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Transgressive wave ravinement on an epicontinental shelf as recorded by an Upper Pennsylvanian soil-nodule conglomerate-sandstone unit, Kansas and Oklahoma, U.S.A.

Wan Yang

Department of Geology, Wichita State University, Wichita, Kansas, 67260, USA
Key Laboratory of Petroleum Resources, Institute of Geology & Geophysics, Chinese Academy of Sciences, 730000, Lanzhou, China

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Abstract

A thin (3–25 cm), persistent conglomerate-sandstone unit occurs at the base of the transgressive systems tract of an Upper Pennsylvanian cyclothem below a transgressive limestone in outcrop and subsurface in SE Kansas and NE Oklahoma. It has an erosional base and a sharp top, and is composed of calcitic clasts, some shell fragments and quartz sand, and rare coal fragments. Clasts are rounded, equant-to-elongate, coarse sand-to-pebble sized, and moderately to well sorted. They are micritic to microsparitic or radial fibrous calcite grains and pisoids. Micritic and microsparitic clasts are heterogeneous and contain rounded to elongate moulds and radiating or concentric, spar or micrite-filled cracks. Pisoids have micrite cores and superficial calcite or clay rims. The clasts have similar texture and composition to the calcitic nodules and rhizoconcretions in underlying paleosols, and thus were probably derived from these soil nodules.

Upper shoreface erosion during shoreline transgression excavated the underlying paleosols and eroded coeval transgressive deposits landwards of the shoreline. The eroded sediments were then reworked and transported to the lower shoreface and inner shelf by storm return flows to be deposited as a soil-nodule conglomerate-sandstone unit. Its base is an amalgamated surface of wave ravinement and initial transgression as well as the lower sequence boundary. The widespread conglomerate-sandstone unit suggests extensive transgressive wave ravinement on an epicontinental shelf. The transgressive record composed of upward-deepening, dominantly fine-grained lithofacies defines a new type (T-C_4) of transgressive record, which is composed of mixed carbonate and siliciclastic lithofacies with a simple transgressive lag on a low-relief shelf.
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Keywords: Pennsylvanian; Wave ravinement; Transgressive systems tract; Conglomerate

1. Introduction

Transgressive deposits, as an integral part of transgressive–regressive sedimentary sequences, contain important surfaces and lithofacies that can provide insights into the processes and stratigraphic responses, which occurred during shoreline transgression, and the temporal significance of the surfaces. They commonly have contrasting stratigraphic attributes (e.g., thickness, distribution, stacking pattern, and component lithofacies) compared to regressive deposits. Thus, a good understanding of transgressive deposits is critical to sequence

E-mail address: wan.yang@wichita.edu.

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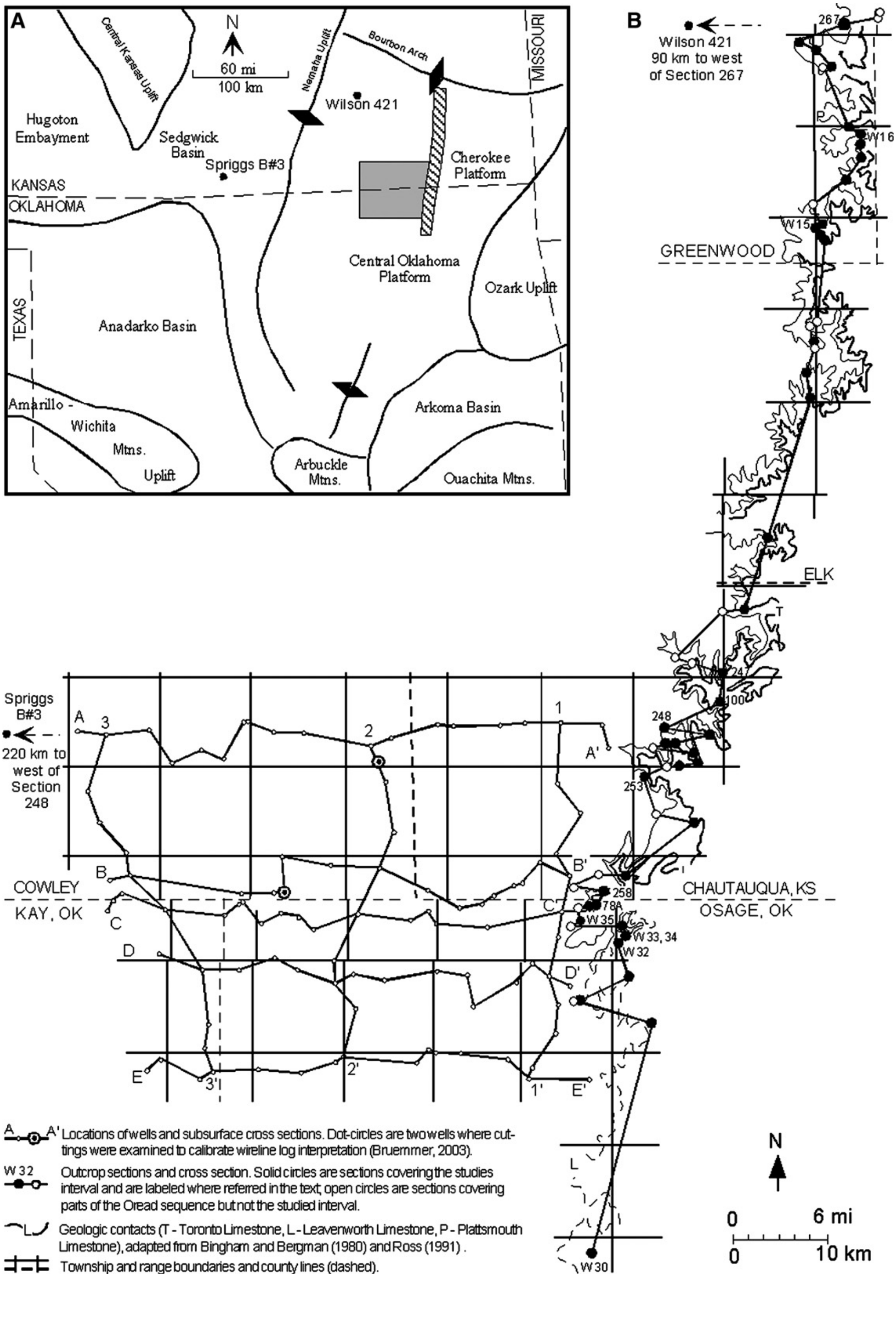

A
N
60 mi
100 km
Central Kansas Uplift
Nemaha Uplift
Bourbon Arch
MISSOURI
Wilson 421
Hugoton Embayment
Sedgwick Basin
Spriggs B#3
Cherokee Platform
KANSAS
OKLAHOMA
Central Oklahoma Platform
Ozark Uplift
TEXAS
Anadarko Basin
Amarillo - Wichita Mtns. Uplift
Arkoma Basin
Arbuckle Mtns.
Ouachita Mtns.
B
Wilson 421 90 km to west of Section 267
267
P
W16
W15
GREENWOOD
ELK
T
24
100
248
253
Spriggs B#3 220 km to west of Section 248
A
3
2
1
A'
B
B'
258
COWLEY
KAY, OK
CHAUTAUQUA, KS
OSAGE, OK
C
C'
78A
W 35
W 33, 34
W 32
D
D'
E
3'
2'
1'
E'
L
W30
N
0 6 mi
0 10 km
Locations of wells and subsurface cross sections. Dot-circles are two wells where cuttings were examined to calibrate wireline log interpretation (Bruemmer, 2003).
W 32
Outcrop sections and cross section. Solid circles are sections covering the studies interval and are labeled where referred in the text; open circles are sections covering parts of the Oread sequence but not the studied interval.
Geologic contacts (T - Toronto Limestone, L - Leavenworth Limestone, P - Plattsmouth Limestone), adapted from Bingham and Bergman (1980) and Ross (1991).
Township and range boundaries and county lines (dashed).

