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Sequence Stratigraphy and Onlap History of the Donets Basin, Ukraine: Insight into Carboniferous Icehouse Dynamics

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Abstract

The degree to which Permo-Carboniferous cyclothemic successions archive evidence for long-term variations in ice volume during the Late Paleozoic Ice Age is insufficiently resolved. Here we develop the sequence stratigraphy and onlap-offlap history for a 33-my interval of the Carboniferous using the U-Pb calibrated succession of the Donets Basin, Ukraine, in order to assess the relationship between sea-level, high-latitude changes in glacial extent, and climate. Integrated subsurface and outcrop data permit meter-scale correlation of 242 biostratigraphically constrained limestones and coals, and in turn individual cyclothems, across ~250 km of the Donets Basin. Rapid uniform subsidence and basinwide continuity of marker beds indicate Pennsylvanian deposition under relatively stable tectonic conditions. Three scales of sequences (avg. durations of ~140 ky, ~480 ky and 1.6 my) are recognized on the basis of stratigraphic stacking patterns and basinwide architecture of marine to terrestrial facies assemblages.

The hierarchy of sequences and the geographic and stratigraphic positions of shifts in base-level sensitive facies across the Donets ramp permit the construction of an onlap-offlap history at a sub-400 ky scale. Major sea-level lowstands occur across the mid-Carboniferous boundary and during the early Moscovian. These lowstands coincide with glacial maxima inferred from high-latitude glacigenic deposits. The middle to late Pennsylvanian is characterized by a stepwise onlap, culminating in an earliest Gzhelian highstand, suggesting contraction of Carboniferous ice sheets prior to the initiation of Early Permian glaciation.

The stratigraphic position of climate sensitive facies within individual Donets cyclothems indicates a turnover from seasonal sub-humid or semi-arid climate to everwet conditions during the late lowstand and maximum ice sheet accumulation. Comparison of the stratigraphic and aerial distribution of coals and evaporites in the Donets Basin with the onlap-offlap history further indicates everwet conditions during lowstands and inferred glacial maxima and drier climate during onlap and inferred ice sheet contraction at the intermediate (~0.8 to 1.6 my) and long (10^6 yr) time-scales. Taken together, the relationship between inferred climate and glacioeustasy suggests a likely teleconnection between high-latitude ice sheet behavior and low-latitude atmospheric dynamics.

Keywords: Donets Basin, cyclothems, sequences, Carboniferous sea level, glacioeustasy, Carboniferous paleoclimate orbital forcing

1. Introduction

Cyclothemic successions, which characterize low- to mid-latitude Permo-Carboniferous successions globally, have long been considered archives of glacioeustasy driven by the waxing and waning of continental ice sheets in high-latitude Gondwana (e.g., Wanless and Shepard, 1936; Heckel, 1977; Algeo and Wilkinson, 1988). The magnitude of these high-frequency (10^5 years) glacioeustatic fluctuations was inferred to be between 50 and >120 meters based on stratigraphic (e.g., Heckel, 1986) and stratal relationships (e.g., Soreghan and Giles, 1999) as well as geochemical proxy records (e.g., Joachimski et al., 2006), suggesting the existence of geographically extensive and long-lived ice sheets throughout the Late Paleozoic Ice Age (LPIA). Recently, studies of chronostratigraphically well-constrained glacigenic deposits in high-latitude successions and interbedded non-glacigenic facies have revealed evidence for a

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climatically more dynamic ice age, one that consisted of a series of discrete (1 to 8 my) glaciations separated by glacial minima or possibly non-glaciated intervals of comparable duration (Isbell et al. 2003; 2008; Fielding et al. 2008; 2010; Gulbranson et al., 2010).

The presence of multiple ice sheets that waxed and waned variably, and perhaps asynchronously, should be archived in Permo-Carboniferous cyclothemic successions given their stratigraphic sensitivity to sea-level changes that would have recorded, in part, the sum of changes in ice volume globally at any given time. Indeed, a few studies of paleotropical cyclothemic successions (Feldman et al., 2005; Fischbein et al., 2009; Bishop et al., 2010; studies summarized in Rygel et al., 2008) provide independent stratigraphic evidence for periods of diminished magnitudes ($\leq$30 m) of short-term glacioeustatic fluctuations and by inference, changes in the extent and rates of growth and decay of continental ice sheets. Moreover, recent climate simulations of the LPIA reveal the high sensitivity of ice sheet size to orbital forcing and pCO_2, suggesting that magnitudes of Permo-Carboniferous glacioeustasy might be expected to have been quite variable (Horton et al., 2007; Horton and Poulsen, 2009). At present, however, the degree to which the tempo and magnitude of glacioeustatic fluctuations evolved throughout the LPIA remains insufficiently resolved.

The cyclothemic succession in the Donets Basin, Ukraine, records near continuous paralic sedimentation in the eastern Pangaean paleotropics throughout the Carboniferous and earliest Permian. Biostratigraphically dated limestones and coals provide laterally extensive marker beds that tightly constrain correlations at the meter-scale across up to 250 km of the basin. In turn, base-level sensitive facies within correlated cyclothems permit the construction of an onlap-offlap curve for a 33-my interval of the Carboniferous of the Donets Basin. In this paper we argue for a eustatic origin for the onlap-offlap history based on a cyclothem-scale correlation of the Donets and Midcontinent successions and reconstruction of a relatively uniform accommodation history for the Donets Basin. Comparison of the onlap-offap curve to high-latitude glacigenic records suggests changes in ice volume as a driver of inferred Pennsylvanian lowstands and highstands. The temporal relationship of the distribution of climate-sensitive facies in the Donets succession to onlap-offlap events and inferred ice volume changes suggests a mechanistic linkage between Pangaean tropical continental climate, ice sheet extent and relative sea level.

2. Geological Setting & Chronostratigraphy

The Donets Basin is part of the northwest-southeast trending Dnieper-Donets intracratonic rift basin (~200 km wide by 700 km long) that formed in the southwestern part of the Eastern European Craton during the Devonian through Carboniferous due to underlying plume activity or to back-arc extension-related subduction along the southern margin of the basin (Fig. 1; Stephenson et al., 2001; 2006; McCann et al., 2003). Thermal post-rift subsidence during the late Mississippian through Pennsylvanian permitted the accumulation of an up to 14 km sedimentary wedge (Stephenson et al., 2006; Sachsenhofer et al., in press). Subsidence slowed significantly in the Early Permian (Fig. 2) and the southeastern part of the basin was tectonically inverted in the late Paleozoic and Mesozoic (Saintot et al., 2003; Stephenson et al., 2006). Notably, the sub-parallel trends in both up-dip and down-dip locations on the Donets long-term accumulation curves (Fig. 2) indicate that depositional rates for the late Mississippian through Pennsylvanian were relatively rapid and regionally uniform throughout the study area.

