraordinarily long period of paleoenvironmental and biotic stability (coordinated stasis) prior to the onset of Taghanic changes (Brett and Baird, 1995; Ivany, et al., 2009). In a strange twist, the Hamilton Fauna returns, displacing the Tully Fauna basinward and briefly dominating shelf biofacies in the upper part of the Tully Formation (Heckel, 1973; Baird and Brett, 2003a; Baird et al., 2003; Baird and Brett, 2008: see Fig. 2). This last flourish of the Hamilton Fauna was followed by its gradual demise within the Appalachian foreland basin, partly due to widespread overspread of anoxia and an associated major pulse of siliciclastic sediment input to the basin which was timed with foreland basin expansion and eustatic sea level-rise, and also partly due to its replacement by post-Taghanic cosmopolitan biotas within the lower part of the siliciclastic Genesee Group succession (Ettensohn, 1985; Johnson et al., 1985; Baird and Brett, 1986; Zambito et al., in press).

Given publication of several recent synthetic papers on the Taghanic biocrisis noted above, we are focusing on a few remaining issues and questions relating to off-platform Tully deposits. This paper presents a brief review of unusual lithologic features of the New York and Pennsylvania Taghanic successions which have a bearing on developing geochemical, tectonic, and circulation models for their genesis. In particular, we examine an array of questions to be addressed through future work. Key issues reviewed herein include: 1, characterization and explanation of lateral gradients between nonfossiliferous and fossiliferous deposits within thick, Taghanic basin successions; 2, the characterization of regional changes within several different beds of ooidal Tully chamosite relative to inferred depth-related facies/biofacies gradients, particularly, spectral gradations from chamositic beds into coeval non-chamositic deposits, and 3, the relationship of the Tully chamosite to standing geochemical models for chamosite genesis.

2. Geologic setting

The type Taghanic region in western and central New York State as well as adjacent central Pennsylvania is located within the northern Appalachian Basin (Fig. 1). During the time of the Taghanic Biocrisis at the end of the medial Givetian (*P. ansatus–O. semialternans* biozones), this region was situated at approximately 30° south latitude

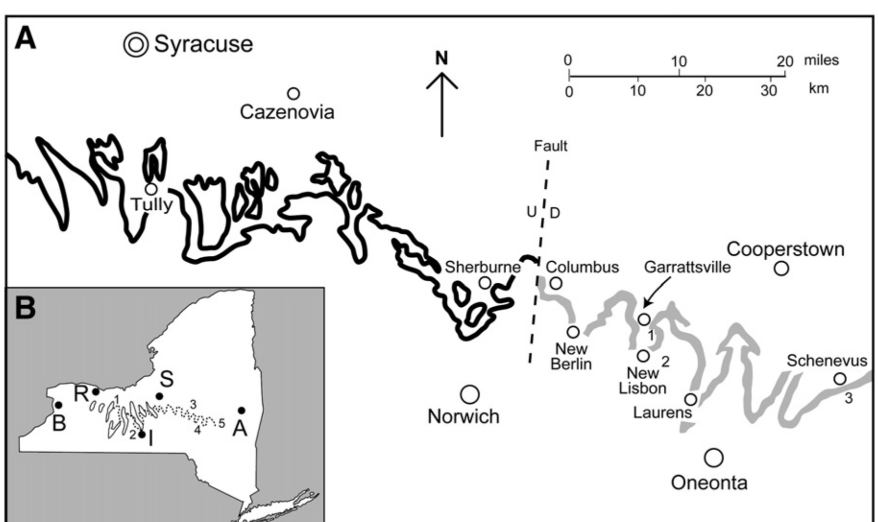

Fig. 1. Study area; A, east–west-trending outcrop belt of Tully Formation (black line) and Tully-equivalent clastic correlative succession (gray belt) relative to inferred fault near Columbus, NY. Numbered outcrops discussed in text include: 1, newly discovered long section near Garrattsville; 2, type section of New Lisbon Member east of New Lisbon; 3, long road cut and creek section southeast of Schenevus; B, Tully sections in New York State. Cities are lettered: B = Buffalo; R = Rochester; S = Syracuse; I = Ithaca; A = Albany. Sections are numbered: 1 = westernmost Tully sections near Canandaigua Lake; 2 = type Taghanic section at Taughannock Falls; 3 = Garrattsville section; 4 = New Lisbon type section; 5 = Schenevus sections (from Baird and Brett, 2008).

Please cite this article as: Baird, G.C., et al., Genesis of unusual lithologies associated with the Late Middle Devonian Taghanic biocrisis in the type Taghanic succession of New York State and Pennsylvania, Palaeogeogr. Palaeoclimatol. Palaeoecol. (2011), doi:10.1016/j.palaeo.2011.11.010

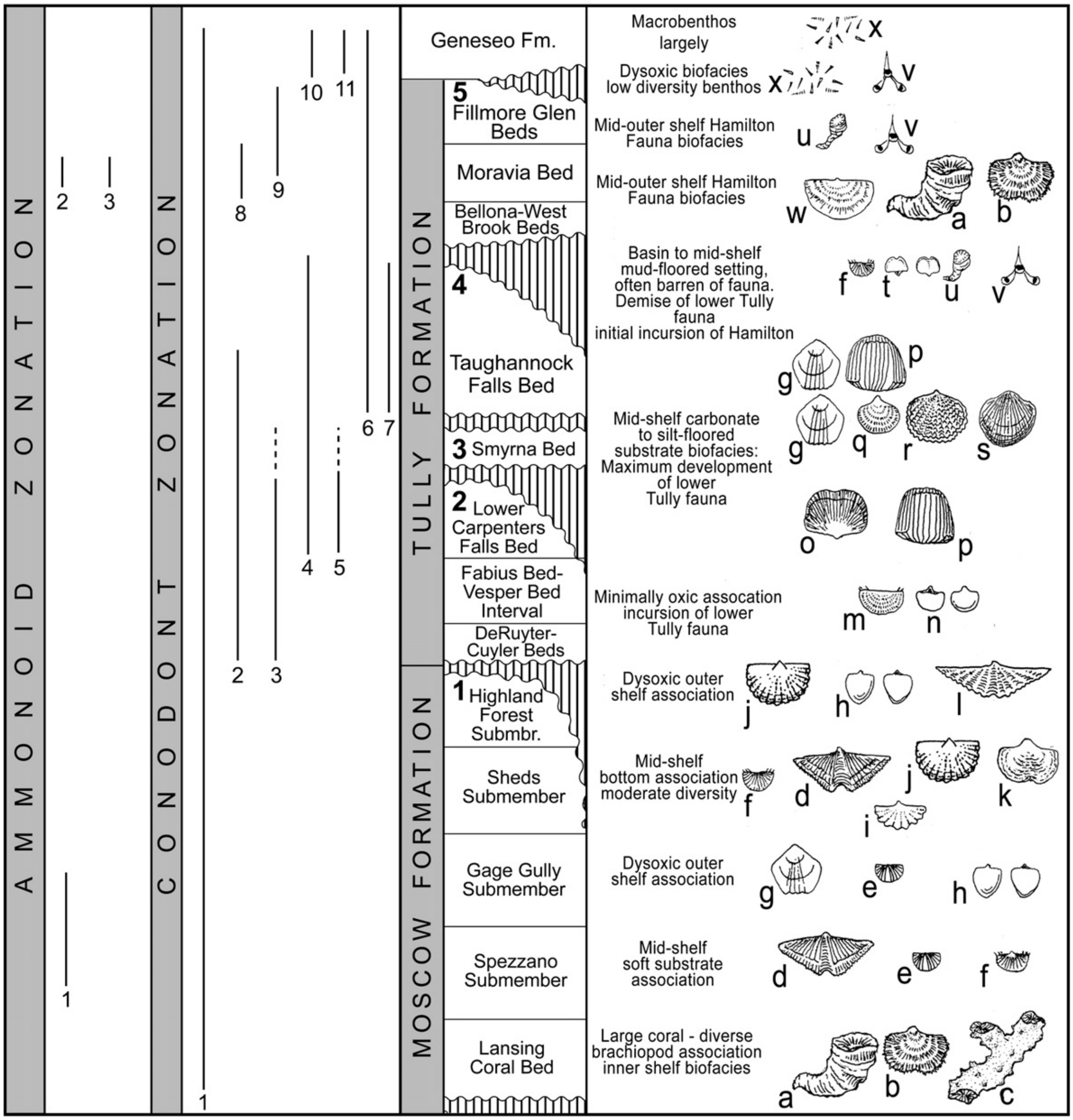

Fig. 2. Generalized faunal succession in the upper Windom Member and Tully Formation succession in central New York (Syracuse meridian) correlated to conodont and ammonoid zonation. This schematic shows the influx of the Tully Fauna at the base of the Tully Formation (DeRuyter Bed-level), reestablishment of the diverse Hamilton Fauna association in the upper Tully Formation (Bellona/West Brook Bed-level), and the decline of faunal diversity in the highest Tully owing to the onset of transgression-related dysoxia in the Moravia Bed-Fillmore Glen Bed-interval. Key lowstand unconformities include: the base-Tully (1), base-middle Tully (2), and base-West Brook (4) sequence disconformities. Maximum flooding surface contacts include: the top-Smyrna Bed unconformity (3) and the top-Fillmore Glen corrosional discontinuity (5). Diagnostic and/or common taxa include: a—*Heliophyllum halli*, b—*Spinatrypa spinosa*, c—large bryozoans, d—Mediospirifer audaculus, e—Allanella tullius, f—*Devonochonetes scitulus*, g—*Camarotoechia ("Leiorhynchus") mesocostale* (in the Tully, this taxon is restricted to the TFCCS in eastern New York and Pennsylvania), h—*Emanuella praeumbona*, i—*Pustulatia (Vitulina) pustulosa*, j—*Tropidoleptus carinatus*, k—*Athyris spiriferoides*, l—*Mucrospirifer spiriferoides*, m—*Rhyssochonetes aurora*, n—*Emanuella subumbona*, o—*Schizophoria tulliensis*, p—*Tullypothyridina venustula*, q—*Echinocoelia ambocoeloides*, r—*Spinatrypa* sp., s—*Pseudoatrypa devoniana*, t—*Ambocoelia umbonata*, u—small rugosan, v—auloporids, w—*Leptaena rhomboidalis*, x—styliolines. Key conodonts include: 1—*Icriodus latericrescens latericrescens*, 2—*Polygnathus timorensis*, 3—*Polygnathus ansatus*, 4—*Polygnathus beckmanni*, 5—*Polygnathus alveoposticus*, 6—*Icriodus difficilis*, 7—*Polygnathus varcus*, 8—*Ozarkodina semialternans*, 9—*Polygnathus latifossatus*, 10—*Polygnathus cristatus*, 11—*Polygnathus disparalvea*. Key goniatites include: 1—*Tornoceras* (*T.*) cf. *uniangulare*, 2—*Pharciceras amplexum*, 3—*Tornoceras* (*T.*) cf. *arcuatum* (modified from Baird and Brett, 2003a, 2008).

at the time of the Taghanic Biocrisis (Figs. 2 and 3). The Tully Group accumulated in an active foreland basin setting associated with oblique convergence of several Avalonian terranes into Laurentia during the Acadian Orogeny (Ettensohn, 1985; Ver Straeten and Brett, 1995, 1997; Ettensohn et al., 2009); these collisions were associated with pulses of collisional thrust loading of the Laurentian craton (tectophases) which caused repeated flexural enlargement and deepening of a foreland basin bordering the orogen (Fig. 3). Erosion of the Acadian collisional highlands during these events produced corresponding phases of progradational basin-filling by the clastic wedge of the Catskill Delta complex. Tully accumulation occurred mainly at the end of the second, and earliest parts of the third collisional tectophase of this orogeny and was anomalously associated with stable shelf conditions and widespread carbonate deposition, particularly across cratonward portions of the type Taghanic region (Heckel, 1973; Baird and Brett, 2003a, 2008; Baird et al., 2003).