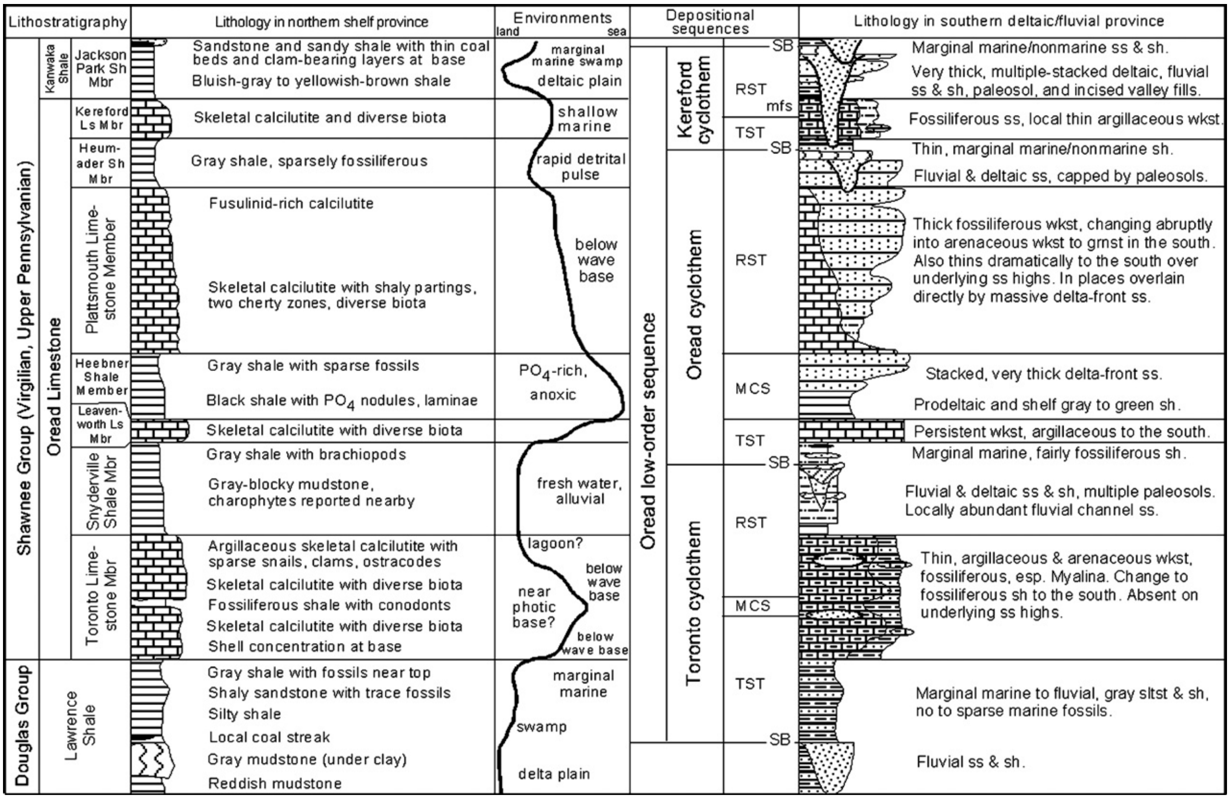


Fig. 2. Lithostratigraphy, sequence stratigraphy, lithology, and environmental changes of component cyclothems/sequences of the Oread low-order sequence in the northern shelf province, SE Kansas, and southern deltaic–fluvial province, NE Oklahoma. Shelf lithostratigraphy and environmental interpretation were modified from Heckel (1994) with reference to Moore et al. (1951). Deltaic–fluvial stratigraphy was modified from Yang et al. (2003). No vertical scale intended.

stratigraphic analysis (Catuneanu et al., 1998). Transgressive successions that formed in different tectonic, climatic, and depositional conditions can be differentiated on the basis of lithologic, paleontological, and geochemical characteristics, stratal stacking patterns, and termination patterns of seismic reflections (Cattaneo and Steel, 2003). Among those characteristics, the types and stacking patterns of lithofacies are particularly useful in outcrop and well-log sequence stratigraphic analyses. Lithofacies of shelf–shoreline–coastal plain systems are sensitive to shoreline movement. Landward erosion during shoreline transgression caused by sea-level rise is common (e.g., Bruun, 1962; Curry, 1964), and generates erosional surfaces, such as tidal and wave ravinement surfaces, bounding and/or within upward-deepening transgressive deposits, (e.g., Stamp, 1921; Swift, 1968; Siggerud et al., 2000). Shoreface erosion by waves and longshore and storm-induced currents, especially, may excavate underlying sediments and cannibalise coeval transgressive sediments landwards of the shoreline. The reworked sediments are transported offshore, and a bed of coarse-grained transgressive lag, such as sandstone, conglomerate, or shell bed, is commonly deposited in the lower shoreface and inner shelf (Swift, 1976; Kidwell, 1989; Van Wagoner et al., 1990; Riemersma and Chan, 1991; Trincardi and Field, 1991; Abbott, 1998; Cattaneo and Steel, 2003).

This paper reports the first documented calcitic-clast conglomerate-sandstone unit above a sequence boundary at the base of a dominantly fine-grained mixed siliciclastic and carbonate transgressive succession in SE Kansas and NE Oklahoma (Fig. 1). Petrographic study suggests that the clasts were derived from calcitic soil nodules in underlying paleosols that were excavated and reworked during landward migration of shoreface and deposited on

Fig. 1. (A) Locations of outcrop (hachured) and subsurface (gray) study areas and regional tectonic elements in Kansas and Oklahoma. Locations of two cores are shown (Well Wilson 421, OXY USA, Inc., in T25S, R5E, Section 8, Butler County, Kansas, and Well Spriggs B#3, Woolsey Petroleum, in T33S R13W, Section 32, Barber County, Kansas). Modified from Mazzullo et al. (1995). (B) Locations of measured outcrop sections, wells, and outcrop and subsurface cross sections.

the lower shoreface and inner shelf. Only a single erosional surface is present at the base of the conglomerate-sandstone unit. It is a merged surface of sequence boundary and surfaces of initial transgression and wave ravinement. The findings provide insight into the processes of transgressive wave ravinement in a mixed carbonate and siliciclastic setting on a vast epicontinental shelf in an icehouse climate.

2. Geological background

The study area covers 4100 km^2 from the limestone-rich Cherokee Platform in SE Kansas to the siliciclastic-rich Central Oklahoma Platform in NE Oklahoma (Fig. 1), in the SW part of the vast epicontinental midcontinent shelf. It was in the easterly trade wind belt during the Late Pennsylvanian (Heckel, 1991). The studied conglomerate-sandstone unit (abbreviated as CSU in the paper) is in the basal transgressive systems tract (TST) of the Upper Pennsylvanian (Virgilian) Oread cyclothem (Fig. 2; Wanless and Shepard, 1936; Heckel, 1986, 1994; Yang et al., 2003). Yang et al. (2003) showed that the Heebner Shale marine condensed section and the highstand systems tract of the "layer-cake" Oread cyclothem sequence in Kansas (e.g., Heckel, 1977; Ross, 1991; Heckel, 1994; Watney et al., 1995) change to dominantly deltaic and fluvial deposits and thicken drastically southward in NE Oklahoma, but the TST remains persistent (Figs. 1, 3; Toomey, 1969; Bingham and Bergman, 1980).

Large sea-level fluctuations associated with Late Paleozoic continental glaciation and deglaciation caused repeated shoreline transgression and regression on the midcontinent shelf (e.g., Wanless and Shepard, 1936; Rascoe and Adler, 1983; Heckel, 1986; Boardman and Heckel, 1989; Heckel, 1994; Watney et al., 1995), resulting in frequent nonmarine to marine environmental shifts. Shoreline transgression was probably fast, given the rapid sea-level rise (e.g., Yang, 1996), short cycle duration (e.g., Heckel, 1986; Yang and Kominz, 1999), and low relief of the shelf (Heckel, 1991). Climate varied from subhumid to semi-arid conditions during transgression and regression, respectively (Yang, 1996), forming calcareous paleosols on the interfluves during the regression (Joeckel, 1994; Turner et al., 2003). The TST of the Oread cyclothem was deposited under such geological conditions (Feldman et al., 2005).