Fluvio-deltaic and nearshore-marine mixed carbonate-siliciclastic sediments were deposited on the Donets ramp, which steepened distally over several hundred km into the Uralian seaway and Peri-Caspian Basin of the northern Tethys Ocean (Alexseev et al., 1996). A low depositional slope (<< 1°) is indicated by the basinwide extent of many marine limestones and the widespread and uniform stratigraphic distribution of deltaic deposits, including coal, across much of the basin. The Donets study area remained in the eastern Pangaean tropics through the Permo-Carboniferous (Fig. 1C; Dercourt et al., 2000; Blakey, 2008).

2.1 Chronostratigraphic Framework

The Carboniferous through lowermost Permian Donets succession was formally divided into formations (designated by capital letters A through S) on the basis of biostratigraphically constrained marine limestones (Tschernyshev and Lutugin, 1897; Lutugin and Stepanov, 1913; Lebedev, 1924). The Carboniferous limestone marker beds (n = 242), as well as numerous coal beds, were correlated over hundreds of km of the Dnieper-Donets aulacogen (Zhemchuzhnikov et al., 1959, 1960, Brazhmikova et al., 1967; Aizenverg, et al., 1975; Einor et al., 1979; Makarov, 1982, 1985; Alexseev et al., 1996), providing an exceptional framework of time lines for sequence stratigraphic analysis.

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Biostratigraphic control in the Donets Basin is based primarily on conodonts, foraminifera, ammonoids, and brachiopods (Brazhnikova et al., 1967; Popov, 1979; Davydov, 1990; Nemyrovska, 1999; Nemyrovska et al., 1999; Vdovenko, 2001; Fohrer et al., 2007). Fossil plants and miospores are used for correlation to terrestrial-dominated successions (Fisunenko, 2000; Inosova et al., 1976; Shchegolev, 1975; Shchegolev and Kozitskaya, 1984). Foraminifera and conodonts provide average zone durations of 1.5 to 2 my, whereas less common ammonoids define zones of 2 to 5 my duration. Donets Basin fauna are correlated to stratotype sections in Europe, the Moscow Basin, and the Urals (Aizenverg, 1979, Aizenverg et al., 1983; Vdovenko et al., 1990; Nemyrovska, 1999; Ramezani et al., 2007; Fohrer et al., 2007) as well as the U.S. Midcontinent succession (Heckel et al., 2007). High-precision, ID-TIMS U-Pb ages (n=12) with +/- 100 ky resolution on zircons extracted from tonsteins (Davydov et al., 2010) further constrain the chronostratigraphic framework (Fig. 2).

3. Methodology

Twenty-seven outcrop sections of Serpukhovian through Gzhelian strata (totaling ~4 km thickness) were measured and described on a dm-scale. We used core logs (n=206) for 78 drill sites (totaling >12 km thickness), distributed over an ~150 x 200 km area of the Donets Basin, that were provided by the Artemovsk Regional Geological Survey (Fig. 3). Previously described core logs (Makarov, 1982; 1985; Poletaev et al., 1991; Nemyroska, 1999; Zhykalyak, unpublished data) were translated from Russian and correlated with select outcrop sections in order to calibrate lithofacies descriptions (Fig. 4). Lithofacies were identified using outcrop sections, subsurface mine observations, and core samples and logs, and were refined by petrographic analysis of ~200 thin sections. Correlations between core logs and outcrop sections and descriptions of regional lithofacies patterns were made using all available biostratigraphy and regionally recognized marker beds (Aizenverg, 1979, Maystrenko et al, 2003). These regionally correlatable marker beds are named in stratigraphic sequence using capitalized Latin letters with consecutive Arabic numeral suffixes (e.g. M1, M2). Marker beds that were designated subsequently are assigned an additional Arabic numeric suffix (e.g., M1-1) and overlie the bed with the simpler name (e.g. M1-1 is above M1). Widespread coal beds are designated with lower case letters (e.g. m1, m2-1). The detailed outcrop maps of Makarov (1982, 1985) were used to project core logs along strike (avg. distance of 7 km) into a dip-oriented transect parallel to the NW-SE trending Donets fold-belt (Fig. 3). Dip-oriented cross sections were constructed for each formation (e.g., K, L, M limestone series), with the youngest marker limestone used as the upper datum.

Named limestones and major coals, considered to be near-isochronous based on high-resolution biostratigraphy (Poletaev et al., 1991), were used as chronostratigraphic datums. U-Pb dates provide absolute ages for certain marker bed time-lines. Time-constrained genetic units exist at multiple scales, from the decameter scale of cyclothems to larger units spanning hundreds of meters and permit a detailed chronology of Carboniferous deposition. Chronostratigraphic diagrams were constructed by placing core and field data in a time-distance framework as determined by their chronologic ages and their cross-sectional position following the methodologies of Wheeler (1959) and Galloway (1989). Construction of onlap-offlap curves is described in detail in the relevant section.

4. Facies Assemblages

Three facies assemblages are defined on the basis of their inferred position along a landward-to-seaward transect in the Donets Basin (Table 1). In general, the marine facies assemblage records the deepest water conditions and the influence of a highly productive, tropical marine ecology. Delta-top facies were deposited across a diverse mosaic of broadly contemporaneous environments in a deltaic system, including nearshore marine and freshwater swamp environments. Fluvial facies in the study area record progradational river systems and associated floodplain deposits lateral to channels. Siliciclastics dominate (93%) the Donets succession with a minor (<7%) component of carbonates and evaporites.

4.1 Marine facies assemblage

Laminated marls and intercalated organic-rich siliciclastic mudstones and siltstones are common in the Donets Basin (Table 1). Marls are subtly bioturbated and contain rare echinoid and brachiopod fragments. Fissile mudstones and siltstones (Fig. 5A) contain *goniatite* ammonoids, conodonts and brachiopods, commonly preserved in calcareous or sideritic nodules.

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Associated marine limestones range from nodular-bedded, silty skeletal wackestones with *Zoophycos* (Fig. 5B) to thick-bedded to massive crinoidal grainstones and rudstones. Microbial bioherms and laminated algal biostromes, with a diversity of heterozoan fauna, occur within some limestones. Typically, limestones (5 cm to 10 m thick) can be traced hundreds of km based on their conodont and fusulinid biostratigraphy. Fossiliferous, cross-bedded calcareous siltstones and sandstones may occur within thick carbonate intervals.

Planar tabular cross-bedded and fine-grained quartz-rich sandstones (Table 1) occur stratigraphically between coarse-grained fluvial sandstones and overlying marine limestones (e.g., O4-6u on Fig. 4). These well-sorted sandstones contain rare crinoid ossicles and have non-erosive bases (Fig. 5C). Fine-grained quartzitic sandstones are ripple-laminated, flaser-, lenticular- and wavy-bedded, and contain micaceous and carbonaceous partings and abundant fossil plant matter.

4.1.1 Interpretation

Organic-rich, poorly fossiliferous marls and interbedded fossil-rich fissile mudstones were deposited below storm wave-base and manifest the deepest water deposition in the region. The dominance of parallel lamination indicates quiet water conditions and the lack of a deeply burrowing infauna, likely far offshore or out on the distal prodelta. During transgressions these deposits migrated far up-dip on the depositional ramp.