3. Inferred depositional and paleoclimatic events

Underlying the Tully Limestone is a much thicker siliciclastic succession comprising the Middle Devonian Hamilton Group which records foreland basin-filling during the second Acadian collisional

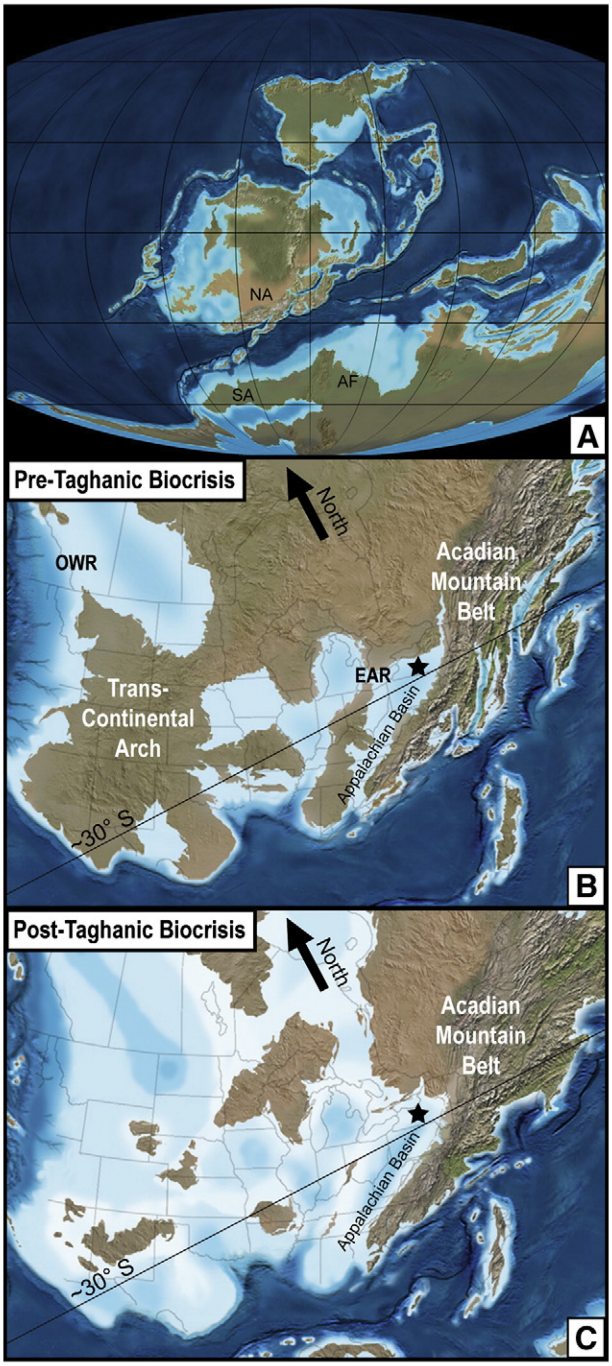

Fig. 3. Paleogeographic reconstruction of the globe (A) and study area respectively before (B) and after (C) the Taghanic Biocrisis. The Appalachian Basin strata of New York State (type area, represented by 'star') that record this biocrisis were deposited approximately 30° south of the paleo-equator. OWR and EAR denote the positions of 'Old World Realm' and 'Eastern Americas Realm' faunas, respectively; note the position of the Trans-Continental Arch ('Continental Backbone' of Johnson (1970)) relative to these faunas. Abbreviations NA, SA, and AF stand for North America, South America, and Africa, respectively. Paleomaps adapted from Blakey (2010); Figure adapted from Zambito et al., in press.

tectophase (Ettensohn, 1985; Ver Straeten and Brett, 1995, 1997). During this time variably shell-rich, detrital sediment accumulated on a gently sloping, subtidal ramp that supported a rich biofacies spectrum of endemic taxa known as the Hamilton Fauna; this association is now understood to be part of the Eastern Americas Realm of endemic southern hemisphere cool temperate water taxa and is particularly important for recording an extraordinarily long episode of community-scale, non-directional evolution ("coordinated stasis") for approximately 4–5 million years (see Brett and Baird, 1995; Brett et al., 2007, 2009; Ivany et al., 2009).

Taghanic biovents commenced with significant changes in tectonic and paleoclimatic conditions. The gentle, westward sloping, pre-Tully submarine ramp was transformed to a broad structural platform in western and west-central New York that bordered the remnants of the foreland basin following deposition of the topmost portion of the Hamilton group succession; these last Hamilton units respectively include the Windom Shale Member in western and central New York and the coeval Cooperstown Siltstone Member in eastern New York (Brett and Baird, 1994; Baird and Brett, 2003a, 2008). Sea level began to rise in a stepwise manner during deposition of the upper part of the Windom Shale allowing limited incursions of deeper-water brachiopods belonging to the lower latitude (warmer water) Old World Realm biota into dysoxic Hamilton habitats (Baird and Brett, 2008; reviewed in Zambito et al., in press). Onset of Tully Group deposition saw continued stepwise advance of the Old World Realm biofacies (the "Tully Fauna") into neritic habitats; each transgressive pulse led to progressive displacement of residual Hamilton taxa from these settings (Sessa, 2003; Baird and Brett, 2008).

Incursion of the Tully Fauna was coincident with changes in stratal geometry and lithology within the Tully Formation. In central and eastern New York State, the Tully is generally carbonate-dominated and characterized by a succession of spatially extensive, and often unconformity-bounded, thin, stacked limestone units (Heckel, 1973; Fig. 2). This "Tully Platform" limestone succession stands in stark lithologic contrast to vastly thicker pre-and post-Tully siliciclastic units across the region. It is the anomalous dominance of dove white, micritic, variably bioturbated limestone within the Tully succession in western New York (Fig. 4A–C) that suggests that a major change in paleoclimatic conditions, which accompanied the incursion of the Old World Fauna (Baird and Brett, 2003a, 2003b; Baird and Brett, 2008; Zambito et al., in press).

The Tully Platform was distinctly bounded to the east and southeast by structural basin settings in which siliciclastic sediment, coeval to the Tully platform carbonates, herein referred to as the Tully Formation clastic correlative succession (TFCCS), accumulated. A narrow N–S trough in east-central New York (New Berlin Basin) separated thin, condensed Tully deposits at its western margin from a siliciclastic shelf region on its eastern side (Heckel, 1973; Baird et al., 2003; Fig. 5). Probable down-to-the-east fault motion, east of the town of Sherburne in the Chenango Valley, accounted, both for the abrupt western margin of this trough and for siliciclastic sediment-starved conditions west of the trough (Heckel, 1973; Baird et al., 2003).

A much larger basin was developed in central Pennsylvania where 70+ meter-thick mixed carbonate-siliciclastic Tully deposits, coeval in age to a 2–7 meter-thick Tully shelf carbonate succession in western New York, accumulated (Heckel, 1969). Rhythmic, thin limestone beds which are essentially devoid of macrofossils characterize much of this deeper-water succession, particularly, in the long roadcut section at Lockport, Pennsylvania (Fig. 4D). As such, these limestone beds are understood to represent platform-derived allodapic carbonates that filled this basin under dysoxic conditions. This trough appears to record a significant flexural downwarping episode, essentially timed with lower and middle Tully deposition and the onset of carbonate accumulation on the western New York shelf. It is probable that the prominent disconformity, flooring the Tully Limestone at the type Taghanic succession at Taughannock Falls near Ithaca, New York (Fig. 4A, B), closes to near-continuity within the thick, ribbon limestone succession in sections west of Williamsport, Pennsylvania. Both the central Pennsylvania basin and the New Berlin trough served as clastic traps for the sequestering of terrigenous sediment, allowing for the accumulation of clean lime mud in a detrital sediment-starved setting on the western New York shelf (Heckel, 1973; Baird and Brett, 2008; Zambito et al., in press). By the time the upper (West Brook Shale-Bellona Bed equivalent) portion of the

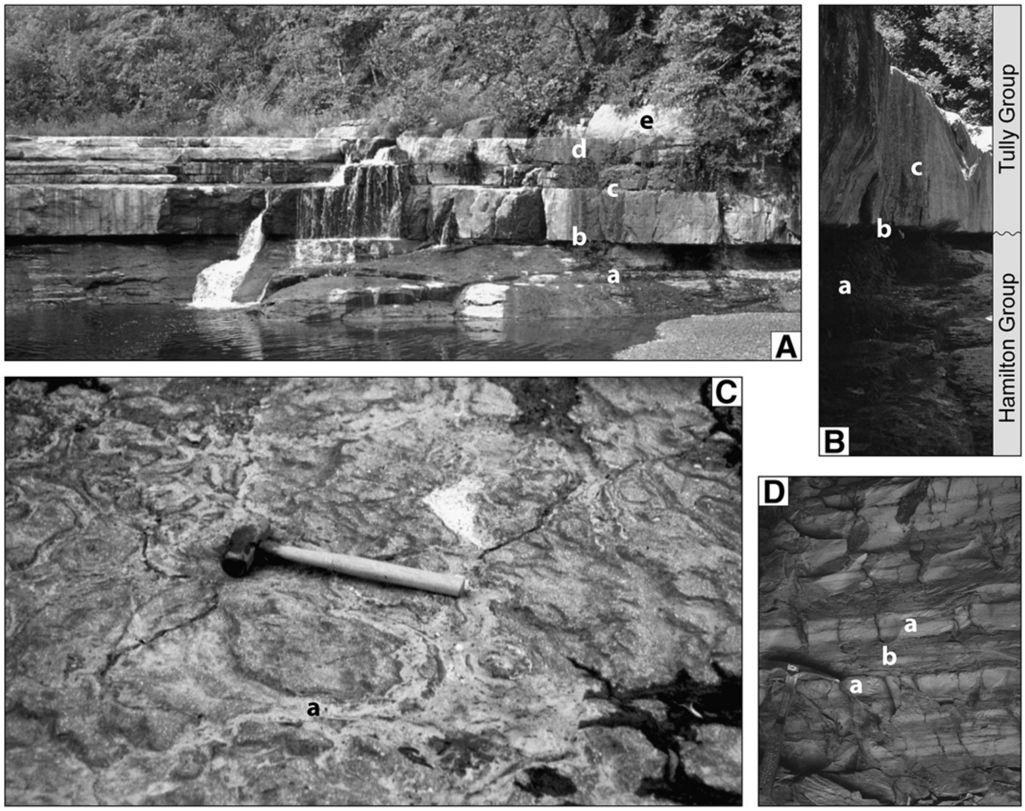

Fig. 4. Tully carbonate facies in outcrop. A, Taghanic type section at Taughannock (Taghanic) Falls State Park in Tompkins County north of Ithaca, New York (Ludlowville 7.5′ Quadrangle).The Tully Limestone disconformably overlies Moscow Formation strata (Windom Shale Member) at this locality. This waterfall is about 6 m high; B, Close-up view of the base-Tully (base-Carpenter Falls Member) contact on the Windom Shale; C, Stromatolitic microbialite crust along unconformity surface at the top of the Carpenter falls Bed along Kashong Creek at Bellona, New York (Stanley 7.5′ Quadrangle), (see also Heckel, 1973), crack hammer for scale; D, Tully basinal ribbon limestone facies exposed in south-facing roadcut at Lockport near Lock Haven, Pennsylvania (Lock Haven 7.5′ Quadrangle), hammer for scale.

Tully was being deposited, this basin had filled completely such that late Tully deposition occurred on a very broad platform across nearly the entire northern Appalachian Basin region (Baird and Brett, 2003a; Baird et al., 2003; Baird and Brett, 2007; schematically reviewed in Zambito et al., in press; Fig. 5).

Tully massive carbonate deposition was largely confined to the western-central New York platform region, though off-platform, fossil-poor, nodular-to-ribbon limestone variants of the lower-into-medial Tully carbonate succession can be seen in central Pennsylvania (Fig. 4D). Onset of massive carbonate deposition (Fabius Bed–Carpenter Falls Bed succession; Figs. 2 and 4A, B) corresponds to maximal incursion of the Old World Realm-related Tully Fauna into shelf habitats as well as a major nadir (outage) of Hamilton Fauna taxa from these same settings (Baird and Brett, 2003a, 2008; reviewed in Zambito et al., in press). This lithologic and faunal change is interpreted as reflecting a major southward advance of denser, more saline, warmer water from the Devonian paleotropics across the Tully shelf with associated set-up of a stratified estuarine-type water column, although, possible episodic anti-estuarine circulation may have occurred dependent on the degree of climatic aridity and resultant runoff volumes (Witzke, 1987 and references therein; Marshall et al., 2010; see model of Zambito et al., in press; Fig. 6). Development of more arid conditions in the late Middle Givetian (Marshall et al., 2010), the effect of detrital sediment trapping in adjacent basins, and the incursion of tropical water masses to the Tully shelf collectively explain the development of massive lower and medial Tully carbonate deposits (Fabius Bed–Carpenter Falls/Smyrna Bed succession) on the platform (Figs. 4A, B and 6).

The lower-medial Tully succession is also particularly notable for the localized occurrence of black ooidal chamosite, often in association with diagenetic siderite, syneresis cracks, and thin microbialite crusts. Chamosite, which occurs at several different levels within the Tully Formation succession, typically occurs as sand-size, discoidal, grains with internal concentric laminations. These grains occur in a mud-supported, bioturbated fabric with poorly preserved, low diversity fossil assemblages (Figs. 7A, B and 8–10). Chamosite development is associated with condensed deposits at the carbonate shelf margin and transgressive lag deposits in basin settings (Baird et al., 2003; Baird and Brett, 2008). The most prominent chamosite accumulation is associated with strongly condensed deposits of the late medial Tully Smyrna Bed where grainstone deposits on the Tully platform can be seen to grade eastward spectrally into chamositic "oolite" at the platform margin and in the New Berlin Basin (see Chamosite genesis below; Figs. 6, 9, 10).