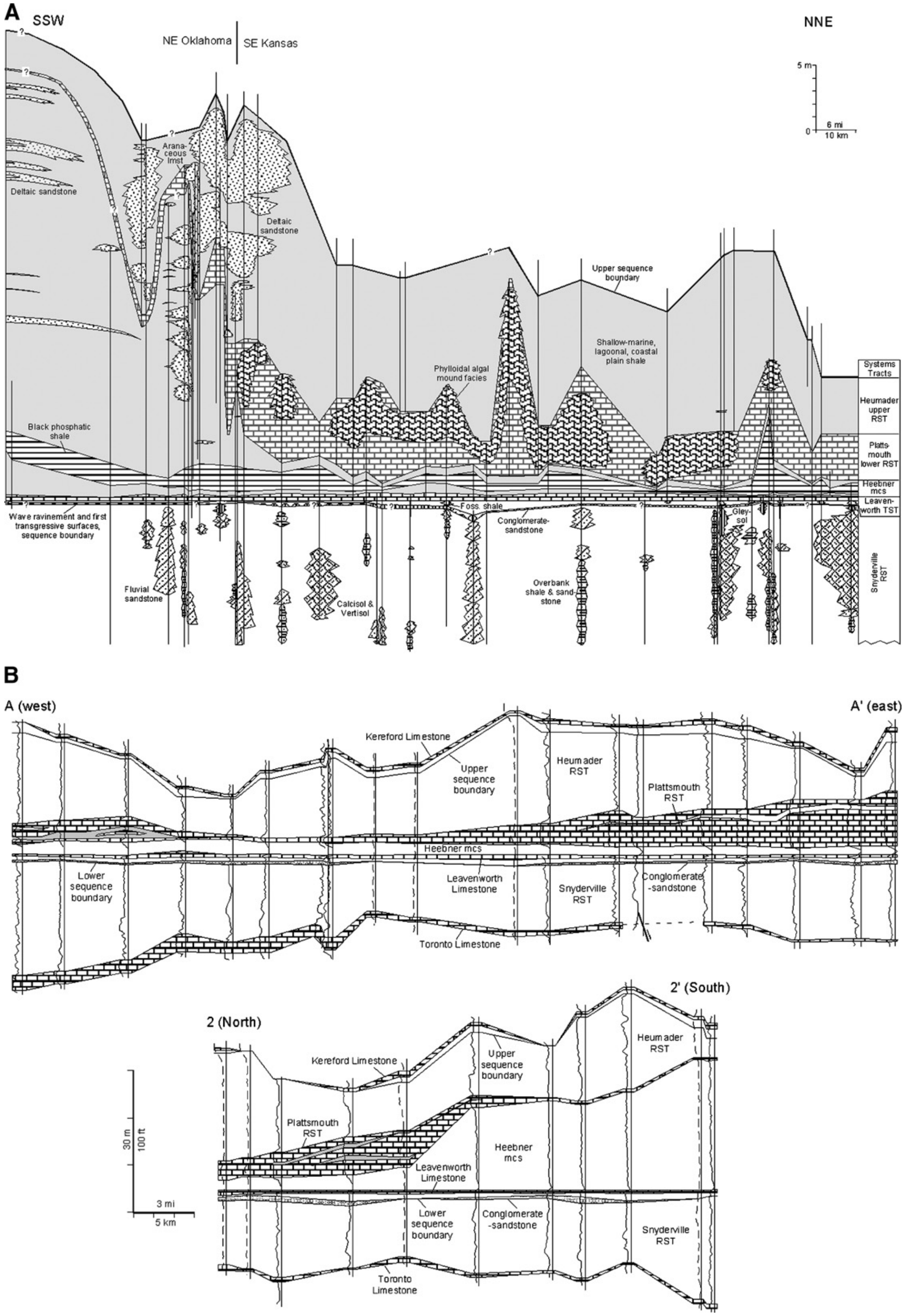
3. Data and methodology

Forty-one sections covering the partial or entire TST of the Oread cyclothem and the regressive systems tract (RST) of the subjacent Toronto cyclothem were measured at a centimeter scale (Figs. 1, 2). The same interval in 100 wells was also interpreted in a 60×50-km^2 area adjoining the outcrop belt (Fig. 1). Among the 41 sections, 15 sections expose the CSU. Thirty-one polished hand samples and 13 thin sections of the CSU and soil nodules from the Snyderville paleosols were examined under binocular and petrographic microscopes for grain composition, texture, fossil content, and sedimentary structures. Spontaneous potential, gamma-ray, resistivity, and some density and porosity wireline logs were used to interpret lithology and thickness of individual rock units and their stacking patterns in the subsurface. Log interpretations were calibrated by nearby outcrop sections, two cores, and cuttings from two wells (Fig. 1; Bruemmer, 2003). The low resolution of well logs and cuttings prohibited accurate reading of the thickness of the thin CSU. Nevertheless, the conglomerate-sandstone unit was confidently and conservatively interpreted on the basis of log patterns and its stratigraphic position underneath the persistent Leavenworth Limestone and Heebner Shale members (Figs. 3B, 4). Depositional systems, systems tracts, and depositional sequences were interpreted on the basis of lithofacies, their vertical stacking patterns, geometry, and boundary relationships and fossil contents according to existing models (e.g., Heckel, 1977, 1984; Watney et al., 1995; Galloway and Hobday, 1996; Yang et al., 2003). They were correlated by tracing persistent stratigraphic markers (i.e. Leavenworth Limestone and Heebner Shale members) and their facies and thickness stacking patterns on outcrop and subsurface (Fig. 3).

4. Lithofacies and depositional environments of the transgressive systems tract

The TST of the Oread cyclothem consists of nonfossiliferous mudstone, conglomerate-sandstone, and fossiliferous shale of the uppermost Snyderville Shale Member in the lower part, and wackestone of the Leavenworth Limestone Member in the upper part (Figs. 2, 3, 5A). It overlies fluvial and paleosol deposits of the RST of the Toronto cyclothem, and underlies the

Fig. 3. Simplified stratigraphic cross sections and facies interpretations of the Oread cyclothem and the Snyderville RST of the Toronto cyclothem in outcrop (A) and subsurface (B) showing sequence architecture. The persistent and thin Leavenworth TST is composed upward of the first-transgressive soil-nodule conglomerate-sandstone unit, shelf shale, and Leavenworth Limestone, and overlies the thick Snyderville RST composed of paleosols and fluvial deposits. On the subsurface sections, gamma-ray logs are solid lines, and SP logs are dashed lines. Stratigraphic datum for all sections is base of Leavenworth Limestone. See Fig. 1 for section locations.


A
SSW
NE Oklahoma
SE Kansas
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5 m
0
6 mi
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Arana-
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lmst
Deltaic sandstone
Deltaic
sandstone
Upper sequence
boundary
Shallow-marine,
lagoonal, coastal
plain shale
Phylloidal algal
mound facies
Black phosphatic
shale
Systems
Tracts
Heumader
upper
RST
Platts-
mouth
lower RST
Heebner
mcs
Leaven-
worth TST
Snyderville
RST
Wave ravinement and first
transgressive surfaces,
sequence boundary
Foss. shale
Conglomerate-
sandstone
Gley-
sol
Fluvial
sandstone
Calcisol &
Vertisol
Overbank
shale & sand-
stone
B
A (west)
A' (east)
Kereford Limestone
Upper
sequence
boundary
Heumader
RST
Plattsmouth
RST
Heebner mcs
Lower
sequence
boundary
Leavenworth
Limestone
Snyderville
RST
Conglomerate
-sandstone
Toronto Limestone
2 (North)
2' (South)
Kereford Limestone
Upper
sequence
boundary
Heumader
RST
Plattsmouth
RST
Heebner
mcs
Leavenworth
Limestone
30 m
100 ft
3 mi
5 km
Lower
sequence
boundary
Conglomerate
-sandstone
Snyderville
RST
Toronto
Limestone

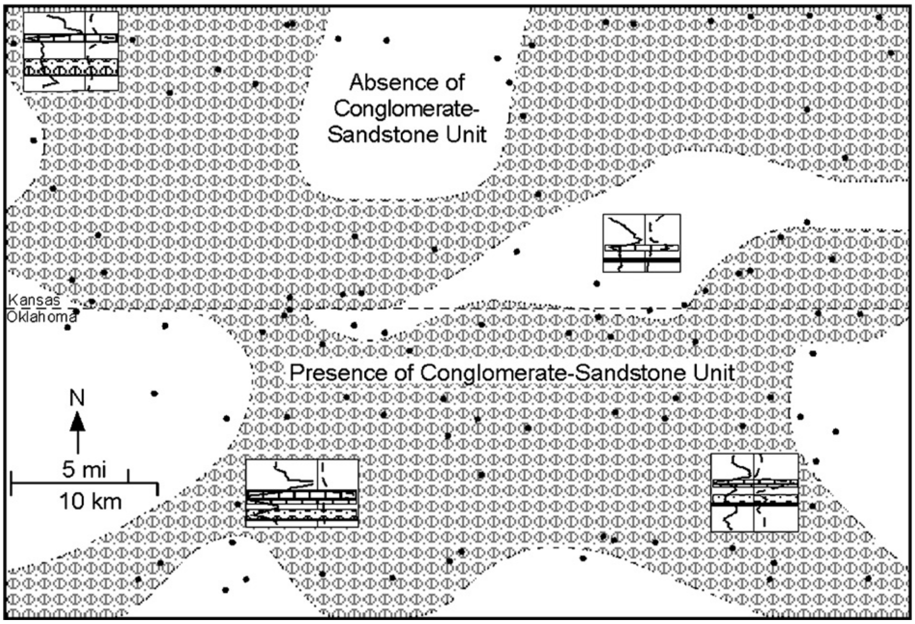


Fig. 4. Subsurface distribution of the soil-nodule conglomerate-sandstone unit in Kansas–Oklahoma border area west of outcrop. Gamma-ray (left, solid line) and resistivity (right, dashed line) logs, interpreted lower sequence boundary (thick horizontal line) at base of conglomerate-sandstone unit, where present, and Leavenworth Limestone are shown in typical log facies of Leavenworth TST. See Fig. 1 for location of subsurface study area.

black shale of the marine condensed section of the Heebner Shale Member.