Laterally extensive carbonate mudstones and wackestones that underlie marly siliciclastics indicate quiet, less deep waters, likely toward the deeper portions of the photic zone. Skeletal packstones and grainstones and microbial boundstones record higher energy, shallow waters updip of contemporaneous finer-grained limestones. The diversity of open-marine fossils indicates well-circulated waters and an active faunal community. Carbonate deposition ranged from above storm wave-base in distal portions of the ramp to above fairweather wave-base in more landward locales. Intercalated planar tabular cross-bedded, calcareous sandstones record episodic deposition of middle to upper shoreface sands.

Fine-grained quartzitic and micaceous sandstones exhibiting flaser, lenticular and wavy bedding predominate in basinward sections recording tidally dominated sediment transport across the delta-plain or within estuaries (Maguregui and Tyler, 1991; Dalyrample et al., 1992). In contrast, well-sorted and rounded, quartz-rich sandstones were derived from the wave- and tidal-reworking of underlying fluvial sands and record deposition in the middle to upper shoreface of barrier bars and beaches.

4.2 Delta-top facies assemblage

This facies assemblage consists of organic-rich fine-grained siliciclastics, coals, and subordinate limestones (Table 1). Siliciclastic mudstones with interbedded siltstones and fine-grained sandstones predominate and display a wide range of sedimentary structures from mm-scale laminations in mudstones (Fig. 5D) to cross-bedded silty sandstones exhibiting climbing and current ripples. Discrete plant fossils (including lycopsids and *Calamites*) and thin coaly partings are common. Thin, lenticular-bedded impure carbonates occur interbedded with siliciclastic mudstones and siltstones (Fig. 4; Table 1). Coals (up to 3 m), which are interbedded with other facies of the delta top assemblage, commonly overlie paleosols and form regional marker beds that are laterally traceable over several tens to hundreds of km. Evaporites occur in uppermost Pennsylvanian delta-top deposits.

4.2.1 Interpretation

This facies assemblage represents a mosaic of broadly contemporaneous delta-top environments (Fielding, 1984; Bhattacharya and Walker, 1992). Fine-grained siliciclastics accumulated across the upper and lower delta plain, as well as within estuarine and alluvial plain environments (Wright, 1985; Emery and Myers, 1996). Planar-bedded siltstones and associated impure limestones likely formed in quiet waters that occupied depressions on the delta top. Widespread and abundant coals are interpreted to be saturated, organic-rich soils (Histosols) of peat-forming mires that developed from the Visean through Kasimovian.

Stratigraphically juxtaposed facies of the delta-top assemblage record active migration of deltaic environments that reflect changes in accommodation as well as autogenic processes such as fluvial avulsion and delta-lobe switching (Allen and Mercier, 1988, Riegel, 1991). The lateral continuity of these deltaic deposits, including over 300 coals that can be traced throughout the study region (Sachsenhofer et al., 2003), indicates the broad lateral extent of Donets deltaic environments, including the peat-forming mires (Aizenverg, 1979). Of these coals, more than fifty in the Serpukhovian through Moscovian interval are mined commercially.

In the Donets Basin, coal deposition decreased after the middle Pennsylvanian with the onset of evaporite deposition in the late-middle Pennsylvanian and into the Permian. The interbedding of evaporites with other facies of the delta-top assemblage suggests precipitation within saline lakes and restricted lagoons dispersed across the delta top, likely within proximity to the shoreline (Ortí-Cabo et al., 1984; McCann, 1998). Episodic replenishment of marine waters must have occurred multiple times given the thick accumulation of many individual evaporite beds.

4.3 Terrigenous facies assemblage

This facies assemblage includes trough cross-bedded sandstones, pebble conglomerates, and paleosols (Table 1). Some multi-story (tens of m thick), trough cross-bedded sandstones with scoured erosional bases are informally named (e.g. Meffert and Tabacco Sandstones, E marker-bed group) given their lateral continuity and thickness. Poorly to moderately well-sorted lithic arenites and arkoses exhibit trough cross-stratification with rare low relief dune stratification. Finer-grained sandstones and minor siltstones are intercalated with the lithic arenites and arkosic sandstones (Fig. 5E). Trough cross-bedded pebble conglomerates, with a fine to medium-grained lithic or arkosic matrix and polymict pebble- to gravel-sized clasts (Fig. 5F) occur at the bases of major sandstone units. Sandstones and pebble conglomerates contain discrete plant fossils including *Calamites* and *Sigillaria*. Stacked beds of sandstones and conglomerates, bounded by scoured erosional surfaces, commonly overlie or are interbedded with finer-grained delta-top facies. These interbedded mudstones and claystones exhibit horizonation, ped structure, slickensides, redoximorphic mottling, and carbonate and Fe-oxide accumulations (Table 1).

4.3.1 Interpretation:

Sandstones of the terrigenous facies assemblage are interpreted as fluvial channel and point bar deposits and crevasse splays. Pebble conglomerates mantle erosional channel bases. Where stratigraphically positioned above finer-grained delta-top facies, they are interpreted as channels that incised delta-plain deposits during sustained falls in base level (Shanley and McCabe, 1994; Hampson et al., 1999). Multi-story channelized deposits are interpreted to record the onset of relative sea-level rise and consequent reworking of older lowstand deposits (Strong and Paola, 2008). Stacked fluvial sandstones that transition into well-sorted quartz-rich marine sandstones in seaward locations indicate reworking of fluvial sands by waves and tides during transgressive migration of the paleoshoreline.

Altered mudstones and claystones of this assemblage are interpreted as fossil soils classified as Protosols, Calcisols, Argillisols, Vertisols and calcic Vertisols (cf., Mack et al., 1993). Paleosols (0.2 to 1 m) are developed in (1) uppermost mudstones of aggrading floodplain deposits, (2) finest grained sandstones capping channelized fluvial deposits, (3) claystones underlying major coals, and 4) as thin brecciated horizons developed on limestones that show rubifaction and clay accumulation (terra rosa). Paleosols record episodes (100s to 1000s of years) of subaerial exposure and plant colonization of floodplain sediments and nearshore-marine limestones during base-level falls and coeval channel incision (Bestland et al., 1997; Marriott and Wright, 1993; Kraus, 1999). Meter-scale zones of pedogenesis can be confidently traced for up to tens of km in the subsurface (e.g., the paleosols underlying the o2-4 coal in Fig. 4).

5. Cyclothems and Sequence Stratigraphy of the Donets Succession

A high-resolution history of retrogradation, aggradation and progradation was constructed for the Donets Basin given that individual marker beds and stratigraphic packages units can be correlated for hundreds of km across the depositional ramp (Aizenverg, 1979; Makarov, 1982). In the following sections (5.1 to 5.3) we define a hierarchy of genetic depositional units and infer their relationship to multiple temporal scales of onlap and offlap (section 6).