The most dramatic event recorded in the type Taghanic region is the reestablishment (ecological "comeback" or "recurrence") of the Hamilton Fauna in Tully shelf habitats with associated seaward exile of Tully Fauna taxa into dysoxic off-shelf settings (Baird and Brett, 2003a, 2008; reviewed in Zambito et al., in press). This biofacies overturn commenced within the Taughannock Falls Bed succession above the Smyrna Bed and culminated in the development of diverse Hamilton coral bed and diverse brachiopod biofacies (see Brett et al., 2007), respectively in the Bellona Coral Bed and West Brook Shale deposits of the upper Tully succession (Figs. 2 and 5). This acme of Hamilton taxa was short-lived, and this association was eventually displaced from the Appalachian Basin, due to end-Taghanic transgression and associated overspread of anoxia timed with the well documented Taghanic onlap event which continued long after Tully deposition ceased (Johnson, 1970; Johnson et al., 1985; House, 2002; Zambito et al., in press). Essentially linked to the late Tully Hamilton Faunal acme is the aforementioned complete filling of the central Pennsylvania and New Berlin basins such that the West Brook Bed–Bellona Bed is regionally expressed as a thin, richly fossiliferous band which appears to have accumulated on a nearly dead-level

Please cite this article as: Baird, G.C., et al., Genesis of unusual lithologies associated with the Late Middle Devonian Taghanic biocrisis in the type Taghanic succession of New York State and Pennsylvania, Palaeogeogr. Palaeoclimatol. Palaeoecol. (2011), doi:10.1016/j.palaeo.2011.11.010

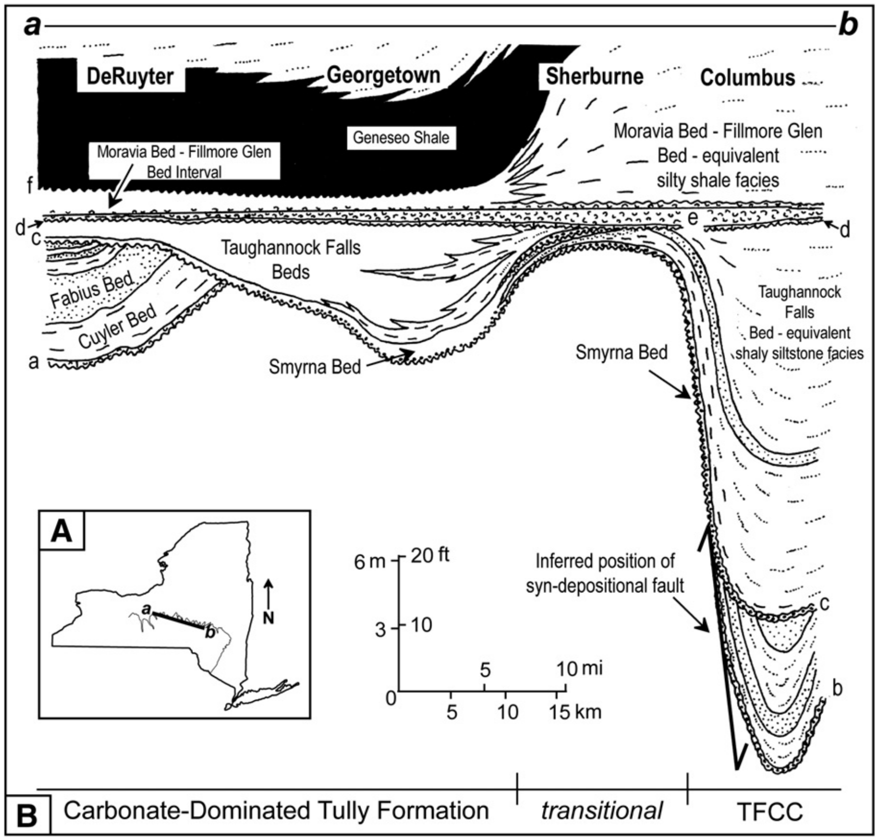

Fig. 5. Regional cross-section of the Tully and basal Genesee Group across east-central New York State showing inferred correlations of Tully Formation divisions with equivalents in the Tully Formation Clastic Correlative succession (TFCCS). Location of section along outcrop belt is shown in inset figure. The underlying Hamilton Group is not shown for ease of Tully unit visualization. The transect shows the rapid eastward thickening of the Tully clastic correlative succession across a possible growth fault east of Sherburne, New York; the sediment-starved, western (structurally upthrown) side of this structure ("Sherburne High"), bounded a local, structurally downthrown, basinal trough which served as a clastic trap. Note the prominent disconformable nature of the mid-Tully sequence unconformity (c) and the upper Tully sequence unconformity (d). Note also the striking thinness and uniformity of thickness of the Bellona Bed/West Brook Shale (e) relative to underlying and overlying units (see text). The Tully–Genesee contact (f) is unconformable across part of the region as shown. Lettered features include: a, DeRuyter Bed; b, chamositic–sideritic bed believed to be equivalent to DeRuyter Bed; c, Smyrna Bed floored by mid-Tully sequence disconformity; d, upper Tully sequence disconformity; e, Bellona Bed/West Brook Shale; and f, black shale-roofed corrosional discontinuity with associated detrital pyrite marking Tully-Geneseo contact. Figure adapted from Baird and Brett (2003a).

submarine shelf plain across central Pennsylvania, eastern New York and on the western New York platform (Fig. 5). In fact, these previous shelf and platform domains, as well as the clastic trap, were no longer distinguishable as bathymetric features at this time (Baird et al., 2003; Baird and Brett, 2008; Zambito et al., in press). This is all the more significant in that onset of the third tectophase (*sensu* Ettensohn, 1985), involving flexural shelf collapse and foreland basin expansion, would commence in full force following Tully deposition. Following West Brook Bed–Bellona Bed deposition was a gradual restoration of the previously differentiated basin and shelf domains during deposition of massive platform carbonate deposits of the thin, upper Tully Moravia Bed, followed, in turn, by general shelf collapse during end-Tully Fillmore Glen Bed deposition. It is notable that the thin, fossiliferous West Brook Shale–Bellona Bed interval is everywhere shaly or characterized by very impure carbonate deposits in marked contrast to typical Tully massive micrite deposits both below and above this level. This anomaly is provisionally interpreted as the result of a breakdown of water column stratification, thereby allowing for the collapse of the carbonate factory and return of the Hamilton fauna to platform habitats (Zambito et al., in press; Fig. 6).

4. Tully chamosite, siderite, and microbialite deposits

4.1. Stratigraphic occurrences

Ooidal chamosite-bearing beds occur at no less than five stratigraphic levels within the Tully Formation succession (Figs. 5, 7–12); these include, in ascending order: 1, the base-New Lisbon Member (*sensu* Baird et al., 2003) lag deposit marking the top-Hamilton base-Taghanic boundary in east-central New York (Figs. 5, 8); 2, the base-Tully-Formation-equivalent (TFCCS succession) lag deposit (*sensu* Baird et al., 2003) in east-central New York (formerly base of "upper New Lisbon Member" *sensu* Cooper and Williams, 1935); this unit is provisionally believed to be equivalent to the condensed base-Tully DeRuyter Bed in central New York; 3, the condensed Smyrna Bed near Sherburne in east-central New York (Figs. 7, 9–10), and at Hughesville in central Pennsylvania (Fig. 10B); 4, locally developed ooidal chamosite facies in condensed deposits of the Taughannock Falls Bed interval near Sherburne, New York, and 5, a lag bed within-, or at the top of, the Moravia Bed near Sherburne, New York. Chamositic ooids are also observed at the base of the Tully in east-central Pennsylvania, but stratigraphic correspondence of this level to New York sections is, as yet, uncertain. Moreover, minor discoidal chamosite also occurs in the topmost beds of the Hamilton Group succession in east-central New York where the transgressive spectral facies transition between the Hamilton group and the lowermost Taghanic succession is most complete (see below). Occurrences at levels 1, 2, 3, and 5 are described below in ascending stratigraphic order.

4.2. Base-New Lisbon Member diastem

The pre-Taghanic (Hamilton Group)-into-base-Taghanic stratigraphic succession is understood to be the most temporally complete in sections near the villages of Garrattsville and New Lisbon in the

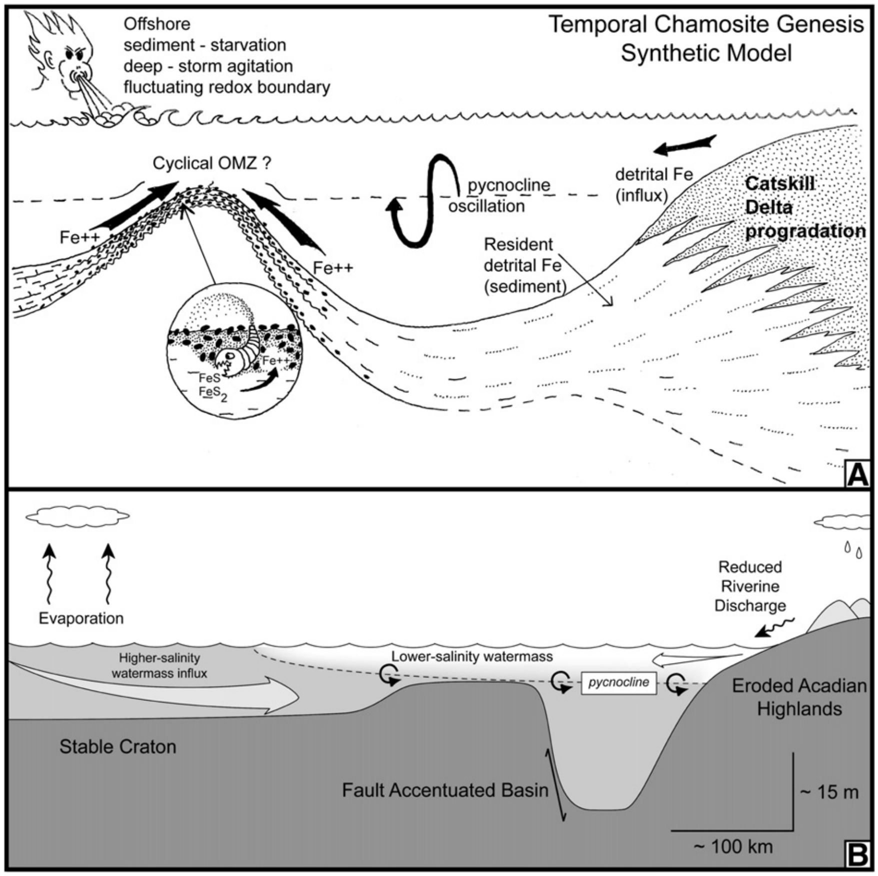

Fig. 6. = Inferred watermass circulation models for Taghanic epicontinental sea in east-central New York. A) Model for Tully chamosite formation advanced by Baird and Brett (2003b) and Baird et al. (2010). Sediment-starvation, intense bioturbation, and periodic development of dysoxic conditions were believed responsible for interstitial chamosite formation along the Sherburne High. Dysoxia was interpreted as being the result of upwelling along this structural axis (see text); B) Alternate watermass circulation model during the lower Tully Formation, which is inferred to be a period of increased aridity (Marshall et al., 2010). In this model, a higher-salinity, warmer and denser cratonic watermass would flow into the basin and below a riverine-controlled, lower-salinity surface layer, resulting in an elevated pycnocline and basin stratification. Basin morphology, in the form of a fault-controlled sill, further accentuates the development of contrasting shallow and deep watermasses (adapted from Zambito et al., in press).

Butternut Valley in east-central New York (Baird et al., 2003; Baird and Brett, 2008; Figs. 8 and 11). This area, as well as the Pittsfield–New Berlin region to the west of it, were affected by localized tectonic subsidence where topmost Hamilton shelf deposits (Cooperstown Member) are succeeded by flaggy siltstone and shale facies of the base-Taghanic New Lisbon Member; onset of New Lisbon deposition marked a significant transgressive event (Baird et al., 2003) where basal Taghanic sediments accumulated in a dysoxic basinal regime. However, this transgression is marked by, at least one diastemic break with an associated lag zone marked by the abundant Tully Fauna brachiopod *Camarotoechia mesocostale*, chamosite, and nodular diagenetic siderite in a dark mudstone matrix (Fig. 11).

In the Pittsfield–New Lisbon area, this intensely bioturbated, thin lag zone is characterized by corroded *C. mesocostale* in association with discoidal to disk-shaped chamosite, concretionary nodules of siderite that enclose some chamosite grains, and subsidiary nodular, diagenetic phosphate and pyrite (Fig. 8). Where chamosite grains are enclosed by nodular siderite or phosphorite, they have a discoidal ("peppermint patty") shape and display good internal concentric laminations, typically around a quartz silt or sand grain nucleus. When they occur in the non-concretionary mudstone matrix outside of the sideritic nodules, they are flattened disks, often with a central protrusion reflecting the position of the nucleus clast. This shape contrast suggests that siderite precipitation took place largely after chamosite grain formation, but distinctly earlier than compactional dewatering of surrounding muds. Shiny black lamellar crusts, possibly also of chamositic composition, occur within the lag interval; these may be films of microbialitic origin.

Stepwise, spectral facies transgression occurring across the uppermost Cooperstown Member-into-New Lisbon Member succession is best illustrated in two closely-paired, west-flowing ravines 0.9 km south-southeast of Garrattsville in the Butternut Valley (Baird and Brett, 2008; Fig. 11). At this locality, a thin coral bed in the upper part of the Cooperstown Member, yielding diverse Hamilton Fauna taxa, marks the highest richly fossiliferous level of the Hamilton Group. This bed gives way to a 2–3 meter-thick succession of soft gray shaly siltstone containing a moderate diversity Hamilton Fauna assemblage which is, in turn, capped by a thin diastemic lag deposit yielding disarticulated Hamilton taxa in association with sparse discoidal chamosite. Above this lowest chamositic bed is a 2–3 meter-thick interval of soft gray-green shale yielding a modest Hamilton Fauna association consisting of small brachiopods and mollusks which is capped by a diastemic lag bed containing chamosite in association with siderite and a complete absence of shelled taxa. This layer is, in turn, followed by a 1–1.5 meter-thick interval of thin-bedded, tabular siltstone beds and thin shale partings which to date has yielded no macrofauna. Finally, this barren unit is succeeded by a 10 meter-thick New Lisbon tabular siltstone-shale succession marked at its base by abundant *C. mesocostale* and rare *Tullypothyridina* in association with diastemic chamosite and siderite (Baird and Brett, 2008). This overall succession defines the stepwise transgressive replacement of diverse aerobic benthic assemblages by distinctly stressed dysaerobic biotas, and it shows that chamosite development is closely linked to episodes of sediment-starvation and reworking during stages of increasing seafloor anoxia (Figs. 2–11).