4.1. Nonfossiliferous mudstone facies

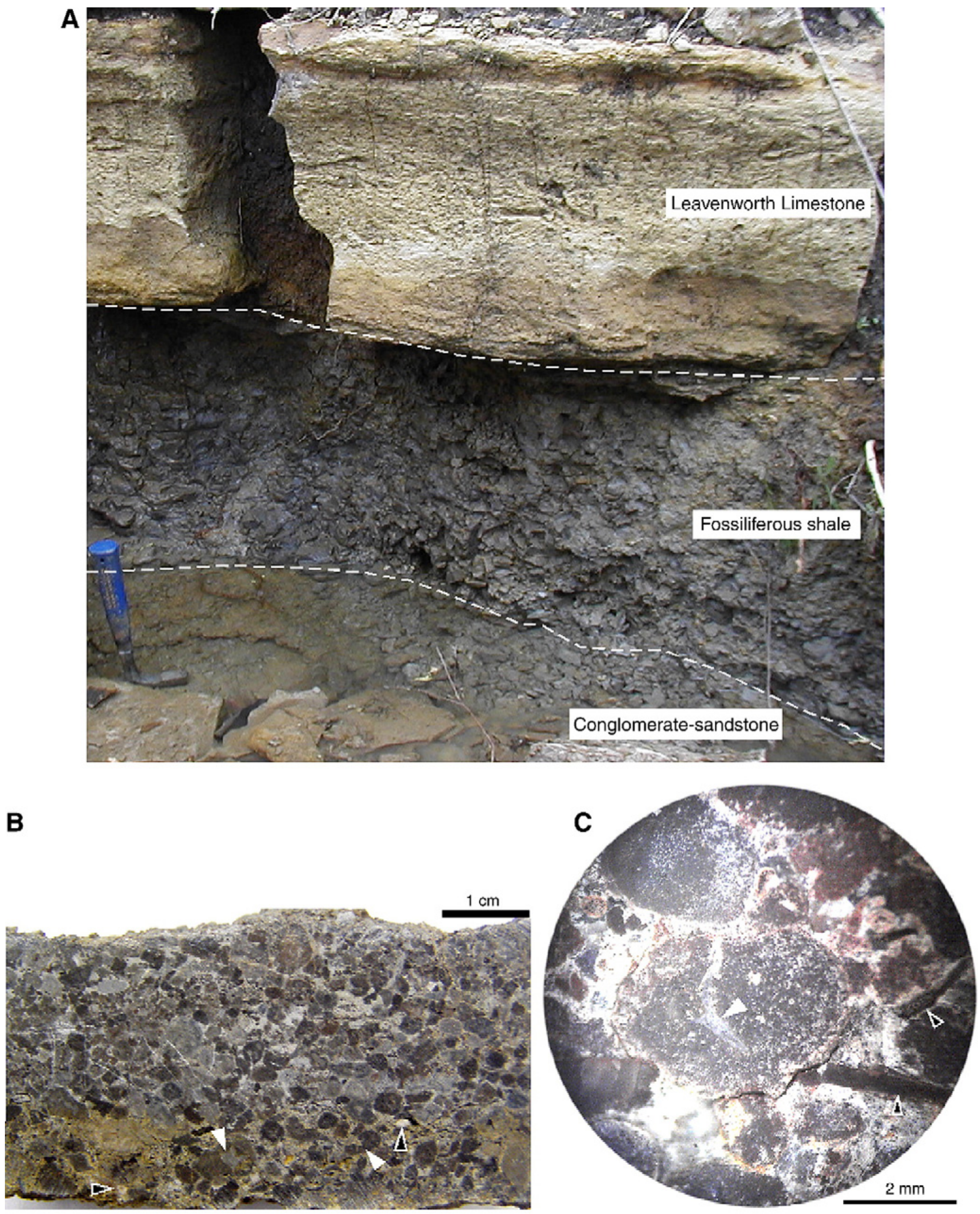
The nonfossiliferous mudstone is dark to blackish gray, variably sandy to silty, and noncalcareous. It contains sparse burrows, rare to common mm-size calcitic nodules in the lower part, disseminated secondary pyrite crystals in the upper part, and no marine fossils. Soil peds are equant, subrounded to rounded, and generally less than 1 cm in size. This facies is 0–120 cm thick. It has a sharp base with the underlying calcareous paleosols and a sharp top with the overlying conglomerate-sandstone. The soil texture, color, lithology, absence of marine fossils, and boundary relationship with the underlying and overlying facies suggest that this facies is a Gleysol (Mack, 1993; Turner et al., 2003). It formed by seawater leaching of muddy soil plasma of the underlying calcareous paleosols during initial marine transgression.

Fig. 5. A) Field photo of conglomerate-sandstone unit, fossiliferous shale, and Leavenworth Limestone of the Oread TST, Section W15. Hammer is 25 cm long. B) Polished slab of clast-supported granule conglomerate. Blackish gray to dark brown micritic clasts are rounded to well rounded and moderately sorted. They have common internal radial and some concentric and random cracks filled with sparry calcite (white arrow), and are calcite-cemented with tangential to linear grain contacts. Brachiopod and crinoid fragments (hollow arrow) are parallel to bedding. Lower left part is bioturbated. Matrix is ~10%, composed of fossil fragments and silt to very fine quartz sand grains. Sample 247–3. C) Binocular photomicrograph of granule conglomerate. Blackened heterogeneous micritic clasts are commonly brecciated internally (white arrow). Shell fragments are moderately abundant (hollow arrows). Sample 248–4. D) Calcite-cemented arenite composed of subrounded to rounded heterogeneous micritic clasts with ferruginous clay coating (a), superficial/single-coat ooids with a micritic nucleus and crude radial cortex (b), calcite spar-filled internal cavity with a sharp or diffuse boundary (c), and subrounded detrital quartz grains (d). Plane light, ×40, Sample 258–3. E) Poorly-cemented, subangular to rounded arenite containing micritic to microsparitic aggregates with a large angular internal brecciation cavity (a) or clay-filled moulds (b), and brachiopod shells and spines (c). Plane light, ×20, Sample W16–1. F) Left panel: Sub-mm to mm laminae of calcitic-clast sandstone (arrows) with sharp, wavy to planar bases and tops, which are embedded in dark gray sparsely fossiliferous shale and are overlain by fossiliferous shale and Leavenworth Limestone. 1447–1448-feet interval, Well Wilson 421. Right panel: Close-up of boxed area in left panel showing whitish gray to brown, heterogeneous calcitic clasts and aggregates, which are calcite cemented. Elongate shell fragments (arrows) are parallel to bedding plane. G) Calcite-cemented, subangular to rounded sandstone composed of heterogeneous micritic to microsparitic aggregates with partial ferruginous clay coatings (a), internal brecciation cracks (b) and possible root moulds filled with sparry calcite (c), and brachiopod fragments (d). Plane light, ×20, Sample 258–3. H) Calcite-cemented sandstone composed of three grain types: fanning radial fibrous micritic clast with partial ferruginous clay coating (a), heterogeneous micritic clast with clay coating and internal cavities filled with sparry calcite or ferruginous clay (b), and ferruginous clay-coated quartz (c). Plane light, ×20, Sample 258–3. See Fig. 1B for sample locations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.2. Conglomerate-sandstone facies

The conglomerate-sandstone is commonly dark gray and clast-supported with no or minimal mud matrix (Fig. 5B). The framework grains are dominantly blackened calcite clasts (95%), and monocrystalline quartz and shell fragments (5%) (Fig. 5C, D, E). The conglomerate samples are very well sorted, containing dominantly (average 80%) fine pebble to granule (10–2 mm) clasts and minor very coarse to medium sand-sized clasts, both subrounded to well rounded. The sandstone samples are moderately to well sorted and rounded, containing dominantly (average 70%) coarse to medium sand grains, with a size range from fine pebble to fine sand. Quartz grains are well rounded, medium to very fine in size, and dispersed in between calcitic clasts. Some quartz grains are coated by ferruginous clay. Shell fragments are dominantly thin-shelled brachiopods and crinoids and minor molluscs and fusulinids. They are highly abraded and are commonly parallel with the bedding surface (Fig. 5F).