5.1 Cyclothems

Deposits of the three facies assemblages form systematic stratigraphic patterns, meters to decameters thick and bounded by channelized fluvial deposits, that reflect a gradual deepening followed by shallowing of inferred water depths. These repeating stratigraphic patterns form the fundamental depositional unit of the Carboniferous: the cyclothem. Donets cyclothems range from 5 to 100 meters in thickness (most between 40-60 m) and are comparable to other Carboniferous cyclothems (e.g. Heckel, 1977, Tandon and Gibling, 1994; Olszewski and Patzkowsky, 2003). Not only are stratigraphic patterns observed in single cores or outcrop, but the laterally extensive marker beds permit the

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up- and down-dip tracking of individual cyclothems and thus the longer term retrogradation, aggradation and progradation of depositional environments (Fig. 6).

The internal facies composition, stacking patterns, and architecture of cyclothems change through time and space, and appear to be dependent on their position in the longer-term accommodation history (Section 5.2). Three cyclothem types are defined in the Donets succession on the basis of their dominant facies assemblage and basinwide architecture.

5.1.1 Retrogradational cyclothems

The marine facies assemblage dominates individual retrogradational cyclothems (avg. thickness of 40 m) and typically thickens down-dip in seaward-most cores and outcrops (Fig. 7). Terrigenous facies, in turn, are proportionally thinner. Major limestone units are typically thickest and exhibit their greatest landward extent within retrogradational cyclothems. Well-sorted, planar-tabular bedded sandstones, representing the transgressive marine reworking of older fluvial sands, are particularly well developed in retrogrational cyclothems. The thickness of delta-top and terrigenous facies is greatest up-dip and thinnest down-dip.

Stacks of retrogradational cyclothems are interpreted to reflect long-term backstepping of facies belts on the Donets ramp during phases of increased accommodation. Thin fluvial deposits in retrogradational cyclothems are constrained to up-dip regions of the ramp. Retrogradational cyclothems occur throughout the Carboniferous but tend to be most abundant in upper Visean through lower Serpukhovian and upper Moscovian through Kasimovian strata, and occur intermittently in the Bashkirian and Gzhelian stages.

5.1.2 Aggradational cyclothems

Delta-top facies, including thick, laterally continuous coals that thicken slightly up-dip, dominate these cyclothems (avg. of 35 m thick) (Fig. 7). Thin fluvial sandstones at the base of these cyclothems exhibit negligible depth of incision (≤5 m). Marine facies are thin and consist of mudstones and limestones that are constrained between thick packages of delta-top deposits. The predominance of delta-top facies, which exhibit relatively uniform thickness across the platform, record the consistent amounts of accommodation space across the ramp during aggradational periods, permitting the accumulation of thick delta plain deposits. Over long time spans, stacks of aggradational cyclothems are interpreted to record episodes of positive accommodation. These cyclothems occur through the Pennsylvanian succession, reflecting transitional phases between long-term episodes of retrogradation and progradation.

5.1.3 Progradational cyclothems

Progradational cyclothems are dominated by the terrigenous facies assemblage, with a significant proportion of the unit composed of stacked fluvial sandstones and conglomerates (Fig. 7). Progradational cyclothems typically thicken down-dip (from ~10-20 m up-dip to ~40-60 m down-dip). Erosional bases of progradational cyclothems exhibit the deepest incision (50 to 70 m; up to 125 m (e.g., below the O5-4 limestone)) with erosion typically truncating underlying delta-top deposits across the entire ramp. Two variants exist: (type 1) those with thicker marine facies and abundant coals, and (type 2) those containing thick evaporites and few coals (Fig. 7). Coal-rich progradational cyclothems are dominant in the uppermost Serpukhovian through mid-Moscovian interval, whereas evaporite-rich cyclothems occur in the upper Moscovian through Gzhelian succession. The marine facies assemblage in both types of progradational cyclothems is dominated by limestones that thicken markedly down-dip; deeper-water mudstones and marls typically are restricted to down-dip regions. Pedogenically-altered horizons are developed in delta-top facies basinwide, with multiple paleosols within individual progradational cyclothems (Fig. 7).

Stacks of progradational cyclothems record seaward migration of facies belts during prolonged episodes of decreased accommodation, as indicated by the predominance of coarse-grained fluvial deposits, the depth of channel incision, and the prevalence of stacked paleosols. The wedge-shaped nature of these cyclothems highlights the predominant down-dip locus of sedimentation. The development of marine-fed, evaporitic shallow ponds on the delta top beginning in the late Moscovian reflects increased aridification at that time. Progradational cyclothems are most common proximal to the mid-Carboniferous boundary and in the lower Moscovian, lowermost Kasimovian and upper Gzhelian intervals of the succession.

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5.2 Sequence stratigraphic model for the Donets Basin

5.2.1 Cyclothem-scale (Sequences)

Individual cyclothems preserve a genetically related set of depositional units that record a single cycle of relative sea-level change modified by variable sediment supply and regional climate. Since cyclothems are by definition bounded at the base and top by chronostratigraphically significant unconformities, we consider cyclothems to be 'sequences' (e.g., Van Wagoner et al. 1987). Sequence boundaries in the Donets record subaerial exposure as surfaces of fluvial incision and/or laterally equivalent pedogenesis, both indicative of base-level fall (Van Wagoner et al., 1988). For the uppermost Mississippian through Pennsylvanian succession in the Donets Basin, 242 sequences are recognized (labeled on Figs. 9-13).

The erosional base of multi-story fluvial sandstones was incised into underlying delta-top deposits as river systems prograded seaward when accommodation dropped to zero or became negative (Fig. 8A; *falling stage systems tract* of Hunt and Tucker, 1992). Time-equivalent, sequence-bounding paleosols are interpreted to record exposure of the delta top during sediment bypassing through incised river valleys (SB on Fig. 8A). The incision surfaces of fluvial erosional unconformities are assumed to be regionally diachronous with estimated ages bracketed by isochronous limestone or coal marker beds above and below (cf. Nummedal and Swift, 1987, Strong and Paola, 2008). Channelized fluvial sandstones and pebble conglomerates, which fill incision surfaces, evolved into stacked, multi-story sandstones as rivers avulsed and represent the *early lowstand systems tract* (Posamentier and Allen, 1999). These deposits developed as the rate of the eustatic fall approached that of subsidence (Figs. 6, black trend on 8A).

As the rate of subsidence outpaced the eustatic fall, river systems retreated landward and a broad mosaic of coastal plain environments developed across the basin (Fig. 8B). Widespread development of thick and relatively uniform packages of delta-top facies record aggradation in response to increasing accommodation provided by tectonic subsidence and sediment loading associated with high sediment supply. Planar tabular cross-bedded sandstones intercalated with deltaic deposits record the intermittent incursion of shoreface barrier bars with initial base-level rise. These sands likely restricted tidal circulation onto the delta top permitting the thick accumulation of fine deltaic siliciclastics and coals. The delta-top facies, which includes regional coals, predate the marked landward shift in facies denoting the onset of marine transgression, and are thus interpreted as the *late lowstand systems tract* (Fig. 6; black trend on Fig. 8B). This differs from previous interpretations of coals as transgressive system tract (Flint et al., 1995; Falcon-Lang et al., 2009; Falcon-Lang and DiMichelle, 2010) or highstand (Heckel, 2008; Falcon-Lang et al., 2011) deposits. Beginning in the late Moscovian, evaporitic, marine-fed hypersaline environments periodically developed in shallow ponds and lagoons on the delta top during this initial slow rise in base level and backstepping of delta-top facies belts.