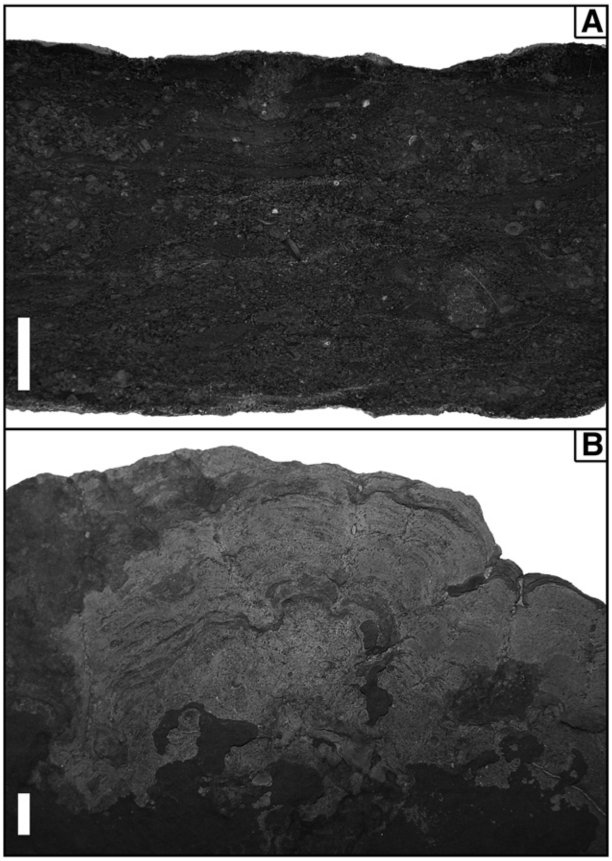

Fig. 7. Smyrna Bed "oolite" and associated capping microbialite crust. A, Smyrna Bed ooidal chamosite from a south-flowing ravine on the south side of Hunts Mountain, 2.7 km southeast of the center of Sherburne, NY (Sherburne 7.5′ Quadrangle). Notice the abundance of sub-spherical (discoidal), sand-sized clasts which are largely matrix-supported within bioturbated, calcareous mudstone; B, top, bedding plane view of stromatolitic microbialite which caps a thin, basinal phase of the Smyrna Bed from a creek section near Walt Phillips Road, 2.45 km southwest of the intersection at Columbus, NY (Sherburne 7.5′ Quadrangle). Chamositic ooids occur within this microbialitic layer (see Fig. 10C), Scale bars = 1 cm.

4.3. Base-Tully clastic correlative succession diastemic contact

In the Butternut Valley of east-central New York, Baird et al. (2003) subdivided the original New Lisbon Member division (*sensu* Cooper and Williams, 1935) into two diastem-bounded units; the lower of these divisions retains the original name, and the upper division is grouped into the succeeding Tully Formation eastern clastic correlative succession herein referred to as TFCCS (Figs. 5, 11–12). The boundary between the newly defined (restricted) New Lisbon Member and succeeding beds is a regional discontinuity that appears to be correlative with the better known base-Tully Formation contact (base of DeRuyter Bed) in central New York (Baird et al., 2003). At Garrattsville and at the type New Lisbon Member section 1.6 km northeast of the hamlet of New Lisbon (Fig. 12), this diastem separates *C. mesocostale*-bearing, thin-bedded siltstone and shale deposits of the New Lisbon from an overlying succession of thick-bedded siltstone layers abounding in *C. mesocostale* but also yielding in greater proportion the characteristic Tully Fauna taxa *Tullypothridina venustula* and *Rhyssochonetes aurora* (Figs. 11 and 12). In the strongly bioturbated lag zone above this contact, the chamosite is less concentrated than at the base-New Lisbon contact, but is of a similar grain morphology. Phosphate nodules also occur sparingly at this level.

4.4. Smyrna Bed chamosite occurrence

West of the Syracuse meridian, massive, 2–4 meter-thick, micrite deposits of the medial Tully Carpenter Falls Bed are capped by a diastemic surface which locally displays subjacent syneresis crack systems, and, more rarely, microbialitic (stromatolites) along its surface (Heckel, 1973; Baird et al., 2003; Fig. 4C). This surface is, in turn overlain by impure, nodular limestone deposits of the Taughannock Falls Bed interval which record a transgressive deepening event, closely associated with the demise of the Tully Fauna and the return of Hamilton biofacies in the upper Tully (Baird and Brett, 2003a, 2008; reviewed in Zambito et al., in press). Beginning at the Syracuse meridian, the Carpenter Falls Bed thins and coarsens dramatically towards the east and southeast, such that it has essentially graded into a thin, compact, packstone–grainstone layer (Smyrna Bed) with a sharply defined base and top at localities in the Highland Forest Metropark in southeasternmost Onondaga County (Fig. 5). Continuing eastward, the Smyrna Bed grades spectrally from a carbonate clast blanket near the village of Sheds, New York into a macrofossil-poor bed of ooidal chamositic grains which is maximally developed near Sherburne in the Chenango Valley east to the vicinity of Columbus, New York (Baird et al., 2003; Figs. 7A, 9, 10A, F). As this unit is traced eastward from Columbus to New Lisbon, across the New Berlin Basin, it thins and gradually loses its chamositic character within the TFCCS succession as it is traced across the New Berlin Basin (Fig. 10F). East of the New Berlin Basin axis, the Smyrna Bed becomes increasingly shell-rich as it is traced from the vicinity of Pittsfield southeastward to Laurens, New York near Oneonta (Baird et al., 2003; Baird and Brett, 2008).

In the region of significant Smyrna Bed chamosite development, the base of the Smyrna Bed becomes markedly erosional (Heckel, 1973). Between Sheds and Sherburne, the entire lower Tully succession, as well as the topmost Windom Member, are cut out by erosion (Fig. 5). The region of maximal chamosite development near Sherburne has been interpreted to have accumulated on a structural axis ("Sherburne high") where the Tully oolites formed in an agitated setting in a sediment-starved, shoal setting which bordered a basinal depocenter to the east (Heckel, 1973; Fig. 5).

From the Syracuse meridian eastward to Otselic, New York, the overlying Taughannock Falls Bed interval thickens into a relatively unfossiliferous lentil of tabular, concretionary limestone beds and calcareous shale, which sharply overlies the Smyrna Bed (Heckel, 1973; Fig. 5). East of Otselic, the Taughannock Falls Bed thins and grades into a stack of thin calcareous siltstone and chamositic beds. Given the overall condensed character of the Smyrna Bed–Taughannock Falls Bed interval and the close association of the chamositic beds with erosional episodes, it is uncertain whether or not the actual Smyrna Bed is, or is not, locally overstepped at the Sherburne meridian (Baird et al., 2003).

West of the village of Columbus, New York, the Taughannock Falls Bed begins to dramatically thicken southeastward, and the lower Tully succession, absent at Sherburne, reappears in the form of siliciclastic, largely basinal, deposits (Fig. 5). Most of this ballooning of the section occurs southwest of Columbus in the vicinity of an inferred down-to-the-east fault that was believed to have been active at this time (Heckel, 1973; Baird et al., 2003; Figs. 1 and 5). The Smyrna Bed thins southeastward from the Sheds area and gradually loses its chamosite content such that no chamosite is observed in this unit from the Butternut Valley eastward. Hence, chamosite occurs maximally on the Sherburne high axis near the eastern margin of the Tully platform, and it is largely restricted to the adjacent, east-facing, western ramp slope of the New Berlin Basin (Figs. 5 and 10F).

In additional to its better known occurrences in New York State, the Smyrna Bed is also tentatively recognized as an 18–20 cm-thick, condensed, nodular limestone bed in a 60+ meter-thick, largely siliciclastic Tully section in the village of Hughesville, Pennsylvania. It unconformably overlies a succession of thick, massive siltstone units which appear to correspond to the medial Tully carbonate succession of the New York platform (Baird and Brett, 2007). The knife-sharp top of this unit marks the base of a 13+ meter-thick shale unit which is

Please cite this article as: Baird, G.C., et al., Genesis of unusual lithologies associated with the Late Middle Devonian Taghanic biocrisis in the type Taghanic succession of New York State and Pennsylvania, Palaeogeogr. Palaeoclimatol. Palaeoecol. (2011), doi:10.1016/j.palaeo.2011.11.010

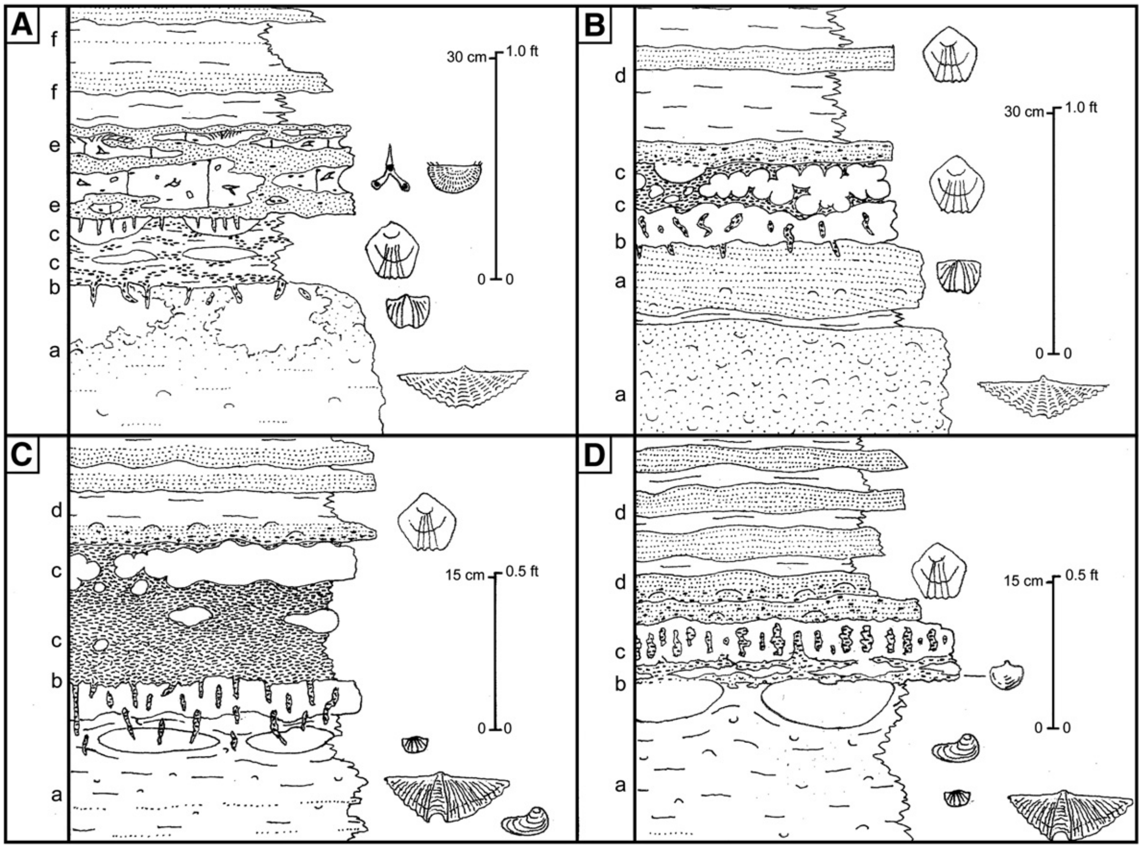

Fig. 8. Base-New Lisbon Member unconformity at four key localities; A, "Greens Gulf", 2.3 km southwest of New Berlin, New York (New Berlin South 7.5′ Quadrangle), showing three inches of base-New Lisbon chamosite-rich shale overlain by Smyrna Bed (interval now concealed under alluvium); B, Northwest-flowing tributary of Wharton Creek 1.2 km south of Pittsfield, New York (New Berlin North 7.5′ Quadrangle) showing spectacular nodular diagenetic siderite "marbled" throughout the black, chamositic basal layer (interval now concealed under shallow alluvium); C, Unnamed gully northwest of former Gross Hill School, 3.7 km northwest of Garrattsville, New York (Edmeston 7.5′ Quadrangle) showing chamosite with associated nodular diagenetic siderite; D, East-facing cutbank along south-flowing tributary of Stony Creek, 2.0 km north-northeast of New Lisbon, NY (Morris 7.5′ Quadrangle) showing easternmost development of chamosite- and siderite-rich sub-New Lisbon Member contact. Note occurrence of this *Emanuella*-rich layer coincident with base of chamositic bed (see text). Lettered units include: a, uppermost typical Cooperstown member (probable Spezzano submember equivalent) succession yielding typical upper Hamilton Group taxa such as *Mucrospirifer*, *Mediospirifer*, *Alanella*, and nuculoid bivalves; b, erosional contact showing chamosite disk-infilled open burrows (or borings) as well as underbed diagenetic siderite nodules; c, black, shiny concentration of discoidal (flattened?) chamositic "ooids" and sideritic nodules; d, interbedded, flaggy shale-siltstone facies of basal New Lisbon Member yielding Leiorhynchids, cf. *Camarotoechia mesacostale*; e, Smyrna Bed containing dilute chamosite, phosphate nodules, nodular limestone and possible stromatolite developmentat top. Unit yields abundant auloporids and rare *Rhyssochonetes*; f, barren flaggy shale-siltstone interval of post-Smyrna strata. (Adapted from Baird et al., 2003).

believed to represent the Taughannock Falls Bed transgression event. Limestone nodules in this bed appear to be closely stacked, concretionary *Thallassinoides* burrow systems in association with auloporid coral networks and comminuted pelmatozoan debris. The topmost two centimeters of this limestone bed contains dilute ooidal chamosite (Fig. 10B). Moreover, the top 1.0–2.5 mm of this bed is marked by an orange colored microbialitic crust which marks the contact with the overlying shale unit.