The calcitic clasts show a variety of internal textures and contain no fossil fragments. Many clasts are micritic to microsparitic and heterogeneous, and commonly



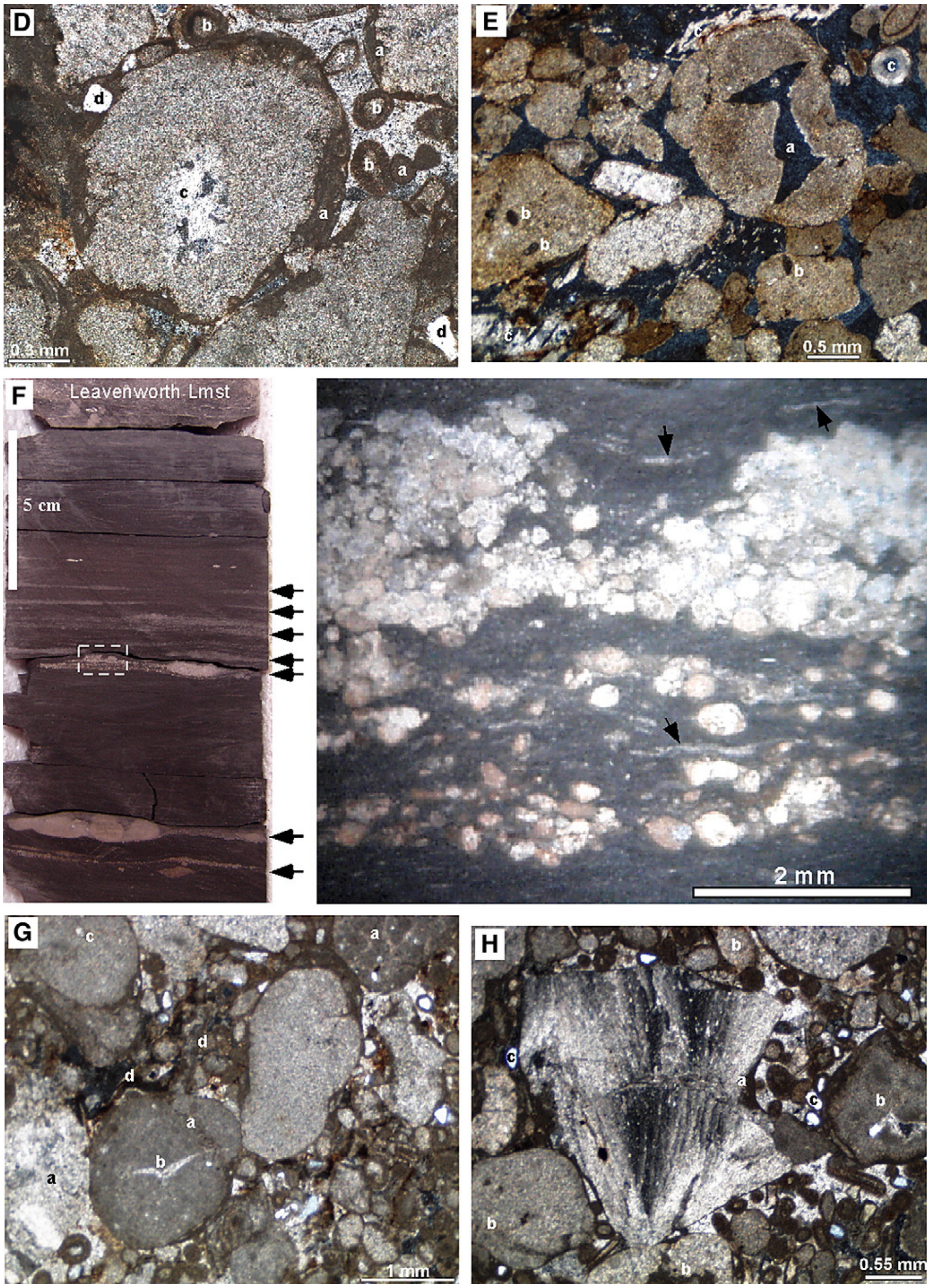


Fig. 5 (*continued*).

contain sparse sand or silt-sized quartz grains as well as cavities filled with calcite spar (Fig. 5C, D, E, G). Some cavities are round to elongate moulds with sharp edges; others are radiating, partially concentric, or irregular cracks, forming a brecciated appearance. Some clasts are fragments of fanning radial fibrous calcite spar with sharp irregular edges (Fig. 5H). Some clasts are rounded pisoids and ooids with a micritic, microsparitic, or sparry calcite, or a heterogeneous core and a single thin (10s of microns) rim of micrite or, in some cases, micritized radial calcite spar (Fig. 5D, H). Finally, some other clasts are aggregates of the aforementioned clasts cemented by micrite or ferruginous clay (Fig. 5G). Commonly the clasts, especially those with concavo-convex edges, are partially coated with laminated ferruginous mud; and the laminated mud and the clast form a rounded, abraded clast as a whole (Fig. 5D, G, H).

The CSU is well cemented by calcite. It is a single, persistent bed 3 to 25 cm thick, with a sharp and even top and base. Bedding is manifested by bedding-parallel elongate fossil fragments and clasts; or it is massive or crudely normal- or reverse-graded. Local cm-size, equant muddy patches suggest bioturbation (Fig. 5B). In the core of Well Wilson 421, however, mm-thick arenite laminae are intercalated within 10-cm-thick fossiliferous shale beds (Fig. 5F). The arenite has a similar calcitic grain composition as described above but is fine to medium sand-sized. The lower surfaces of the laminae are sharp and, in some cases, slightly erosional; the upper surfaces of the laminae are sharp but uneven and, in some cases, are asymmetrically rippled with a mm-scale relief. At the same stratigraphic position in sections W4 and 100, the CSU is replaced by 10 cm and 40 cm, respectively, of highly fossiliferous lithic quartz arenite, composed of about 70% quartz, 10% fossil fragments, and 20% calcitic clasts. Nevertheless, the texture and structure of the quartz arenite suggest an origin similar to that of the calcitic-clast CSU. In Section W35 (Fig. 1B), a 24-cm-thick coquina replaces the CSU. It contains well-imbricated brachiopod shells and ~10% sand matrix, suggesting high-energy transport and reworking.

The texture and structure and the marine fossils suggest that the clasts were reworked and transported by high-energy currents in a marine environment. The sharp to slightly erosional contacts with the underlying Gleysol and overlying marine shale suggest a shallow marine, probably lower shoreface to inner shelf environment. Moreover, its persistent thickness and wide distribution (Figs. 3 and 4), despite its thinness, suggest that the CSU was deposited on a low-relief shelf. The origin of the calcitic clasts is discussed later in the Discussion section.

4.3. Fossiliferous shale facies

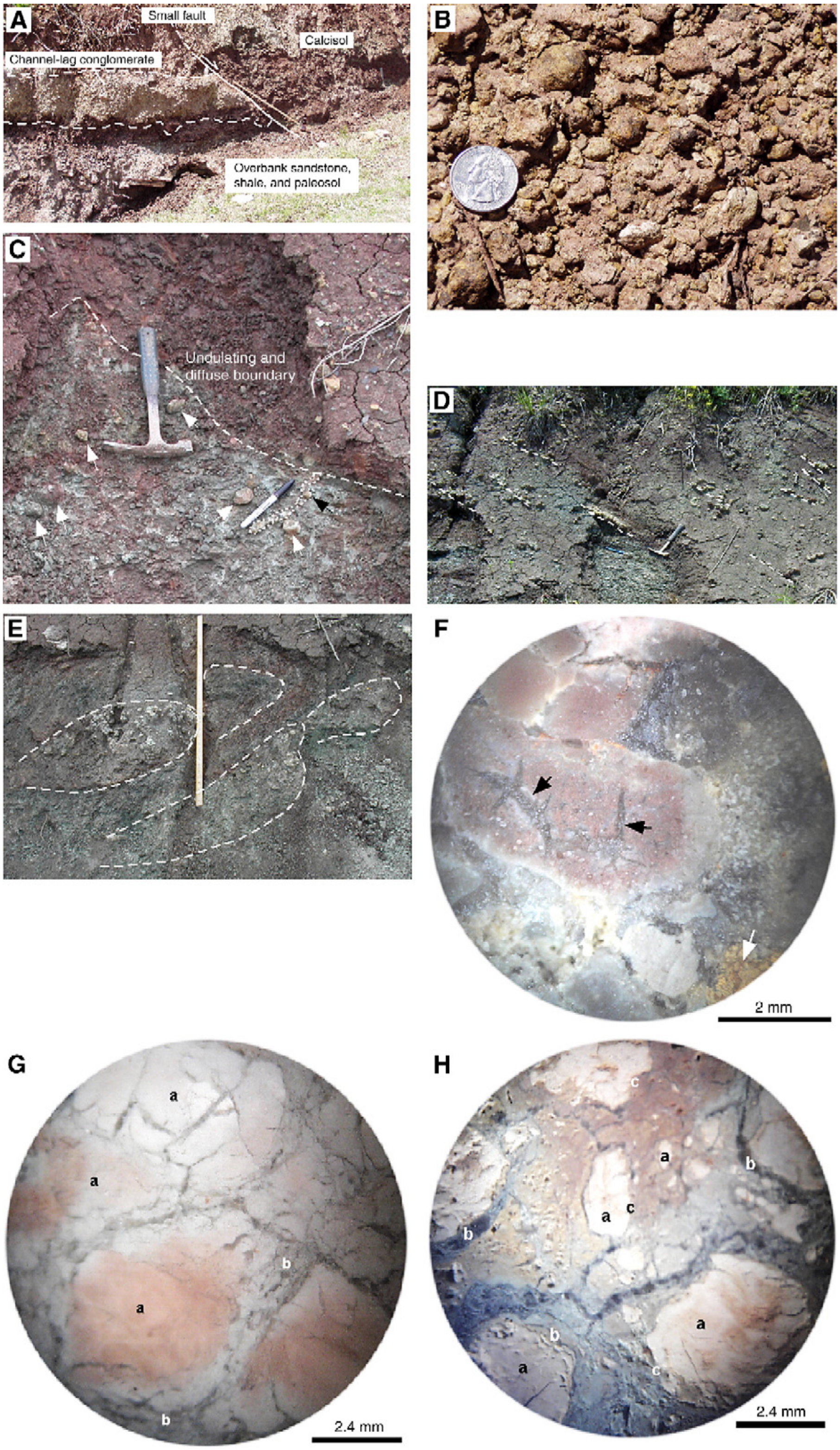
The fossiliferous shale facies consists of dark gray shale, minor mudstone, and rare laminae of silty shale, siltstone, or very fine to fine-grained sandstone (Fig. 5A). The shale is platy to thickly laminated, becoming better laminated upwards. The mudstone is massive to platy and mottled with relict laminations and, in some cases, possible burrows. Disseminated pyrite crystals are pervasive, and minute plant remains are present locally. Commonly, fossiliferous argillaceous limestone nodules and lentils are present in the upper part and become larger (cm thick, 10s of cm long) and less argillaceous upward. Fossils include fusulinids, crinoids, and thin-shelled brachiopods and molluscs that become more abundant and better preserved upwards. This facies is up to 105 cm thick and is persistent (Fig. 3). It has a sharp and even base and sharp to gradational and even top. The upwards-increasing abundance of marine fossils and limestone and the upwards-development of better lamination and fossil preservation suggest that this facies was deposited in a shallow, low-energy shelf environment that deepened and received less terrigenous mud input overtime.