The presence of thick (up to 3 m), laterally extensive coals within delta-top facies in the lower portion of Donets cyclothems (Figs. 6, 8B) requires the sustained accumulation of peat given peat-to-coal compaction ratios of between 1.2-to-2:1 (Nadon, 1998) and 10:1 (McCabe, 1984). This indicates the episodic abandonment of broad parts of the delta plain permitting the prolific formation of peat-forming mires (cf. Feldman et al., 2005). The gradually increasing accommodation of the late lowstand would have permitted the accumulation of thick packages of peat given the long-term subsidence rates of the Donets Basin (0.15 to 0.3 m/ky) and accumulation rates of modern tropical peats (0.05 to 0.25 m/ky) (cf. McCabe and Parrish, 1992). However, the formation of regionally distributed Donets coals likely required the additional influence of climate change to markedly wetter conditions (Cecil et al., 2003; DiMichele et al., 2010).

Shallow marine inundation of the coastal plain and development of a subtropical carbonate platform (Fig. 8C) occurred with the onset of eustatic rise. Slow initial rates of rise due to ice sheet hysteresis (Pollard and DeConto, 2005) would have permitted the widespread deposition of limestones throughout the Donets Basin. The lower surface of marker bed limestones that formed during this time is a reasonable approximation of a transgressive surface (TS) and marks the base of the *transgressive systems tract* **(**Fig. 6; Catuneanu et al., 2009). Carbonate sedimentation terminated as the platform was drowned and buried by marine muds, silts and marls as peak accommodation was reached (MFS of Fig. 8C). Fluvio-deltaic systems backstepped up-dip out of the study area during this phase of peak flooding. Marine marls and mudstones represent maximum flooding on the ramp. In progradational cyclothems, which typically lack marine siliciclastic facies, maximum flooding occurs in marker bed limestones.

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The *highstand systems tract* that forms the uppermost facies of Donets sequences is represented by aggradational-to-progradational delta plain deposits, including abundant fine-grained siliciclastics, thin and discontinuous coals, and paleosols (Fig. 6). These deltaic sediments were laid down under progressively decreasing accommodation as the rate of relative sea-level (base-level) rise gradually decreased (Cross, 1988). Sequence deposition terminated as the rate of eustatic fall outpaced subsidence, the rate of accommodation change approached zero once again, and fluvial systems prograded and incised to create the next *falling stage systems tract* and sequence-bounding unconformity (Fig. 8A).

5.2.2 Composite & longer-term composite sequences

At the larger scale, sequences (cyclothems) stack into predictable sets of longer-term depositional units interpreted as 'composite sequences' (Mitchum and Van Wagoner, 1991). As with sequences, the internal architecture of composite sequences preserves a genetically related set of strata that collectively record a long-term cycle of relative sea level change. We define seventy-five composite sequences in the Donets succession with Figure 9 illustrating the hierarchy for Moscovian strata.

In general, the stratigraphic architecture of composite sequences and individual sequences is similar. Many composite sequences (e.g., Mo-IV on Fig. 9) exhibit an upward progression from fluvial-dominated progradational sequences at the base, to delta-top-dominated aggradational sequences and/or marine-dominated retrogradational sequences in the middle, to aggradational-to-progradational sequences toward the top. Composite sequence boundaries commonly coincide with widespread unconformities that extend to the seaward margin of the study area. These unconformities predictably occur toward the top of a set of delta-top-dominated aggradational sequences and below one or more fluvial-dominated progradational sequences. Intervals of maximum flooding occur within the thickest marine shales and limestones that exhibit the greatest landward extent within a set of retrogradational sequences.

Groups of composite sequences build into 'longer-term composite sequences' (LTCS) whose architecture reflects that of the composite sequences that define them. Each LTCS boundary coincides with a composite sequence boundary that denotes a marked shift from dominantly progradational below to overall retrogradational composite sequences above (Figs. 9, 11, 12). Laterally extensive and multistory fluvial sandstones, typically reaching to the basinward margin of the study area, directly overlie LTCS boundaries (e.g., upper boundary of Mo-1 on Fig. 9). Longer-term composite sequences are named for the stage in which the majority of the genetic unit occurs (e.g., Mo = Moscovian).

5.3 Duration of sequences and composite sequences

Durations of sequence and composite sequences were estimated for the Moscovian interval constrained by 6 high-precision ($\leq 10^5$ yr uncertainty) U-Pb ages (Table 2). The estimated average duration of Moscovian sequences is 140 ky with a range of 100 to 230 ky. The average duration of composite sequences is 480 ky with a range of 430 to 600 ky. The average durations fall within the temporal scale of long- (400 ky) and short-term (100 ky) eccentricity (Laskar et al., 1993; 2004), which have been widely recognized in Permo-Carboniferous strata (e.g., Heckel, 1986; Boardman and Heckel, 1989; Maynard and Leeder, 1992; Weedon and Read, 1995; Rasbury et al., 1998; Strasser et al., 2006). Longer-term composite sequences (LTCS) in the U-Pb constrained Moscovian interval have an average duration of 1.6 my (±0.5 my), which is in the range of the long-period modulation of obliquity (~1.2 My) and eccentricity (~2.4 My) (Laskar et al.,1993; 2004). The influence of long period obliquity variations on the waxing and waning of continental ice sheets and glacioeustasy has been called upon for the origin of other Carboniferous depositional sequences of the stratigraphic scale of the Donets LTCS (Elrick and Scott, 2010).

5.4 Comparison to previous stratigraphic studies of the Donets succession

Izart and others (1996, 2003) defined sequences for the Pennsylvanian succession in the Donets Basin using select cores (typically three per formation) from the Makarov dataset (1982; 1985) that, in general, are similar in stratigraphic-scale to the hierarchy of genetic sequences presented here. Within each formation, "4^{th}-order sequences" were defined by Izart and others (1996, 2003) using the stratigraphic occurrence of limestone beds of maximum up-dip extent and channelized fluvial sandstones exhibiting the greatest degree of erosion at their bases. Further classification of stratigraphic packages into sequences of lower or higher order was assigned on the basis of thickness, estimates of duration for each formation, and a presumed duration of stratigraphic orders: 10^4 ky = 5^{th}-order, 10^5 ky = 4^{th}-order, and 10^6 ky = 3^{rd}-order.