Texturally, the Smyrna Bed "oolite" is characterized by abundant black, discoidal chamositic grains which are matrix-supported within intensely bioturbated, calcareous lime mud in association with subsidiary amounts of nodular phosphate and pyrite (Figs. 7A, 9, 10A). Ooidal grains are randomly oriented and reflect the fine-scale burrowed texture of the sediment. Macrofossils are scarce in this facies with the exception of corroded auloporid coral material and pelmatozoan debris. Heckel (1973) recorded the occurrence of a cluster of the articulated rhynchonellid brachiopod *Tullypothyridina* within a burrow in the Smyrna Bed at West Brook, 5.2 km south-southeast of Sherburne. Although "grape clusters" of *Tullypothyridina* characteristically occur in non-chamositic Smyrna Bed and Carpenter Falls Bed deposits further west, later excavation into the Smyrna Bed layer at West Brook and at other adjacent sections by the present authors yielded no *Tullipothyridina* or any other brachiopod genera. This indicates that macrofossils are rare in this facies, due to taphonomic corrosion and/or unfavorable bottom conditions, although not entirely absent.

In the Columbus–New Berlin area, within the western part of the New Berlin Basin, the chamosite is locally capped by thin, microbialite crusts which directly underlie non-chamositic basinal shale deposits. In a creek adjacent to Walt Phillips Road, 2.45 km southwest of Columbus, good stromatolitic texture occurs at the top of what appears to be good Smyrna Bed chamosite in loose Tully blocks along the creek (Figs. 7B and 10C); seen in thin section vertical profiles, scattered chamositic ooids can be seen within this stromatolitic fabric (Fig. 10C), and both larger-scale syneresis cracks and concretionary siderite are well developed within the ooidal chamosite bed under the microbialitic layer. Syneresis cracks are commonly interpreted as the result of the contraction of swelling clay lattices due to salinity changes, often beneath microbialitic mats (Plummer and Gostin, 1981; Pflueger, 1999), or, more recently, sudden sediment dewatering as a result of seismic shaking (Pratt, 1998). Few fossils occur in the ooidal chamosite or in the overlying stromatolitic layer at this locality; corroded remnants of auloporid coral networks and one specimen of the chonetid *Rhyssochonetes* were the only taxa observed in these units.

Smyrna Limestone sections, further west in the Tully Valley and also in the Highland Forest Park, are composed of variably silty calcarenitic packstone–grainstone deposits that are variably bioturbated

Please cite this article as: Baird, G.C., et al., Genesis of unusual lithologies associated with the Late Middle Devonian Taghanic biocrisis in the type Taghanic succession of New York State and Pennsylvania, Palaeogeogr. Palaeoclimatol. Palaeoecol. (2011), doi:10.1016/j.palaeo.2011.11.010

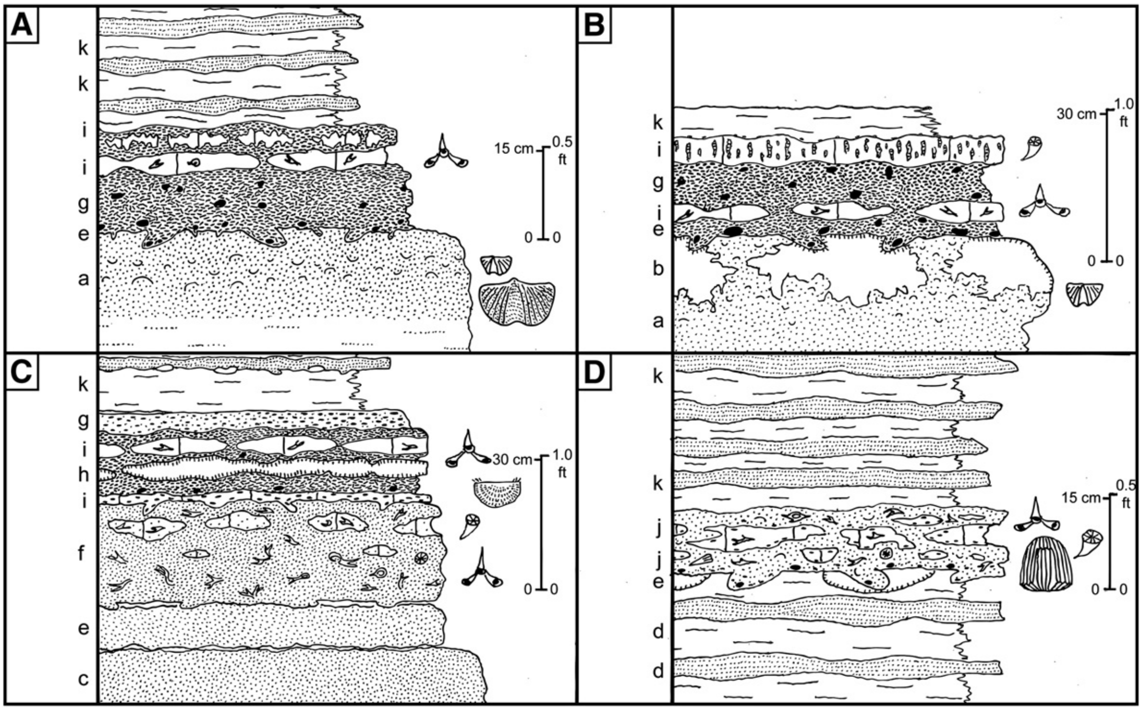

Fig. 9. Smyrna Bed in Tully clastic correlative succession. Locality sequence shown includes: A, Un-named gully south of Bingham Road 2.45 km northwest of Columbus, NY (Sherburne 7.5′ Quadrangle). Photomicrograph 10 A is from the Smyrna Bed at this section; B, un-named creek west of Winton Road and 2.7 km west-southwest of Columbus, NY (Sherburne 7.5′ Quadrangle); C, un-named creek southeast of Balcom Hill Road, 3.2 km south-southeast of Columbus, NY (Sherburne 7.5′ Quadrangle); and D, northwest-flowing tributary of Wharton Creek, 1.3 km south of Pittsfield, NY (New Berlin North 7.5′ Quadrangle) . Lettered units include; a, uppermost (Spezzano Member equivalent?) division of Cooperstown Member yielding *Alanella* and *Spinocyrtia*; b, Cooperstown Member siltstone suffused with diagenetic, under-bed siderite related to proximity of sub-Tully contact; c, massive, bioturbated (Fabius Bed equivalent?) siltstone bed in lower Tully Formation succession; d, flaggy shale-siltstone facies in lower Tully "Laurens Member" succession; e, sub-Smyrna Bed erosion surface; f, lower Smyrna, non-chamositic, auloporid-pelmatozoan debris-rich limestone bands and nodules within chamosite; j, bioturbated siltstone with lean chamosite and bioclastic limestone nodules yielding auloporids, rugosans, *Tullypothyridina* and *Rhyssochonetes*; k, barren, flaggy shale-siltstone interval in medial Tully Formation succession. (Adapted from Baird et al., 2003).

(Figs. 2, 5, 10D, E). Clusters of *Tullypothyridina* mixed with *C. mesocostale* are present locally within burrow systems, and auloporid corals are common, indicating modest faunal diversity in this unit. Carbonate clasts include degraded pelmatozoan ossicles and unidentifiable clasts of cryptocrystalline carbonate which were interpreted by Heckel (1973) as physically abraded and comminuted material which had been repeatedly buried and reworked in an agitated setting. Long-term winnowing of metastable carbonate debris on the Smyrna submarine platform, coupled with episodes of diagenesis (syntaxial recrystallization) and mechanical abrasion, would have produced numerous clasts of unidentifiable origin (Heckel, 1973). Heckel (1973) also entertained the idea that some of this carbonate could have been the result of direct inorganic precipitation ("whitings") from the water column, a process documented from several tropical carbonate platforms settings (Cloud, 1962; Shinn et al., 1989), and likely facilitated by the proposed physio-chemical water-mass mixing front associated with the pycnocline (Fig. 6).

Heckel (1973) recorded significant ooidal chamosite in the Smyrna Bed as far west as a roadcut section along Dugway Road, 4.7 km northeast of Sheds, New York. At this section, a mixture of abraded or corroded pelmatozoan ossicles, polycrystalline clasts of uncertain origin, and ooidal chamosite grains is observed (Fig. 10D). A significant number of carbonate grains display coatings and overgrowths of chamosite such that the grains are not discoidal, but shape-controlled by the enclosed clast nucleus. This indicates that the Dugway Road section records conditions marginal to good chamosite development. Baird and Brett (2003b) and Baird et al. (2003) later found some chamosite still further west at the top of a 5–8 cm-thick condensed bed at the top of the Carpenter Falls Bed along Wormwald Road on the east side of the Tully Valley, 4.9 km south-southwest of Tully, New York (Fig. 10E). At this section, very dilute chamosite is associated with a 1–2 cm-thick stromatolitic crust and associated syneresis development at the top of this condensed bed. Chamositic grains within the microbialite crust do not display good internal lamellar structure. Moreover, they appear to be replacements of angular clasts which may represent fecal pellets (Fig. 10E). The authors sampled the thin, top-Carpenter Falls Bed stromatolitic crust documented by Heckel (1973) at Kashong Creek at Bellona, New York (Fig. 4C). No chamosite was found at this locality, although numerous polycrystalline grains of unknown origin occur within this microbialite layer.

4.5. Moravia Bed chamosite occurrence

A thin dilute carbonate or calcareous siltstone bed yielding black, flat, discoidal to irregular grains resembling chamosite is developed in the upper Tully between the village of Sherburne Four Corners on the west side of the Chenango Valley eastward to sections in the Unadilla Valley. This layer closely overlies the Bellona Bed and it appears to either represent a condensed phase of the lower part of the Moravia Bed or the entire Moravia Bed. In the Chenango Valley, this 6–14 cm-thick bed contains small corals, phosphatic nodules, and the dark, disk-shaped grains in an intensely bioturbated fabric. Above this unit is an abrupt upward change to a green-gray fissile shale unit yielding few fossils which apparently coeval to topmost Tully carbonate deposits observed west of the Chenango Valley.

Further east, near Columbus, this layer becomes thinner, but significantly richer in the chamosite disks. Moreover, the top contact of this bed with the overlying barren, fissile shale becomes knife sharp. At one locality, 0.6 km west of Walt Phillips Road and 2.8 km southwest of Columbus, this chamositic bed is capped by complex domal stromatolitic growths which extend into the base of the succeeding

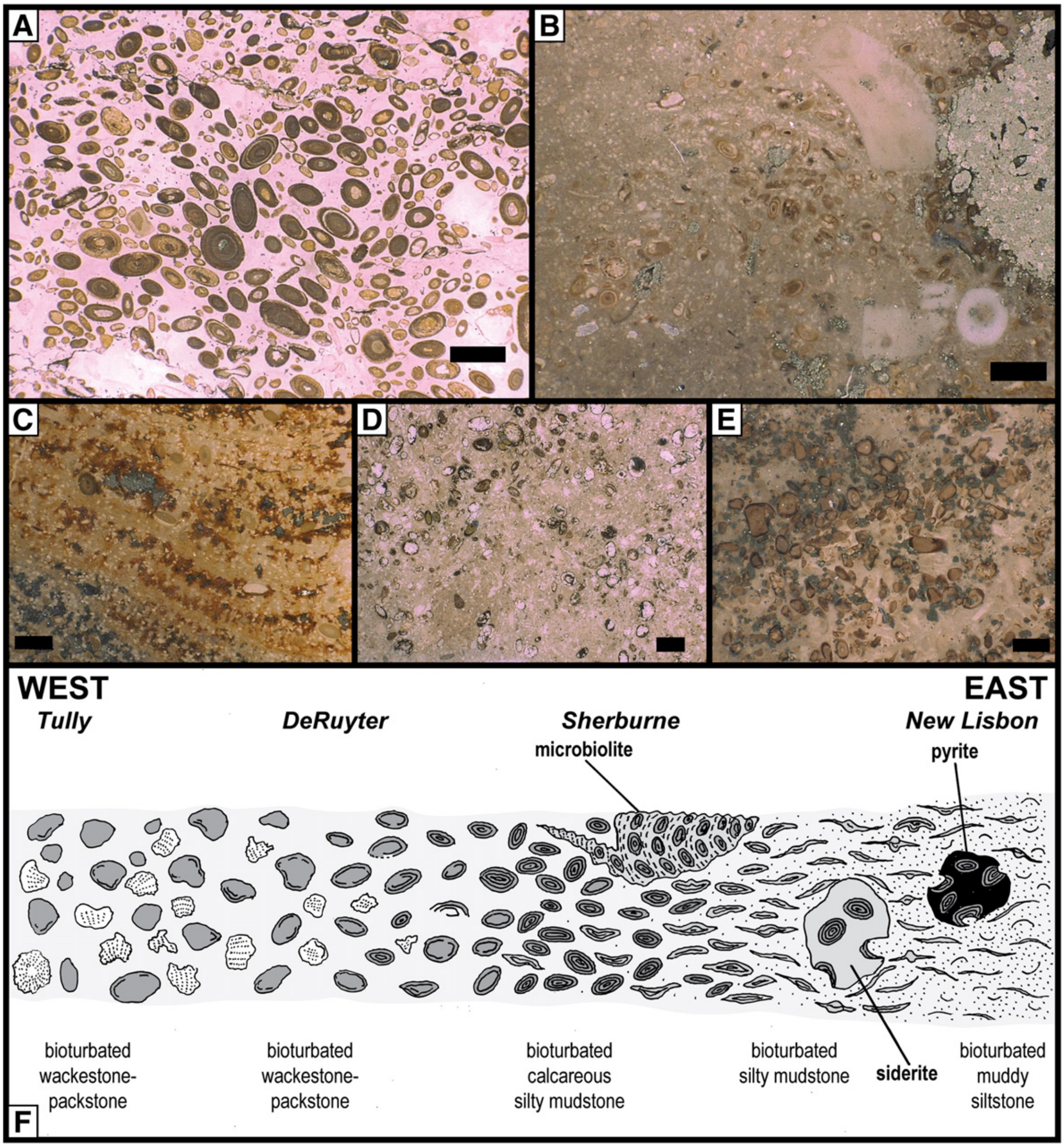

Fig. 10. Chamosite microstructure as viewed in thin sections (All scale bars equal one millimeter). A, Maximal expression of Smyrna ooidal chamosite as seen in a small gully south of Bingham Road, 2.45 km northwest of Columbus, New York and 8.3 km east-northeast of Sherburne, NY (Sherburne 7.5′ Quadrangle). Chamosite is developed as greenish, yellow-brown accretionary overgrowths centered on nucleus clasts; B, Diffuse chamositic ooids in bioturbated calcareous mudstone beneath a microbialite crust at a section at the junction of PA routes 220 and 405 in Hughesville, Pennsylvania (Hughesville 7.5′ Quadrangle). This layer is believed to be a regional expression of the Smyrna Bed within the Central Pennsylvania Basin (see text); C, ooidal chamosite within stromatolitic layer illustrated in Fig. 7 B. Note the distribution of ooids in bands parallel to the microbialitic laminae; D, Incipient chamosite development within Smyrna Bed calcarenite as observed in a section along Dugway Road 4.7 km northeast of Sheds, NY (Erieville 7.5′ Quadrangle). Note that chamosite is developed only as peripheral crusts on carbonate and quartz clasts; E, Incipient chamosite development within a stromatolitic capping layer at the top of the Carpenter Fall Bed along Wormwald Road near its junction with NY Route 11 at the east side of the Tully Valley, 4.9 km south-southwest of Tully, NY (Tully 7.5′ Quadrangle). Note the irregular shape of several grains as well as the resemblance of certain grains to coprolites; F, Generalized, eastward, spectral gradation of Smyrna Bed calcarenite to an ooidal chamosite phase across central New York. Note also the eastward (downslope) transition of robust chamositic ooids, seen at the Sherburne meridian, to flattened (compressed) disks within lean chamositic basinal deposits in the axis of the New Berlin Basin (see text).