4.4. Wackestone facies

Wackestone of the Leavenworth Limestone Member is dark bluish gray with 20–50% grains. It contains local argillaceous laminae and burrows, and oncoids in the uppermost part. Fossils include fusulinids, crinoids, gastropods, and rare ammonoids (Toomey, 1969). Pyritization of fossils is common. The facies is tabular and bioturbated with rare current laminations in the lower part (Fig. 5A). It is persistent in thickness (40–50 cm) and lithology on the Kansas Shelf (Fig. 3; Toomey, 1969), and has a sharp and even upper contact with the overlying Heebner Shale. In the southernmost study area (Section W30; Figs. 1B, 3A), the facies changes to argillaceous and arenaceous wackestone interbedded with calcareous shale.

The fossil content, wide distribution, extreme facies homogeneity, and persistent thickness suggest a low-energy, low-relief shelf environment, which had uniform water-column and seafloor conditions and was far away from any siliciclastic sources. The common framboidal and replacive pyrite suggests dysaerobic conditions on the sea floor, indicating the onset of shelf anoxia. The facies change in the southernmost part suggests interfingering between marine limestone and marginal marine siliciclastic sediments derived from the south (Toomey, 1969; Yang et al., 2003).

The wackestone is overlain by the black shale facies of the Heebner Shale Member. In SE Kansas, it is 1–3 m thick and persistent (Fig. 3). Heckel (1977; see also Heckel, 1991; Coveney, 1985; Heckel, 1994) interpreted as deposited on an anoxic to dysoxic shelf with a water depth of ~100 m during a sea-level highstand, mainly on the basis of high organic content, occurrence of phosphatic nodules, and microfossil assemblages (Fig. 2). Yang et al. (2003) interpreted the black shale facies as a marine condensed section. In NE


A
Small fault
Calcisol
Channel-lag conglomerate
Overbank sandstone, shale, and paleosol
B
C
Undulating and diffuse boundary
D
E
F
2 mm
G
a
a
b
a
b
2.4 mm
H
c
a
b
a
c
b
b
a
a
c
2.4 mm

Oklahoma, the Heebner Shale thickens abruptly (10–30 m) and contains one or more upward-coarsening and thickening successions, which were interpreted as a shelf to deltaic succession (Evans, 1967; Yang et al., 2003).

4.5. Summary

The TST of the Oread cyclothem is an upward-deepening unit, indicating shoreline transgression across the Snyderville peneplain and ensuing shelf deepening. The advancing sea eroded and gleyed the paleosols to form the nonfossiliferous mudstone facies, and deposited the CSU as a transgressive lag (see Discussion section). Fossiliferous mud accumulated on the shallow shelf to form the fossiliferous shale facies. When the shoreline migrated farther away from the study area to the northeast and terrigenous mud influx diminished, wackestone was deposited. When the shelf deepened below the photic zone, carbonate accumulation stopped and anoxia developed in the water column. As a result, pelagic to semi-pelagic mud accumulated in the outer shelf to form the black shale facies as a condensed section.

5. Discussion

5.1. Source of calcitic clasts in the conglomerate-sandstone unit

Potential sources for calcitic clasts in the CSU include contemporary deltaic gravels, relict fluvial channel-fill gravels on the peneplain, and/or gravels within underlying fluvial sediments and paleosols. The persistency of the CSU along both depositional strike and dip (Figs. 3, 4) argues against a point source, such as a delta. This is supported by the absence of any transgressive deltaic deposits in the study area (Yang et al., 2003). Concentrated calcitic gravels in a small fluvial channel in the Snyderville RST were observed in Section 78A (Fig. 6A, B). Extraordinary mechanisms, however, are needed to rework the gravels to form such a persistent CSU. In addition, only one such deposit was observed among numerous channel fills in the Snyderville RST (Fig. 3A). Thus, the limited amount of calcitic channel gravels cannot account for the abundance of the conglomerate-sandstone.

Stratigraphic and petrographic evidence suggests the calcitic nodules in the Snyderville paleosols as the source of clasts in the CSU. Multiple and single-story calcareous Vertisols and vertic Calcisols are abundant in the fluvial deposits of the RST, especially the upper part, of the Toronto cyclothem (Fig. 3A; Joeckel, 1994; Turner et al., 2003). They contain a variety of abundant calcitic nodules in mudstone and sandstone plasmas (Fig. 6C). Elongate, subvertical, downward-tapering rhizoconcretions are mm-cm wide and 10s of cm long. Cylindrical calcite-filled burrows are 1–2 cm wide and 5–15 cm long. Tabular calcitic plates along soil slickensides are 1–10 cm thick and several to 30 cm long (Fig. 6D). Equant, irregular, discrete calcitic nodules are mm–15 cm in diameter and highly concentrated in 50–100-cm-thick B_k horizons. In addition, soil and fluvial processes may have locally concentrated the soil nodules. In a B_k horizon in section 267, three imbricating sigmoidal bodies of concentrated calcitic nodules, each ~50 cm thick and ~1.5 m long, are well defined by an ~5-cm-thick zone of contact-aligned peds (Fig. 6E). The body geometry and aligned peds in the contact zone suggest shearing and syn-pedogenic soil creep, which may have concentrated the hard soil nodules. Calcitic nodules were also locally concentrated in fluvial channels. In Section 78A, a channel-shaped soil-nodule conglomerate body encased in overbank mudstone and shale is ~ 70 cm thick and a

Fig. 6. A) Field photo showing a small channel-fill conglomerate encased in fluvial overbank shale and Calcisols in upper Snyderville RST, Section 78A. Ruler parallel to fault is 1 m long. B) Close-up of clast-supported pebble conglomerate shown in A. Clasts are calcitic, subrounded, and coated with ferruginous clay. Coin is 2.4 cm in diameter. C) Field photo showing abundant discrete calcitic nodules (white arrows) in variegated, blocky soil plasma in the B_k horizon of a Calcisol in the uppermost Snyderville RST. Nodules are subvertical to oblique, elongate, irregular, or equant. Elongate ones may be rhizoconcretions or calcite-filled burrows (black arrow). Hammer is 25 cm long. Section 267. D) Field photo showing oblique soil slickensides lined with tabular calcitic plates in a calcareous Vertisol in the uppermost Snyderville RST. Hammer is 25 cm long. Section 267. E) Field photo showing two imbricating paleosol bodies that contain concentrated equant to irregular calcitic nodules and are bordered by a 5-cm-thick zone of contact-parallel peds in the uppermost Snyderville RST. These bodies may have been formed by syn-pedogenic soil creep. Ruler is 1 m long. Section 267. F) Binocular photomicrograph of conglomerate shown in A and B. Purple, gray, and brown granule to coarse sand-sized micritic clasts are subangular to rounded, commonly auto-brecciated (black arrow), and cemented by sparry calcite. Sandstone and shale clasts are sparse (white arrow). Fine-grained sand matrix is ~5%. Sample 78A-N6. G) Binocular photomicrograph of a tabular calcitic nodule lining a large slickenside, showing auto-brecciated micritic nodules (a) of a dominantly diffuse boundary with soil plasma (b) and sparry calcite-filled cracks. Sample 267–20. H) Binocular photomicrograph of the same sample as in G, showing discrete micritic nodules (a) of variable sizes and sharp grain boundaries. They are angular to subrounded, partially lined by sparry calcite (b) or in sharp contact with silty ferruginous clay plasma (c). They were interpreted as being dislodged from the mother nodules as in G, and transported downward along slickensides or cracks for a short distance during pedogenesis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