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In contrast, the hierarchy of sequences in this study was defined using an expanded set of the Makarov's core logs (206 core logs from 72 well sites versus 3 to 4 sites) including many up-dip cores (n=43) and outcrop sections (n=27). The numerous outcrops and core logs integrated in this study permitted the recognition of the large-scale architecture of genetic packages and onlap-offlap relationships across the Donets depositional ramp. A comparison with Izart and other's (1996) '4th-order' sequences reveals correspondence of fewer than 50% of the composite sequences identified in this study. This disparity is particularly large for the Serpukhovian (13 composite sequences vs. five '4th-order sequences' of Izart et al. (1996)) and Bashkirian (21 vs. their 13). For the remaining Pennsylvanian strata, the difference is moderate (6 to 14%), with the greatest similarity in the Moscovian interval.

Davydov and others (2010) applied Izart and others' 4th-order sequences to calibrate the Pennsylvanian time-scale and assign ages to the associated stage boundaries. This involved applying a 400-ky periodicity inferred from sequence counting between six U-Pb ages in the Moscovian interval. In order to maintain this assumption of the 400-ky (astronomical) tuning of 'fourth-order' sequences throughout the succession, Davydov and others (2010) were required to down- or up-grade a few of the fourth- and fifth-order cycles in the lowermost Moscovian and Kasimovian succession. If their astronomically tuned stage boundaries are correct, durations for our composite sequences range from 423.5 (Serpukhovian) to 454 ky (Moscovian) (Table 2).

Of note, 400 ky-tuning of the thirteen Bashkirian composite sequences of Izart and others (1996; 2003) yields a mid-Carboniferous boundary of 319.8 Ma, which is comparable to the value (318.1 Ma ± 1.3 my) assigned in the Geologic Time-Scale of Ogg and others (2004). In contrast, tuning of the 21 Bashkirian composite sequences defined in this study yields a mid-Carboniferous boundary of 323 Ma, within 200 ky of the recent estimate of 322.8 Ma (Davydov et al., 2010), without requiring upgrading or downgrading of the stratigraphic order of sequences.

6. Donets Basin Onlap-Offlap History

The Donets stratigraphy has long been interpreted to archive relative changes in Carboniferous sea level (Lutigin and Stepanov, 1913; Aizenverg, 1979; Izart et al, 1996). We use the spatial and temporal variations in the three scales of sequences along with lateral tracking of base-level sensitive facies to build an onlap-offlap history for the Pennsylvanian of unprecedented resolution (sub-400 ky) and duration (33 my). Given that a basin's accommodation history and its internal stratigraphic architecture are governed by the interplay of tectonics, sediment supply, sediment and water loading and eustasy, we first evaluate the long-term accommodation history of the Donets Basin.

6.1 Long-Term Accommodation

The unusual thickness of the Carboniferous succession in the Donets Basin has been attributed to high rates of subsidence driven by tectonic reactivation in the region (Izart et al., 2003; Stephenson et al., 2006). Our high-precision U-Pb and biostratigraphically constrained record of long-term accommodation in the Donets Basin (Fig. 2) documents the high rates of subsidence throughout the late Mississippian and Pennsylvanian, consistent with extensional subsidence. Sub-parallel accumulation trends of both up-dip and down-dip locations in the Donets Basin further indicate that subsidence was relatively uniform throughout Pennsylvanian deposition presumably reflecting *regionally* uniform tectonic conditions. Up- and down-dip accumulation trends also indicate the lack of significant unconformities in the succession including at the mid-Carboniferous and the middle to late Pennsylvanian (Desmoinesian-Missourian) boundaries. Moreover, the basinwide continuity of marine limestones and major coals preclude episodic uplift or downdrop in disparate parts of the basin given that active faulting would have resulted in considerably skewed core-log correlations across the basin, which is not the case here. Previous studies have documented that faulting in the Donets Basin had no significant influence on the stratigraphy (Izart et al., 1996; 2003) and distribution of coals (Sachsenhofer et al., in press). Importantly, the rapid accommodation rates in the Donets Basin dampened erosion associated with sequence boundaries, preserving one of the most stratigraphically complete Pennsylvanian successions in the world.

The relatively uniform rates of long-term sediment accumulation across the Donets basin (Fig. 2) further indicate that variations in sediment supply and loading were unlikely a primary influence on stratigraphic and onlap-offlap patterns. We conservatively attribute the driver of stratigraphic architecture to relative sea-level variations at multiple scales given that long-term accommodation in the Donets Basin was undoubtedly influenced by multiple processes including eustasy.

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6.2 Chronostratigraphy and onlap-offlap history

Dip-oriented chronostratigraphic diagrams were constructed for the Visean through Ghzelian succession in the Donets Basin based on the assumption that marine limestones, transgressive sandstones and fluvial sandstones define time-lines that are near-isochronous. In turn, the data from the chronostratigraphic diagrams were used to construct a temporal history of onlap and offlap. Figures 10-12 illustrate the data used in the procedure for select intervals in the Moscovian, the Kasimovian/Gzhelian and the mid-Carboniferous boundary.

Marine limestones, as well as fluvial and transgressive sandstones, are all highly sensitive to changes in base level and shoreline position and thus their maximum up-dip or down-dip extent can be used to define a record of onlap-offlap for the Donets Basin (cf., Kendall and Lerche, 1988; Franseen et al., 1993). The landward-most occurrences of biostratigraphically constrained marine limestones were used as 'pinning points' of maximum onlap. The up-dip limit of transgressive sandstones defines the paleo-shoreline position early in the retrogradational phase of each sequence. The down-dip extent of channelized fluvial sandstones and conglomerates (and paleosols where channelized sands are absent) define the offlap pinning points. The time-distance relationships of these pinning points were used to construct an onlap-offlap record for a 33 my interval of the Visean through Gzhelian (Fig. 13). Given the geographic limits of our database, marine limestones whose most landward positions coincide with the margins of the study area provide minimum estimates of onlap. Accordingly, fluvial sandstones and paleosols at the seaward margin of the study area provide minimum estimates of offlap.

The chronostratigraphy and onlap curve for several Moscovian sequences is shown in Figure 10. The lateral extent of marine limestones and fluvial and transgressive sandstones were plotted as isochronous horizontal lines, with vertical spacing between lines determined by stratigraphic thickness. Pinning points of base-level sensitive facies were plotted along each time-line, marking the position of the paleo-shoreline through time. The blank space between time-lines represents the accumulation of delta-top and marine facies or intervals of non-deposition. The history of onlap and offlap was determined by plotting the stratigraphic and geographic positions of pinning points. In general, each onlap-offlap event corresponds to an individual sequence (cyclothem) with an average duration around 140 ky. In order to show lower frequency onlap events, a five-point running mean was fit to all of the pinning point data. This is the primary curve used in the subsequent discussion and loosely corresponds to the scale of composite sequences (~400 ky).