shale unit. The chamosite-bearing layer is characterized by corroded limestone clasts in a matrix composed of chamosite disks and siltstone along creeks south of Columbus. Still further to the southeast near New Berlin and Pittsfield, this layer thickens into a massive ledge of siltstone and the chamosite becomes gradually more dilute before disappearing in sections.

5. Chamosite stratinomy

Given that Tully chamosite occurs at numerous stratigraphic levels and that chamosite at each level can be seen in multiple localities, several generalizations can be made concerning its occurrence in sections; proceeding from micro- to macroscale, these include: 1, chamosite grains usually occur as black, sometimes shiny, discoidal grains displaying optically greenish, concentric lamellae around a nucleus particle; 2, chamositic discoidal grains are randomly oriented within ooidal concentrations; 3, chamositic grains are usually mud- or carbonate-supported; 4, Beds containing significant chamositic grains are intensely bioturbated and that orientation of discoidal grains is controlled by bioturbation microfabric; 5, chamosite is usually closely associated with diagenetic siderite; 6, where siderite and chamosite overlap, chamosite enclosed by siderite is uncompacted indicating that the siderite precipitation most likely

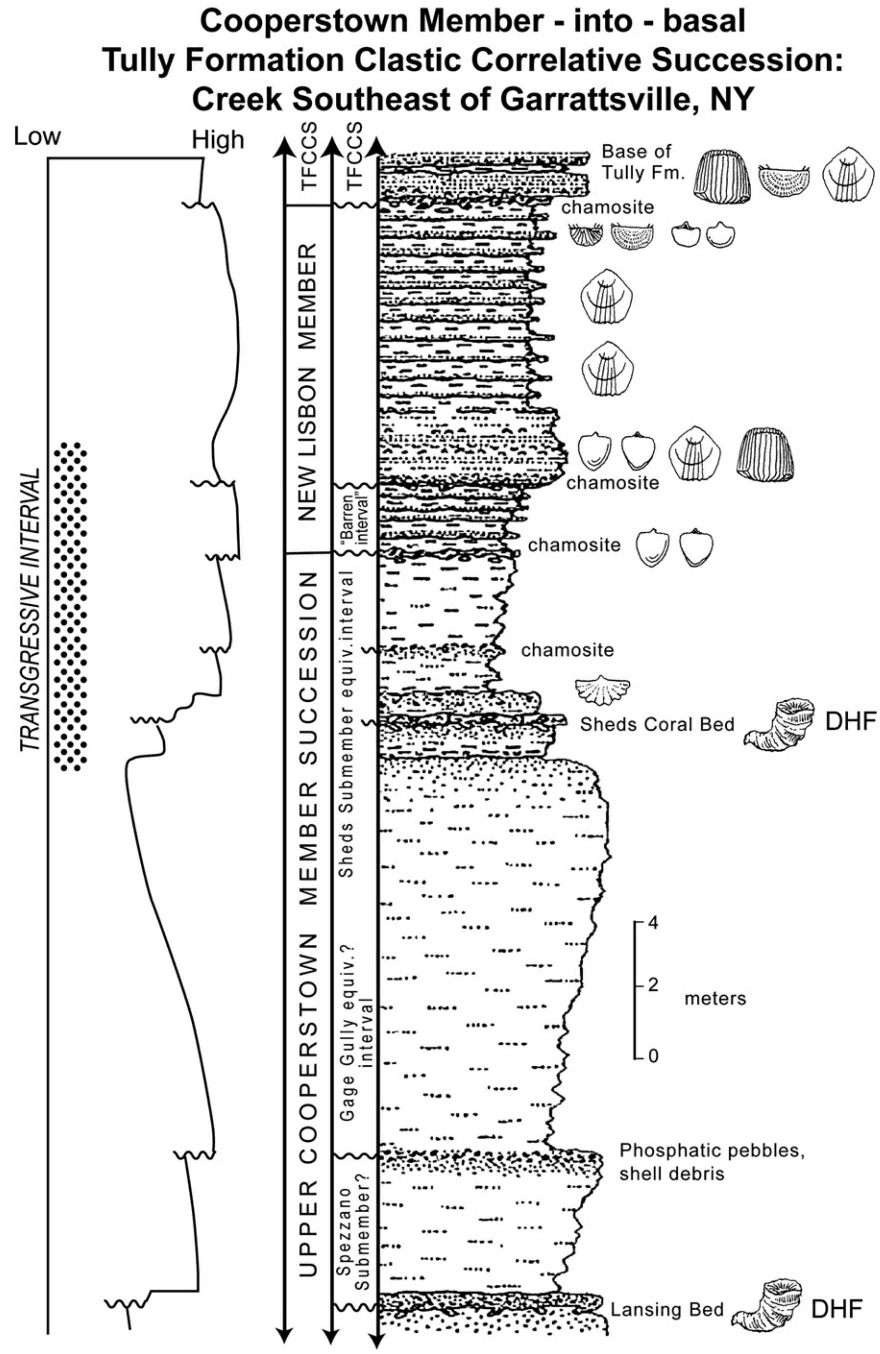

Fig. 11. Part of newly discovered long section associated with two adjacent, northwest-flowing ravines, 0.9 km south-southeast of Garrattsville, NY (Edmeston 7.5′ Quadrangle) showing Cooperstown-into-basal TFCCS interval. These ravines are not adequately displayed as flowing gullies on the map. This section shows both basal and top contacts of the lower (pre-Tully) division of the New Lisbon Member which is herein labeled "New Lisbon" on column. Because the New Lisbon Member, as originally defined by Cooper and Williams (1935), is now found to display, respectively, two divisions, the lower one pre-Tully, and the upper one within the basal TFCCS, we provisionally restrict the term New Lisbon Member to the lower division only (see text). Note the occurrence of *Tullypothyridina* and chamosite in basal New Lisbon beds (above the discontinuity lag beds marking the base of the New Lisbon) and the occurrence of rare *Rhyssochonetes* near the top of the unit. This locality displays the most complete Moscow Formation-lower Tully succession observed in New York State. Fossils shown are keyed to symbols in Fig. 2. DHF = Diverse Hamilton Fauna. The stippled symbol on the left denotes a major transgressive interval between the top-Sheds coral bed and the lower part of the New Lisbon Member; this is characterized by several diastems recording stepwise marine deepening and overspread of dysoxic bottom conditions. Chamosite occurs at three levels in this interval (see text). (Figure adapted from Baird and Brett, 2008).

occurred shortly after chamosite grain formation, but that both formed significantly earlier than compactional sediment dewatering; 7, chamosite is often associated with syneresis crack systems and microbialitic (thin stromatolitic) crusts; 8, where microbialitic stromatolites are associated with chamosite, they cap ooidal beds and directly underlie non-chamositic, often terrigenous, transgressive facies; 9, beds of concentrated ooidal chamosite yield low diversity macrofossil assemblages; 10, calcareous macrofossils within chamositic beds are usually fragmental and often corroded; 11, chamosite often occurs in regionally mappable beds between coeval limestone and siliciclastic phases of each given layer; 12, chamosite is closely associated with condensed beds and reworked lag deposits above submarine unconformities; 13, some chamosite accumulations appear to be developed in dysoxic, basinal facies; 14, several chamositic beds are seen to occur in a stepwise sequence of discrete, condensed lag deposits, recording transgressive backstepping from neritic to basinal conditions; 15, chamosite is preferentially associated

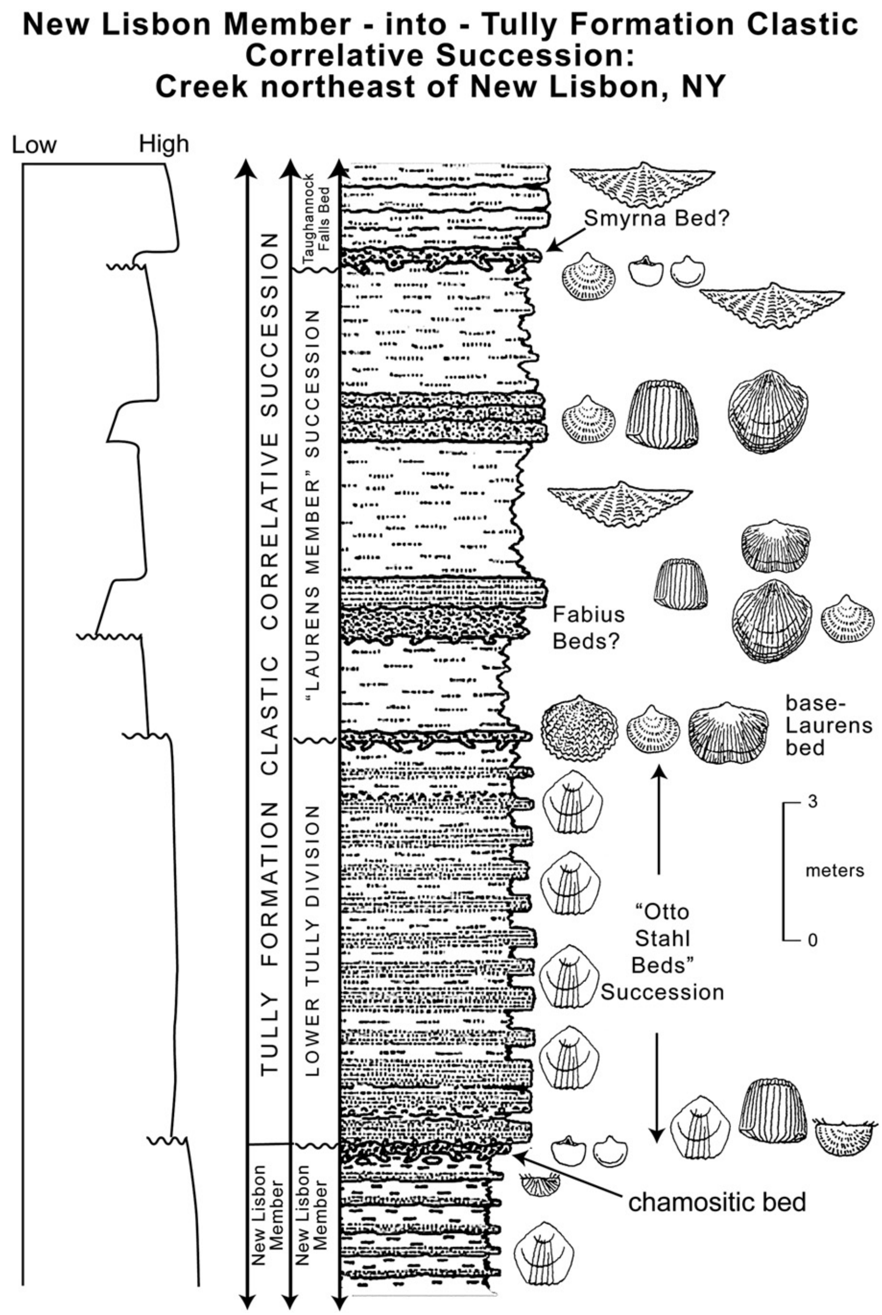

Fig. 12. Lower end of section 1.6 km northeast of New Lisbon, NY along Otto Stahl Road. This is Cooper and Williams (1935) type section of the New Lisbon Member. It displays the top of the lower part of the pre-Tully New Lisbon succession (herein labeled "New Lisbon" on column). The former upper part of New Lisbon ("Otto Stahl" Road quarry sandstone beds), above the chamositic discontinuity layer, is now included in the basal interval of the TFCCS (see text). Note the occurrence of *Tullypothyridina*, *Rhyssochonetes*, and *Emanuella* in the base-TFCCS discontinuity lag layer and the dominance of *Camarotoechia mesocostale* in the succeeding 8-meter sandstone interval. Fossils shown are keyed to symbols in Fig. 2. (Figure adapted from Baird and Brett, 2008).

with the Taghanic biocrisis succession in the Taghanic type area. These generalizations provide critical background for assessing models for its origin in the Taghanic succession.