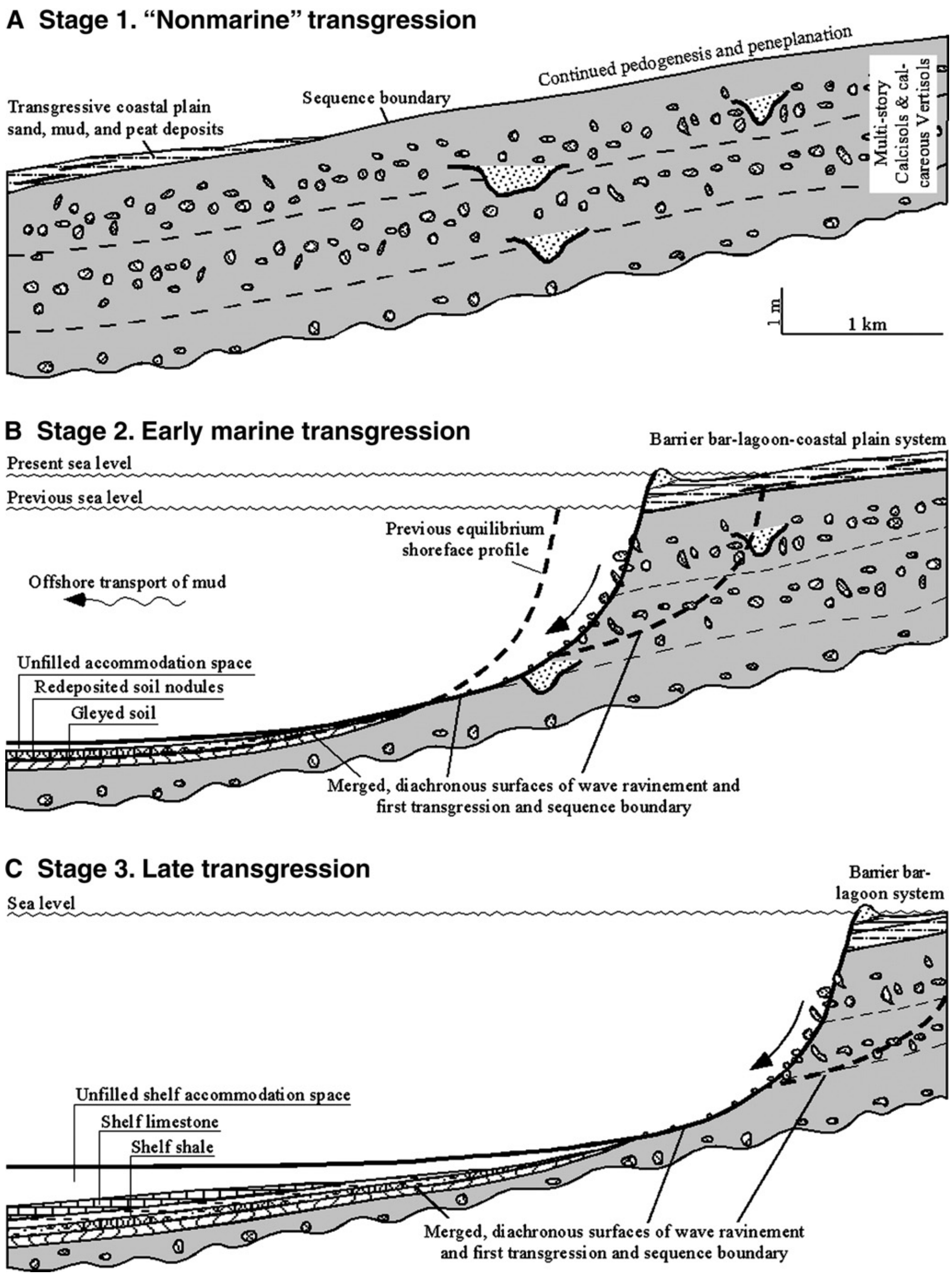


Fig. 7. Schematic cross section showing major processes and stratigraphic surfaces and units during three stages of shoreline transgression. A) Stage 1 — nonmarine transgression. Nonmarine coastal plain deposition occurred near approaching shoreline on fluvial peneplain composed of multi-story paleosols. B) Stage 2 — early marine transgression. Wave and current erosion of underlying paleosols and coeval shoreline and coastal–plain deposits was active on the upper shoreface, which was migrating landward. Eroded soil nodules and coarse sediments were transported down slope by bottom storm return flow and deposited in the lower shoreface and inner shelf seaward of the intersection point between the present and previous equilibrium shoreface profiles. Underlying remnant paleosols were gleyed by seawater. Surfaces of wave ravinement and first transgression and the sequence boundary are merged. C) Stage 3 — late transgression. Mud was deposited on the inner and outer shelf, followed by carbonate deposition, when the shelf deepened and the shoreline migrated farther away from the depositional site. Scale is approximate.

minimum of 5 m long, with an erosional base and a sharp top (Fig. 6A). The soil nodules and some (<5%) sandstone and mudstone clasts are mm–4 cm in diameter, subrounded, moderately sorted, and tightly packed (Fig. 6B, F). This conglomerate is interpreted as a lag deposit in a small channel on the flood plain. Finally, abundant calcitic soil nodules are also present in the Snyderville RST in two cores (Fig. 1).

More importantly, the soil nodules and the calcitic clasts in the transgressive CSU have similar textures. The soil nodules are highly heterogeneous, composed of mainly micritic to microsparitic calcite, some interspersed quartz silt and sand, irregular patches or irregular to curvilinear lenses of mud, and cavity-filling calcite. Cavities are prominent and may be filled with sparry or micritic calcite and/or ferruginous mud. They include radiating to irregular elongate cracks signifying auto-brecciation (Fig. 6F, G), partially concentric fissures interpreted as calcite precipitation around roots, or rounded to elongate moulds as root moulds. Two types of component grains are distinct in soil nodules, one with diffuse grain boundaries and the other with sharp boundaries. Equant to irregular grains with diffuse boundaries are demarcated by mm–sub-mm-thick, ferruginous clay-rich zones grading from the dense calcitic interior (Fig. 6G). The aligned clays suggest argillo-ferruginous illuvial accumulation. Equant to irregular, angular calcite grains with sharp boundaries are demarcated by microfractures, which may be filled with sparry calcite, iron oxide, or clay. They are interpreted as auto-breccias. Some discrete calcitic grains, sub-mm to 1 cm in diameter, are present along mm–cm-wide cracks and embedded in mud plasma (Fig. 6H). They are partially or completely coated by sub-mm-thick ferruginous clay laminae of probably an illuvial origin or sub-mm micritic or sparry calcite rims to form soil pisoids, or not coated at all. Partial detachment of the discrete grains from the large mother grains was also observed. These discrete grains were interpreted as being dislodged from the mother grains at the edge of open cracks or slickensides, transported down the crack over a short distance, and mechanically or chemically rounded to some degree (Fig. 6H).

Some dissimilarities exist between soil nodules and their component grains and the calcitic clasts in the CSU. In comparison to the calcitic clasts, the nodules and grains have a larger average size and a much wider size range, a highly variegated color of white, gray, purple, red, and brown, a complex gradational or diffuse grain boundary, and a much more angular shape.

The similarities in composition and texture between soil nodules and their component grains, and the calcitic clasts in the CSU suggest that the former are the source of the latter. Improved roundness and sorting, decreased grain size, and sharp grain boundaries of the calcitic clasts indicate mechanical breakup and abrasion of the source soil grains and nodules by high-energy water currents. The gray to blackish gray color of the calcitic clasts was probably caused by seawater gleying.