For Moscovian strata (Fig. 10), twenty-eight onlap events correspond to named sequences Mo-1 through Mo-28. This interval is characterized by relatively subdued onlap, with only a few limestones episodically extending far landward. Sequences and composite sequences are primarily progradational through this interval, suggesting a prolonged phase of sea level lowstand. Figure 11 illustrates the onlap history for the upper Serpukhovian though lower Bashkirian bounding the mid-Carboniferous boundary. Serpukhovian marker limestones show extensive onlap onto the ramp before abruptly shifting seaward just prior to the boundary. Onlap is restricted to the basinward edge of the study area for ~1 my of the lower Bashkirian before extensive flooding of the ramp occurs within sequences Ba-13 and -14. During the lowstand conditions surrounding the boundary interval, fluvial facies are virtually absent and are likely offset far seaward out of the study area. Paleosols become more abundant, suggesting prolonged episodes of subaerial exposure. Figure 12 shows the hierarchy of sequences and the onlap history for the latest Moscovian through earliest Ghzelian. A lowstand in the early Kasimovian is defined by sequence boundaries around composite sequence Ka-II. Onlap characterizes later Kasimovian time, culminating in a brief lowstand at the Kasimovian-Gzhelian boundary and subsequent highstand in the earliest Ghzelian. Individual chronostratigraphic diagrams and onlap histories were stacked to produce the Carboniferous onlap-offlap curve shown in Figure 13.

Several trends and events are illustrated on the Carboniferous onlap-offlap curve (Figs. 13 and 14). Relatively stable sea level during the late Visean (Stage 1 on Fig. 14) is followed by a moderate-magnitude, long-term cycle of onlap and offlap through the Serpukhovian (Stage II). This Serpukhovian onlap is 'stepwise', reflecting the superposition of shorter duration sea-level cycles (~1my ±0.2 my) of moderate magnitude. Long-term offlap through the late Serpukhovian, defined primarily by progradational sequences (Fig. 14), culminates in a significant sea-level lowstand across the mid-Carboniferous boundary of ~1.5 to 2 my duration (Stage III). During the latest Serpukhovian, pinning points of all facies reveal an abrupt basinward shift in sedimentation resulting in sediment bypassing and widespread erosion throughout up-dip regions of the ramp. The mid-Carboniferous lowstand likely was of substantially greater magnitude than suggested by our onlap curve as indicated by the paucity of fluvial sandstones in the down-dip region, suggesting the shoreline migrated far basinward of the eastern limits of our database.

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The Bashkirian is characterized by a ~6 my interval of stable long-term sea level, with multiple higher-frequency, higher magnitude events superimposed (Stage IV on Fig. 14). These short-term sea-level fluctuations are notably regular in their asymmetry and duration (~0.8 myr ±0.1 myr) and are defined by stacks of intercalated retrogradational, aggradational and progradational sequences (Fig. 13). The early Moscovian is marked by stepwise, long-term offlap, culminating in a prolonged lowstand (Stage V on Fig. 14). This sea-level fall (composite sequences Mo-II-VIII) is defined by strongly progradational sequences and the greatest amount of relative offlap for the entire Pennsylvanian in the Donets Basin.

A subsequent long-term (~9 myr), stepwise onlap spans the late Moscovian and Kasimovian, culminating in an earliest Gzhelian highstand (composite sequence Gz-I) (Fig. 13) of maximum magnitude for the Pennsylvanian. Seven to nine shorter-term onlap-offlap events (herein referred to as cycles) of between 0.8 and 1.6 my duration are superimposed on the longer-term onlap and correspond broadly to LTCS Mo-2 through Gz-1 (right column of Fig. 13; Stage VI on Fig. 14). Notably, the extent of offlap associated with each short-term cycle decreases upward through the interval, whereas the landward extent of each short-term onlap increases. Stacks of retrogradational sequences occur throughout the long-term onlap with thin intervals of progradational sequences associated with superimposed prominent short-term lowstands. The early Gzhelian highstand is defined by a landward shift of the shoreline by >200 km in less than 400 kyr. The remaining Gzhelian time is marked by a sharp, stepwise phase of offlap (Stage VII).

7. Discussion: Comparison to other records

Comparison of the Donets onlap-offlap history with other Carboniferous relative sea-level curves provides a test of to what degree variations were eustatic (Fig. 14). The Donets-based curve compares broadly, within the uncertainties of biostratigraphic correlation, with a regional onlap curve derived from the carbonate-dominated succession of the intracratonic Moscow Basin (Alekseev et al., 1996). Apparent disparity between the two onlap curves may be attributed to differences in the techniques used to derive sea-level history and significant difference between the accommodation histories of the Donets Basin (rapid rates and high overall accommodation) and the Russian Platform (slow rates and overall low accommodation) (Izart et al., 2003). For the Visean and Serpukhovian, the curves identify certain major offlap events, but unequivocal correlations are not possible. Although both curves illustrate the mid-Carboniferous lowstand (Fig. 14) it is unconformable only in the Moscow Basin. The overall lower relative sea level of the Moscow Basin during the Bashkirian likely reflects uplift in the basin at that time (Izart et al., 2003). Conversely, the major lowstand during the mid-Moscovian defined by the Donets record is only suggested by a series of high-frequency offlap events in the Moscow Basin. The long-term onlap of the mid-to-late Pennsylvanian is defined in both records (Fig. 14), including the superimposed short-lived sea-level falls of the earliest Kasimovian and mid-Gzhelian, despite a notable decrease in tectonic subsidence in the Moscow Basin during this time (Izart et al., 2003). The similarity between these records in this interval argues for a primary eustatic influence on sedimentation in both basins during the mid-to-late Pennsylvanian.

Recently, Heckel and others (2007) used a succession of conodont faunas to correlate the mid-to-upper Pennsylvanian (307 to 302.5 Ma) cyclothemic succession in the U.S. mid-continent with that of the Donets Basin. Overall the 'major' midcontinent cyclothems in this ~ 5 million-year interval correlate one-for-one with the Donets composite sequences (Fig. 15). Moreover, using these correlations (Heckel et al., 2007), it is apparent that groupings of two to four 'major' cyclothems in the mid-continent correspond precisely to several of the intermediate-scale (0.8 to 1.6 my) onlap-offlap cycles delineated by the time-equivalent portion of the Donets record (cycles 3-7 of Stage VI, Fig. 14). The oldest Midcontinent cyclothems to be correlated biostratigraphically to the Donets Basin are the upper Moscovian Upper Fort Scott and Pawnee and the lowermost Kasimovian Altamont cyclothems (Fig. 15). Their equivalent composite sequences in the Donets succession define the onlap portion of cycle 3 (Fig. 14). Early Kasimovian onlap-offlap cycle 4, which defines the most prominent short-term lowstand on the overall longer-term rise (Fig. 14), corresponds to the Lost Branch and Hertha major cyclothems of the Midcontinent (Fig. 15). These two Midcontinent cyclothems show evidence, including thick incised valley fill deposits, for two major regressive events that have been interpreted as the most substantial withdrawals of the Midcontinent Sea during the mid-to-late Pennsyvanian (Heckel, 2008; Falcon-Lang et al., 2011).