6. Formation of chamosite

Chamosite is usually an optically greenish, diagenetic phase of chlorite which has been observed in a variety of inferred paleosettings, but in distinctly fewer modern environments. Due to a paucity of modern analogs, the origin of ooidal chamosite is poorly understood. However, some generalizations concerning its mode of formation can be made. Numerous workers have cited sediment-starvation, reducing conditions, and warm humid climates as favorable settings for chamosite development (Huber and Garrels, 1953; Maynard, 1986; Kim and Lee, 2000), but see Rehrlich et al. (1969) for an example of chamosite formation under cool conditions. Similarly, some workers have argued that proximity to shorelines, particularly deltas is critical for development of a sufficient source of Iron in the chemical system to support the formation of this mineral (Hallam, 1966; Porenga, 1967; Rehrlich et al., 1969). This latter observation is relevant to the present study in that the chamositic beds herein discussed occur differentially in marine deposits somewhat proximal to the deltaic coastline system of the Catskill Delta complex. Chamosite grains sometimes occur as spherical ooids and occur in grain-supported concentrations reflecting probable surface transport of diagenetic grains to form ferruginous oolite shoals (Akande and Mücke, 1993; Mücke, 2006). However, chamosite is generally understood to be an early diagenetic mineral which forms in weakly reducing, near-surface deposits.

Arno Mücke, analyzed numerous different chamosite and related ironstone deposits and modeled the formation of early diagenetic chamosite in a geochemical context (see Mücke, 2006). In this model, chemical weathering of terrestrial hinterland silicates leads to a supply of transported kaolinite as well as ferric oxides and hydroxides to marine waters. Accumulation of these products with organic matter in a variety of coastal settings produces a protolith that is subsequently acted upon by diagenetic processes. Rapid bacterial consumption (oxidation) of near-surface organic matter leads to early development of weakly reducing post-oxic interstitial conditions. Availability of Fe, combined with the extraction of Ca and Mg from the overlying seawater, provides a critical condition for the precipitation of lamellar, ooidal chlorite (chamosite) phase, and, often, a smaller volume of idiomorphic, "rice grain" textured siderite. Continued bacterial oxidation of remaining organic matter leads to onset of sulfidic conditions with the formation of framboidal pyrite, followed by strongly reducing conditions characterized by the formation of later diagenetic, massive, xenomorphic siderite. Key evidence for this petrographically would be temporal cross-cutting of chamosite by framboidal or massive pyrite and by concretionary siderite (in the form of partial to complete replacement of chamositic clasts).

Mücke (2006) illustrated examples of chamosite in certain formations and systems which had been secondarily ferruginized to ferric oxides and hydroxides (hematite and goethite) to form oolitic iron ores. Some of this later oxidation was related to secondary reworking of chamosite as detrital grains under oxic conditions. In contrast, Tully chamosite is always black in color, usually mud-supported, and generally characterized by pristine interior laminations. This suggests that Tully chamosite both formed in-, and remained within, interstitial reducing environments. This is also suggested by the random orientation of chamosite disks within thoroughly bioturbated Tully muds; the chamosite may have been reoriented during its formation by the displacing action of burrowers. The model of Mücke (2006) also positively links the amount of later diagenetic, methanic siderite to the amount of consumed organic matter in the original sediment; the more organic matter buried or otherwise fluxed into the sediment by burrowers, the more siderite produced (Mücke, 2006). It is significant that most of the diagenetic siderite is associated with chamosite in basinal deposits of the New Lisbon Member where dysaerobic faunas (*C. mesocostale* of the "Leiorhynchus" biofacies) were developed (Baird and Brett, 2008). This basinal setting would have favored the downward diffusion of organic matter into burrowed surface muds to produce post-oxic conditions below the sediment–water interface followed by later methanic bacterial activity. Given that chamosite requires a protolith of weathering-derived kaolinite and ferric oxides and hydroxides, it is suspected that times of chamosite genesis would require both warm and humid paleoclimatic conditions in source hinterland regions. Rapid evolution of land plants and the spread of the first multistory forests both prior to, and during, the Taghanic biocrisis suggest the presence of humid conditions which would have led to increased chemical weathering of source terrains with consequent protolith supply to basins (Algeo et al., 1995; Algeo and Scheckler, 1998; Bartholomew, 2002); however, work by others shows that at least some portion of Tully deposition likely corresponded to an arid paleoclimatic interval (Marshall et al., 2010).

7. Synthetic model for Tully carbonate and ooidal chamosite genesis

Baird et al. (2010) argued that Taghanic chamosite formed within near-surface sediments associated with periodically or pervasively oxygen-starved marine settings. This is particularly true for chamosite observed in the New Berlin and central Pennsylvania basins where facies context is distinctly basinal. However, for Smyrna Bed chamosite genesis, a range of paleosettings, ranging from shelf to basin, is indicated. Baird et al. (2010) evoked upwelling as a possible mechanism to explain the ooidal chamosite acme on the Sherburne High; cooler, nutrient-rich water from the epicontinental basins would have been driven by currents and abetted by winds to rise from the New Berlin Basin to produce a belt of upwelling coincident with the Tully Platform eastern margin (Fig. 6A). This, in turn, would have periodically created zones of bottom hypoxia along and east of the Sherburne High which would have killed off macrofauna and effected sediment diagenesis in complex ways. Extreme sediment-starvation, repeated phases of bioturbation, bottom colonization, and oxidation of organic matter would have favored the formation of ooidal chamosite and corrosion of biogenic skeletal carbonate. Westward change from chamosite to calcarenite within the Smyrna Bed would have reflected limits to the reach of hypoxic conditions west of the Sherburne High.

Zambito et al. (in press) and Baird et al. (herein) present an alternative synthetic model to explain the dominance of Taghanic lime mud carbonate, the incursion of the Old World Realm Tully Fauna, and the occurrence of chamosite (Fig. 6B). In this model, the incursion of the Tully Fauna onto the Tully Platform was the result of an episode of climatic warming which resulted in transgressive connection of marine basins and displacement of the cooler water Hamilton Fauna to as-of-yet unknown, though probably higher southern latitude refugia , with synchronous incursion of Old World Fauna taxa into the study area (Johnson, 1970; Johnson et al., 1985; Boucot, 1988; Hüneke, 2006, 2007). Coupled with this transgression would have been increased basin eutrophication possibly due to enhanced nutrient flux associated with increased terrestrial weathering associated with the spread of plants at this time (Algeo et al., 1995; Algeo and Scheckler, 1998; Bartholomew, 2002).

Given this pattern of paleoclimatic warming, transgressive connection of basins, and the southward advance of tropical organisms, the present authors favor a variant of the estuarine circulation model of Algeo et al. (2008). In this scenario, the Tully epicontinental sea was vertically stratified with warm, dense, saline water below a surface layer of distinctly less saline and lower density water. The lower water layer would have been variably dysoxic owing to the stratification. Stratification would have been maintained by the (paleo)northward flow of densely saline, warm water from hypersaline lower latitude settings on the North American continent (Day, 1996; Witzke and Bunker, 1996). The lower salinity watermass, originating from fluvial runoff from the Catskill Delta, would have flowed over this denser layer, creating a regional pycnocline (Fig. 6B). As the denser layer would have occupied deeper water settings, these areas would have had a variably restricted circulation and would have supported low diversity portions of the Tully Fauna. Where the upper layer prevailed on the shelf, nutrient circulation and oxygenation would have been better, supporting the more diverse Hamilton Fauna. Where the saline wedge terminated against the counter flow of the upper layer, a mixing front would have developed where the biofacies would change downslope at the boundary (Zambito et al., in press; Figs. 5 and 6B). It is possible that the volume of lime mud (micritic limestone) observed within the Tully overall, in part, reflects direct precipitation of carbonate from the water column from the supersaturated warm water layer or from the interaction of the two layers along the pycnocline or at the mixing front.

This stratified water mass condition is believed to have prevailed during early and medial Tully deposition when the New Berlin and central Pennsylvania basins were well developed (Figs. 5 and 6B). The lower, dense water layer is envisioned to have occupied both the Tully Platform and New Berlin Basin with a strong southward (shoreward) flow; it is reconstructed as having flowed southward over the Sherburne High to spill basinward into the western part of

Please cite this article as: Baird, G.C., et al., Genesis of unusual lithologies associated with the Late Middle Devonian Taghanic biocrisis in the type Taghanic succession of New York State and Pennsylvania, Palaeogeogr. Palaeoclimatol. Palaeoecol. (2011), doi:10.1016/j.palaeo.2011.11.010

the depocenter (Fig. 6B). As benthic biotas improve eastward across the New Berlin Basin at several stratigraphic levels, it is suspected that the dense, saline water was dynamically stopped along the west-facing, eastern slope of that basin at the hypothetical mixing front (Figs. 5 and 6B). It is significant that a diverse assemblage of bottom taxa (the brachiopods *Pseudoatrypa*, *Spinatrypa*, *Tylothyris*, *Mucrospirifer tulliensis*, *Cyrtina*, *Tullypothyridina*, *Echinocoelia*, *Strophodonta*, bivalves, cryptostome bryozoans, and conulariids) is developed in strata equivalent to the Smyrna Bed on the neritic, eastern Tully, clastic shelf near the Oneonta meridian (Cooper and Williams, 1935; Baird et al., 2003; Baird and Brett, 2008). This biota, though containing several non-Hamilton Fauna genera, appears to represent healthy neritic bottom conditions in dramatic contrast to assemblages observed in lower and medial Tully carbonate facies across the similarly neritic Tully platform further west.

To what degree the two models, herein presented, are valid, is, as yet, unknown. However, both the vertical biotic shifts between the Hamilton and Tully faunas coupled with this lateral east–west faunal contrast between Smyrna carbonate/chamosite facies and shoreward Smyrna Bed-equivalent deposits, clearly shows that a strong correlation between Taghanic bioevents and correlative lithofacies changes can be established. Ongoing carbon and oxygen isotopic analyses of these classic sections (Zambito, et al., 2011, in prep) should produce a much more detailed temperature curve and understanding of the carbon-cycle for the type Taghanic succession; this may produce surprises that would shed light on specific events in this strange time-slice.

8. Conclusions

Lithologic anomalies in the type Taghanic (Tully Formation) succession, including development of massive lime mud carbonate lithofacies and unusual ooidal chamosite deposits, are timed with temporal biotic changes linked to widespread (global?) Taghanic bioevents. Massive Tully limestone deposition on the neritic Tully platform in western and central New York State contrasted with the deposition of much thicker, ribbon limestone or thin, tabular siltstone bed (turbidite?) successions in deeper-water, peripheral troughs (New Berlin and central Pennsylvania basins) adjacent to the platform. The ooidal chamosite, characterized by sand-granule-sized, black, discoidal, mud-supported grains, displaying greenish interior accretionary laminations, is closely associated with thin, condensed, bioturbated lag deposits which overlie discontinuity surfaces. This chamosite, which occurs at more than five stratigraphic levels in the Taghanic succession, was deposited in shelf, slope, and basin settings in association with minimally oxic to strongly dysoxic bottom waters. Ooids formed in a weakly reducing post oxic interstitial setting which was locally followed by iron- and sulfate reducing conditions leading to later diagenetic concretionary siderite and pyrite formation. Chamositic ooids were rarely, if ever, reworked at the sediment–water interface, but were probably extensively reoriented by intensive burrowing activity. Microbialitic stromatolites sometimes occur within- or on the topmost ooid accumulations; they record maximal, transgressive sediment-starvation, typically prior to accumulation of onlapping basinal sediments. In the New Berlin Basin in east-central New York, the upward transition from pre-Taghanic (topmost Hamilton Group) neritic shelf deposition into basinal lower Taghanic deposits of the New Lisbon Member, is marked by a succession of increasingly basinal, diastem-bounded units recording transgressive backstepping as the basin deepened. Chamosite is closely associated with condensed lag deposits associated with these diastems and is maximally developed in the most transgressive, dysoxic (upper) part of this succession in association with initial, deeper-water, incursion of portions of the Tully Fauna. Both the abundance of Tully carbonate and the repeated accumulation of ooidal chamosite are suggestive of warm, episodically wet, paleoclimatic conditions allowing for global marine transgression, warm water incursion from the tropics, and significant terrestrial weathering to supply critical dissolved and detrital components to support chamosite formation.

Southward incursion of the Tully Fauna across the neritic Tully platform and associated deposition of lower-medial Tully carbonate facies is herein believed to be due to development of water mass stratification owing to southward advance of dense, warmer, highly saline water from the cratonic interior below a counter flow of less dense, surface water which was influenced by the output from coastal rivers. Low diversity of lower-medial Tully Limestone (Tully Fauna) assemblages, coupled with accumulation of Smyrna Bed chamosite on the Sherburne High, suggests that this water stratification may have created pervasive shelf dysoxia, oligotrophic conditions, and/or other forms of bottom stress. Observed eastward (shoreward) transition within the Smyrna Bed from nearly barren chamosite in the western part of the New Berlin Basin to richly fossiliferous, non-chamositic, neritic deposits in eastern New York, suggests that the counter flow of oxygen-rich and nutrient-rich, lower salinity water had prevented the lower water layer from reaching the eastern Tully shelf. Ongoing isotopic work is directed to detailed isotopic analysis of sections, not only to better link area vertical biotic and lithologic changes to the known global paleotemperature curve, but to identify key excursions not recorded in sections elsewhere which may be closely matched to the strange deposits and events discussed here.