5.2. Formation of the conglomerate-sandstone

A simple two-dimensional shoreline-perpendicular model was conceived to depict the processes and stages of transgressive deposition, especially the formation of the CSU of the Oread cyclothem (Fig. 7), on the basis of observations of this and other Holocene studies (e.g., Swift et al., 1972; Demarest and Kraft, 1987; Wright, 1995). Prior to shoreline transgression, the study area was a low-relief, westward-dipping exposed surface, as indicated by the persistent thin units of the TST of the Oread cyclothem (Fig. 3; see also isopach and structural maps of the Leavenworth Limestone in Yang et al., 2003). Later transgressive shoreface erosion may have further reduced the relief (see below). Interfluvial deposition was minimal. As a result, multi-story paleosols were developed under a semi-arid to subhumid climate (Fig. 7A; Joeckel, 1994; Turner et al., 2003). The approaching shoreline had raised the groundwater table, and a swampy coastal plain was migrating eastward into the study area. Rare coal fragments in the CSU suggest the existence of a temporary coastal peat swamp.

During initial marine transgression, a coastal plain–shoreline–shelf environment was migrating into and across the study area (Fig. 7B). The marine environments may have included a lagoon–barrier bar, estuary, or strandplain, an erosional upper shoreface, and a depositional lower shoreface and inner shelf. The lagoon–barrier bar or strandplain system was likely poorly developed due to rapid shoreline transgression, which was caused by rapid sea-level rise on a gentle slope. The paucity of quartz sand deposits in the basal TST supports this speculation. In the steep upper shoreface, wave agitation and storm flows eroded underlying poorly-consolidated calcareous paleosols (Bruun, 1962; Swift, 1968). The calcitic soil nodules and other coarse grains were plucked out and transported, along with shell fragments, down the upper shoreface as bedload by storm return flows, while the fine sediments were winnowed into suspension and transported offshore (Swift, 1976). The soil nodules were disintegrated, abraded, and increasingly rounded and sorted during transport. In addition, the landward-migrating shoreface cannibalised the contemporary shoreline and coastal plain deposits (e.g., Abbott, 1998). This is supported by the absence of barrier bar–lagoon/strandplain and coastal plain deposits in the TST, which indicates low rates of subsidence and sediment supply in the study area (Thorne and Swift, 1991). The calcitic soil clasts were being deposited on the lower shoreface and inner shelf where storm return flow weakened. Further wave and current reworking would have increased the roundness and sorting of the clasts and spread them laterally and basinward. Bedload deposition occurred there also because of the available accommodation space, which is the space between the sea floor and the flattened lower shoreface of the theoretical equilibrium shoreface profile (Bruun, 1962). The shoreface may not have achieved equilibrium because of the short residence time of the shoreline at a specific site due to rapid shoreline transgression (Cant, 1991; Thieler et al., 1995; Cooper and Pilkey, 2004). As a result, the seaward-expanding accommodation space was likely small. This may have contributed to the thin but persistent occurrence of the CSU, because any accumulation above the equilibrium profile would have been eroded (Bruun, 1962) or redistributed. This speculation implies that the lower shoreface accommodation space may have been overfilled to just slightly under-filled. In the meantime, the underlying paleosols were being gleyed by percolating seawater.

The last stage was transgressive shelf deposition (Fig. 7C). The shelf deepened and accommodation space increased quickly due to fast glacial eustatic sea-level rise. Suspended mud delivered from the upper shoreface started to settle on top of the calcitic gravels in the inner shelf at depth greater than the normal wavebase to form the fossiliferous shale facies. Further shelf deepening and diminishing coastal mud influx due to farther eastward shoreline transgression promoted carbonate accumulation, carpeting the study area to form the Leavenworth wackestone facies. Shelf anoxia progressed and culminated during the maximum shoreline transgression and shelf deepening, when the condensed Heebner black shale facies was deposited.

5.3. Nature of the wave ravinement record

The stratigraphic architecture of the TST of the Oread cyclothem is relatively simple (Figs. 3, 4). The dominantly fine-grained lithology suggests an overall low-energy coastal–shoreline–shelf environment and/or a shortage of coarse clastic supply. Deposition in the lower shoreface and shelf was slow and uniform. Nevertheless, upper shoreface erosion during its landward migration had occurred, producing the CSU as the only coarse clastic facies in the transgressive record. Tidal currents may also have contributed to shoreline erosion. However, the lack of typical tidal deposits, such as tidal bundles and tidal-channel and delta deposits (cf. Archer and Feldman, 1995), suggests that wave and wave-induced currents were the dominant erosional agents and the base of the CSU is a wave ravinement surface.

The landward shoreface movement was probably slightly upward and nearly parallel to the exposed surface, but at some distance (i.e. the erosional depth of upper shoreface) below the exposed surface. If the upward movement had been significant, some contemporary coastal and shoreline deposits would have been preserved. The erosional depth is difficult, but desirable, to estimate. Cattaneo and Steel (2003) suggested that it is commonly in the order of 10 m, roughly corresponding to the depth of the fair-weather wavebase (see also Saito, 1994; Rodriguez et al., 2001). The depth of shoreface erosion is determined by the balance between the rates of sediment influx and sediment removal in the upper shoreface. These are controlled by the interplay of many factors, such as sediment supply, wave and current regime, bedrock erodability, and rate of shoreline transgression, which are, in turn, controlled by the rate of sea-level rise and peneplain topography (e.g., Trincardi and Field, 1991; Thieler et al., 1995; Abbott, 1998; Rodriguez et al., 2001; Cattaneo and Steel, 2003 and references within). A mass balance calculation equating the volume of soil nodules in the CSU and in the source paleosols may provide estimates of the erosional depth by using observed abundance of soil nodules in the paleosols. Nevertheless, the rapid shoreline transgression and limited terrigenous sediment supply as postulated above argue for a shallow erosional surface (Cattaneo and Steel, 2003); persistent easterly winds in the trade-wind belt may have suppressed formation of large waves, keeping erosion to a minimum (Heckel, 2006, personal communication); and one or more stories of paleosols, each 1–2 m thick, could have been eroded.

The wave ravinement surface at the base of the CSU is composed of many short preserved segments of the erosional upper shoreface because shoreface erosion at any one time is limited in extent (Fig. 7B). Therefore, the surface is diachronous and is younger northeastwards. For the same reason, the CSU and overlying transgressive deposits also become younger eastwards (Jervey, 1988). The wave ravinement surface juxtaposes the first marine transgressive unit (i.e. the CSU) with the underlying RST of the Toronto cyclothem. Thus, the surface is also the lower boundary of the Oread cyclothem as well as the first transgressive surface. Alternatively, the sequence boundary could be placed at the base of the Gleysol, if it were interpreted as a transgressive nonmarine deposit. This alternative was not adopted here because the Gleysol was interpreted as the product of seawater leaching of the original calcareous paleosols (cf. Yang et al., 2003). Where the Gleysol developed on an original Histosol, which is a likely nonmarine transgressive coastal plain deposit, it would have been appropriate to place the sequence boundary at the base of the Gleysol or the nonmarine transgressive deposits (e.g., Yang, 1996).

Finally, the transgressive succession of the Oread cyclothem is similar to the type T-C_1 succession in Cattaneo and Steel's (2003) classification. The Oread cyclothem is, however, composed of mixed carbonate and siliciclastic rocks. Considering the wide occurrence of Upper Paleozoic mixed carbonate and siliciclastic transgressive successions in the midcontinent of North America and other parts of the world and during other time periods, a new type of transgressive succession, T-C_4, can be added to Cattaneo and Steel's (2003) classification, defined as a record composed of a simple transgressive lag overlain by shelf shale and limestone in a low-relief mixed carbonate and siliciclastic setting.

6. Conclusions

1. The transgressive record of the Upper Pennsylvanian Oread cyclothem in the midcontinent of North America consists of an upward-deepening succession of thin, persistent, dominantly fine-grained siliciclastic and carbonate rocks. It indicates uniform deposition in an overall low-energy regime during a rapid landward shift of coastal plain, shoreline, and shelf environments associated with rapid shoreline transgression and shelf deepening on a vast low-relief epicontinental shelf.
2. A widespread, thin marine conglomerate-sandstone unit is the only coarse-grained clastic deposit in the transgressive record, composed mainly of well-rounded and well-sorted calcitic clasts. The clasts were derived from calcitic soil nodules in the Calcisols and calcareous Vertisols of the underlying cyclothem. Wave and storm-current erosion in the upper shoreface extracted the nodules and cannibalised contemporary shoreline and coastal plain deposits during landward shoreface migration. The eroded coarse sediments were then reworked, transported, and deposited in the lower shoreface and inner shelf by storm return flows to form the conglomerate-sandstone unit as a transgressive lag.
3. The conglomerate-sandstone unit indicates extensive wave ravinement, which "bulldozed" the underlying regressive paleosols. The wave ravinement surface at the base of the conglomerate-sandstone unit is also a diachronous sequence boundary and the first transgressive surface. The transgressive record can be classified as a new T-C_4 type transgressive succession, composed of a simple transgressive lag overlain by shelf shale and limestone in a low-relief mixed carbonate and siliciclastic setting.

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