Acknowlegments

We thank Tim Phillips for help with figure preparation; field work in New York and Pennsylvania was partially supported by grants from the National Science Foundation grant EAR 921807, and from the Donors to the Petroleum Research Fund, American Chemical Society. Additional support came from the American Museum of Natural History, the Evolving Earth Foundation, Geological Society of America, Society for Sedimentary Geology, and the American Association of Petroleum Geologists. We have benefitted from discussions with Alex Bartholomew, Pat McLaughlin and Charles Ver Straeten and from useful input from Phil Heckel and the anonymous reviewer in preparation of this paper. Gary Lash and Adam English (SUNY Fredonia) assisted in thin section preparation.

References

Aboussalam, S.Z., 2003. Das «Taghanic-Event» im höheren Mittel-Devon von West-Europa und Marokko. Munstersche Forschungen zur Geologie und Palaontologie 97, 1–332.

Akande, S.O., Mücke, A., 1993. Depositional environment and diagnosis of carbonates at the Mamu-Nkporo Formation, Anambra Basin, southern Nigeria. Journal of African Earth Sciences 17, 445–456.

Algeo, T.J., Scheckler, S.E., 1998. Terrestrial-marine teleconnections in the Devonian; links between the evolution of land plants, weathering processes, and marine anoxic events. Philosophical Transactions—Royal Society of London, Biological Sciences 353, 113–130.

Algeo, T.J., Berner, R.A., Maynard, J.B., Scheckler, S.E., 1995. Late Devonian oceanic anoxic events and biotic crises; "rooted" in the evolution of vascular land plants? GSA Today 45, 64–66.

Algeo, T.J., Heckel, P.H., Maynard, J.B., Blakey, R., Rowe, H., 2008. Modern and ancient epeiric seas and the super-estuarine circulation model of marine anoxia. In: Holmden, C., Pratt, B.R. (Eds.), Dynamics of Epeiric Seas: Sedimentological, Paleontological and Geochemical Perspectives: Geological Association of Canada Special Publication, pp. 7–38.

Baird, G.C., Brett, C.E., 1986. Erosion on an anaerobic seafloor: significance of reworked pyrite deposits from the Devonian of New York State. Palaeogeography, Palaeoclimatology, Palaeoecology 57, 157–193.

Baird, G.C., Brett, C.E., 2003a. A. Shelf and off-shelf deposits of the Tully Formation in New York and Pennsylvania: faunal incursions, eustasy and tectonics: CFS. Courier Forschungsinstitut Senckenberg 242, 141–156.

Baird, G.C., Brett, C.E., 2003b. B. Unusual facies associated with the Late Middle Devonian (Givetian) Taghanic Bioevent in New York State; problems of interpreting recurrent chamosite beds in the Tully Formation. Geological Society of America, Annual Meeting, Seattle, p. 509.

Baird, G.C., Brett, C.E., 2007. Late Middle Devonian (Late Givetian) Tully Formation in Pennsylvania: comparison with Tully Limestone and equivalent clastic deposits in New York State. Geological Society of America, Abstracts with Programs, Durham, NH, p. 39.

Baird, G.C., Brett, C.E., 2008. Late Givetian Taghanic bioevents in New York State: new discoveries and questions. Bulletin of Geosciences 83, 357–370. doi:10.3140/bull.geosci.2008.04.357.

Baird, G.C., Bartholomew, A.J., Brett, C.E., 2003. Late Middle Devonian biotic and sedimentologic events in east-central New York: Tully Formation clastic correlative succession in the Sherburne–Oneonta area: Guidebook—New York State Geological Association, Meeting, 75, pp. 1–54.

Baird, G.C., Zambito, J.J., Brett, C.E., 2010. Lithologic signature of the late Middle Devonian Taghanic bioevent in it type area: anomalous carbonate and chamosite accumulations in the Tully Formation interval, New York State. In: Aldridge, et al. (Ed.), Programme and Abstracts, International Palaeontological Congress, London.

Bartholomew, A.J., 2002. Correlation of high order cycles in the marine-paralic transition of the upper Middle Devonian (Givetian) Moscow Formation, Eastern New York State. M.S., University of Cincinnati, Cincinnati, OH. 114 pp.

Blakey, R., 2010. NAU Geology, Paleogeographic Reconstructions. http://jan.ucc.nau.edu/~rcb7/RCB.html2010Checked February, 15 2010.

Boucot, A.J., 1988. Devonian biogeography; an update. Memoir—Canadian Society of Petroleum Geologists 14, 211–227.

Brett, C.E., Baird, G.C., 1994. Depositional sequences, cycles, and foreland basin dynamics in the late Middle Devonian (Givetian) of the Genesee Valley and western Finger Lakes region. In: Brett, C.E., Scatterday, J. (Eds.), Guidebook—New York State Geological Association, Meeting, pp. 505–586.

Brett, C.E., Baird, G.C., 1995. Coordinated stasis and evolutionary ecology of Silurian to Middle Devonian faunas in the Appalachian Basin. In: Erwin, D.H., Anstey, R.L. (Eds.), New Approaches to Speciation in the Fossil Record. Columbia Univ. Press, pp. 285–315.

Brett, C.E., Ivany, L.C., Schopf, K.M., 1996. Coordinated stasis; an overview. Palaeogeography, Palaeoclimatology, Palaeoecology 127, 1–20.

Brett, C.E., Bartholomew, A.J., Baird, G.C., 2007. Biofacies recurrence in the Middle Devonian of New York State: an example with implications for habitat tracking. Palaios 22, 306–324.

Brett, C.E., Ivany, L.C., Bartholomew, A.J., DeSantis, M.K., Baird, G.C., 2009. Devonian ecological-evolutionary subunits in the Appalachian Basin; a revision and a test of persistence and discreteness. Geological Society Special Publications 314, 7–36.

Bridge, J.S., Willis, B.J., 1994. Marine transgressions and regressions recorded in Middle Devonian shore-zone deposits of the Catskill clastic wedge. Geological Society of America Bulletin 106, 1440–1458.

Cloud Jr., P.E., 1962. Environment of calcium carbonate deposition west of Andros Island. Bahamas. U. S. Geological Survey Professional Paper 350. 138 pp.

Cooper, G.A., Williams, J.S., 1935. Tully Formation of New York. Geological Society of America Bulletin 46, 781–868.

Day, J., 1996. Faunal signatures of Middle-Upper Devonian depositional sequences and sea-level fluctuations in the Iowa Basin, U.S. Midcontinent. In: Witzke, B.J., Ludvigson, G.A., Day, J. (Eds.), Paleozoic Sequence Stratigraphy: Views from the North American Craton-Geological Society of America Special Paper, 306, pp. 277–300.

Ettensohn, F.R., 1985. In: Woodrw, D.L., Sevon, W.D. (Eds.), The Catskill Delta complex and the Acadian Orogeny; a model: Special Paper—Geological Society of America, 201, pp. 39–49.

Ettensohn, F.R., Lierman, R.T., Mason, C.E., Clayton, G., 2009. Changing physical and biotic conditions on eastern Laurussia: evidence from Late Devonian to Middle Mississippian basinal and deltaic sediments of northeastern Kentucky, USA. Field Trip No. 2, North American Paleontological Convention, Cincinnati. 81 pp.

Hallam, A., 1966. Depositional environments of Liassic ironstones, considered in the context of their facies relationships. Nature 209, 1306–1309.

Heckel, P.H., 1969. Devonian Tully Limestone in Pennsylvania and comparison to type Tully Limestone in New York. Pennsylvania Geological Survey, 4th Series, Bulletin IC60. 33 pp.

Heckel, P.H., 1973. Nature, origin, and significance of the Tully Limestone; an anomalous unit in the Catskill Delta, Devonian of New York. Geological Society of America Special Paper138. 244 pp.

House, M.R., 2002. Strength, timing, setting and cause of mid-Palaeozoic extinctions. Palaeogeography, Palaeoclimatology, Palaeoecology 181, 5–25.

Huber, N.K., Garrels, R.M., 1953. Relation of pH and oxidation potential to sedimentary iron mineral formation. Economic Geology and the Bulletin of the Society of Economic Geologists 48, 337–357.

Hüneke, H., 2006. Erosion and deposition from bottom currents during the Givetian and Frasnian: response to intensified oceanic circulation between Gondwana and Laurussia. Palaeogeography, Palaeoclimatology, Palaeoecology 234, 146–167.

Hüneke, H., 2007. Pelagic carbonate ooze reworked by bottom currents during Devonian approach of the continents Gondwana and Laurussia. In: Viana, A.R., Rebesco, M. (Eds.), Economic and Palaeoceanographic Significance of Contourite Deposits: Geol. Soc. London. Spec. Publ, 276, pp. 299–328.

Ivany, L.C., Brett, C.E., Wall, H.L.B., Wall, P.D., Handley, J.C., 2009. Relative taxonomic and ecologic stability in Devonian marine faunas of New York State; a test of coordinated stasis. Paleobiology 35, 499–524.

Joachimski, M.M., Breisig, S., Buggisch, W., Talent, J.A., Mawson, R., Gereke, M., Morrow, J.R., Day, J., Weddige, K., 2009. Devonian climate and reef evolution: insights from oxygen isotopes in apatite. Earth and Planetary Science Letters 284, 599–609.

Johnson, J.G., 1970. Taghanic onlap and the end of North America Devonian provinciality. Geological Society of America Bulletin 81, 2077–2105.

Johnson, J.G., Klapper, G., Sandberg, C.A., 1985. Devonian eustatic fluctuations in Euramerica. Geological Society of America Bulletin 96, 567–587.

Kim, Y., Lee, Y.I., 2000. Ironstones and green marine clays in the Dongjeom Formation (Early Ordovician) of Korea. Sedimentary Geology 130, 65–80.

Marshall, J., Brown, J., Newman, M., Davidson, R., 2010. The Old Red Sandstone of Scotland. IPC3 Pre-Conference field Trip/Subcommission on Devonian Stratigraphy, International Palaeontological Congress, London. 54 pp.

Maynard, J.B., 1986. Geochemistry of oolitic iron ores, an electron microprobe study. Economic Geology and the Bulletin of the Society of Economic Geologists 81, 1473–1483.

Mücke, A., 2006. Chamosite, siderite, and the environmental conditions of their formation in chamosite-type Phanerozoic ooidal ironstones. Ore Geology Reviews 28 (2), 235–249.

Pflueger, F., 1999. Matground structures and redox facies. Palaios 14, 25–39.

Plummer, P.S., Gostin, V.A., 1981. Shrinkage cracks: dessication or synaeresis. Journal of Sedimentary Petrology 51, 1147–1156.

Porenga, D.H., 1967. Glauconite and chamosite as depth indicators in the marine environment. Marine Geology 5, 495–501.

Pratt, B.R., 1998. Syneresis cracks; subaqueous shrinkage in argillaceous sediments caused by earthquake-induced dewatering. Sedimentary Geology 117, 1–10.

Rehrlich, V., Price, N.B., Calvert, S.E., 1969. Chamosite in the recent sediments of Loch Etive, Scotland. Journal of Sedimentary Petrology 39 (2), 624–631.

Sessa, J., 2003. The dynamics of rapid, asynchronous biotic turnover in the Middle Devonian Appalachian Basin of New York. M.S. thesis, University of Cincinnati, Cincinnati, OH, 80 pp.

Shinn, E.A., Steinen, R.P., Lidz, B.H., Swart, P.K., 1989. Whitings, a sedimentologic dilemma. Journal of Sedimentary Petrology 59, 147–161.

van Geldern, R., Alvarez, F., Day, J., Jansen, U., Joachimski, M.M., Ma, X.P., Yolkin, E.A., 2006. Carbon, oxygen and strontium isotope records of Devonian brachiopod shell calcite. Palaeogeography, Palaeoclimatology, Palaeoecology 240, 47–67.

Ver Straeten, C.A., Brett, C.E., 1995. Lower and Middle Devonian foreland basin fill in the Catskill Front; stratigraphic synthesis, sequence stratigraphy, and Acadian Orogeny: Guidebook—New York State Geological Association, Meeting, 67, pp. 313–356.

Ver Straeten, C.A., Brett, C.E., 1997. Lower and Middle Devonian foreland basin fill in the Catskill Front: stratigraphic synthesis, sequence stratigraphy, and the Acadian Orogeny. In: Brett, C.E., Ver Straeten, C.A. (Eds.), Devonian Cyclicity and Sequence Stratigraphy in New York State, Fieldtrip Guidebook, International Union of Geological Sciences, Subcommission on Devonian Stratigraphy. University of Rochester, Rochester, NY, pp. 23–54.

Witzke, B.J., 1987. Models for circulation patterns in epicontinental seas applied to Paleozoic facies of North American craton. Paleoceanography 2 (2), 229–248.

Witzke, B.J., Bunker, B.J., 1996. Relative sea-level changes during Middle Ordovician through Mississippian deposition in the Iowa area, north American craton. In: Witzke, B.J., Ludvigson, G.A., Day, J. (Eds.), Paleozoic Sequence Stratigraphy: Views from the North American Craton-Geological Society of America Special Paper, 306, pp. 307–330.

Zambito, J., Joachimski, M., Baird, G., Brett, C., Davis, W., Over, D.J., 2011. Preliminary analysis of conodont apatite oxygen isotope ratios through the Late Givetian global Taghanic Biocrisis in the northern Appalachian Basin. Geological Society of America, abstracts with programs, NE-NC Regional meeting, Pittsburgh, PA.

Zambito, J., Brett, C., and Baird, G. (in press). The Late Middle Devonian (Givetian) Global Taghanic Biocrisis in its type area (northern Appalachian Basin): Geologically rapid faunal transitions driven by global and local environmental changes. UNESCO/International Year of Planet Earth volume entitled 'Global Biodiversity, Extinction Intervals and Biogeographic Perturbations through Time'; John Talent (Ed.)