Donets onlap-offlap cycle 5 corresponds to the Swope, Dennis, Dewey and Iola major cyclothems of the Midcontinent succession that in part record a subsequent large magnitude transgression in the Midcontinent Sea (Falcon-Lang et al., 2011) and Northern Appalachian Basin (Best et al., 2011). The mid-Chanute and Nellie Bly incised valley fills underlying the Midcontinent Iola limestone (equivalent to the O4-3H limestone in the Donets) are contemporaneous with the prominent offlap capping cycle 5. Late Kasimovian onlap-offlap cycle 6 corresponds to the Stanton, Cass and

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Oread major cyclothems of the Midcontinent succession (Fig. 15). The major sea-level rise inferred from the Oread cyclothem (Heckel, 2008) is dampened in the Donets record (O6 limestone, Fig. 14). Rather in the Donets succession, the largest magnitude onlap is recorded by the stratigraphically overlying composite sequence and associated marker limestone (O7). The incised valley fills (Stranger and Lawrence sandstones) of the Midcontinent Cass cyclothem (O5 limestone in the Donets) correlate to the moderate-scale short-term sea-level fall within cycle 6. Lastly, early Gzhelian onlap-offlap cycle 7 likely corresponds to the Lecompton, Deer Valley, and Topeka major cyclothems of the Midcontinent, although Heckel and others' correlations do not extend beyond the LeCompton cyclothem.

Comparison of the stratigraphic packages and onlap-offlap history for the Donets with the U.S. Midcontinent succession confirms Heckel and others' (2007) 'digital' correlations and argues for a eustatic driver on deposition in both regions. Recent comparison of a series of time-equivalent Midcontinent and Northern Appalachian Basin cyclothems (Best et al., 2011) documents a common sea-level history for both regions further supporting a eustatic link for the cyclostratigraphy of all three basins. The implications of these correlations and their relationship to the Donets relative onlap-offlap curve are two-fold. Firstly, late Desmoinesian through Virgilian cyclothems developed during a ~9 my period of overall sea-level rise following the prolonged lowstand of the early Moscovian (Atokan). This is consistent with the low- to moderate-amplitudes (20–40 m) of some fluvial incision events inferred from upper Missourian (mid-to-late Kasimovian) through upper Virgilian (mid-Gzhelian) strata (Feldman et al., 2005; Fischbein et al., 2009; cf. Bishop et al., 2010). Secondly, the major cyclothems recognized in the U.S. and time-equivalent composite sequences of the Donets Basin are part of a hierarchy of sea-level fluctuations (from ~100 ky to 0.8 to 1.6 my). This hierarchy of sea-level fluctuations, all within the range of orbital forcing, is superimposed on large magnitude, longer-term (stage-scale) relative sea-level changes. The possibility that the longest-term sea-level changes were also glacioeustatic is addressed in the following section.

7.1 Paleotropical - high-latitude linkages

The seven phases of relative sea-level change inferred from the Donets succession (Stages I-VII, Fig. 14) correspond broadly with the timing of glacial maxima and minima inferred from high-latitude Gondwanan basins. To date, chronostratigraphically well-constrained glacigenic deposits and glacial features are limited to northwestern Argentina (Gulbranson et al., 2010), eastern Australia (Fielding et al., 2008), and southern Africa (Stollhofen et al., 2008). The timing of glaciation in the Parana Basin, Brazil, which may have involved up to nine discrete cycles of glacial advance and retreat (Holz et al., 2008), remains poorly resolved, with estimates ranging from latest Mississippian through Early Permian (Rocha-Campos et al., 2008; Holz et al., 2010).

The two major lowstands inferred from the Donets Basin (mid-Carboniferous boundary and early Moscovian) occur during the only interval in the Pennsylvanian for which widespread glaciation is documented, including the less well dated, oldest glacigenic deposits of the Parana Basin (within the *A. cristatus* palynomorph Zone of late Serpukhovian to early Moscovian range, Cesari et al., 2011). The oldest Parana diamictites are capped by extensive (10s of km long and 100s of m thick) incised-valley fills (Vila Velha-Lapa sandstones) that are unique to the Parana Permo-Carboniferous succession (Camp-Rochas et al., 2008; Holz et al., 2008). This suggests that ice buildup may have been greatest in this region of Gondwana during the latest Mississippian and early Pennsylvanian. The superposition of short-term, high magnitude fluctuations on the relatively stable yet overall higher sea-level of the Bashkirian may suggest a post-mid-Carboniferous decrease in ice sheet expanse or could reflect a period of unrecognized increased subsidence in the Donets Basin. Recent climate simulations of the Late Paleozoic Ice Age reveal that only moderate-sized ice sheets (as opposed to large ice sheets) could wax and wane at a scale capable of driving eustatic fluctuations of the magnitude inferred from the Bashkirian and mid-to-late Pennsylvanian intervals of the Donets onlap-offlap curve (Horton et al., 2007; Horton and Poulsen, 2009).

Notably, the stepwise long-term onlap through the later half of the Moscovian and Kasimovian (Stage VI) coincides with the interval for which chronostratigraphically well-constrained high-latitude successions indicate the restriction of ice sheets to one or possibly three discrete intervals in the Kalahari-Karoo (Stollhofen et al., 2008) and Parana (Holz et al., 2008) basins. The current uncertainty in age of the older deglaciation sequences in southern Africa (DS-1 & 2 on Fig. 14) and of diamictites in the Campo Mourao Fm., Parana Basin (hachured blue bar on the far right of Fig. 14) precludes further evaluation of their temporal relationship to Donets onlap-offlap events (Stollehofen et al., 2008; Campo-Rochas et al., 2008; Holz et al., 2010). The culminating earliest Gzhelian transgression, of the largest magnitude in the Donets record, may record contraction of the ice sheets in the late Pennsylvanian. The ensuing mid-Gzhelian sea-level fall, of magnitude equivalent to that of the mid-Carboniferous lowstand, suggests the renewed buildup of ice sheets before the close of the Carboniferous.

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If prominent lowstands inferred from the Donets succession were glacioeustatic, then they reveal a Carboniferous glaciation history analogous to that of the Cenozoic icehouse. We hypothesize that the transition from the relatively deglaciated climate state of the Mississippian to one of major ice sheets in southern Gondwana occurred stepwise through a series of short but increasingly longer-lived glaciations over a six million year period (330 to 324 Ma). Three of the four glaciated periods leading up to the mid-Carboniferous event (i.e., offlaps of Stage II, Fig. 14) occurred within one composite sequence (< 400 ky). This behavior of ice sheet growth is analogous to the early Cenozoic initiation of the Antarctic ice sheet (Coxall et al., 2005; Liu et al., 2010) suggesting that the stepwise buildup of the Carboniferous ice sheets could record the role of orbitally forced climatic preconditioning across a climate threshold (cf., Palike et al., 2006). The superposition of this series of brief glaciations on the longer-term moderate sea-level rise of the Serpukhovian further suggests instability in the climate system during the late Mississippian icehouse-to-greenhouse transition.

A reciprocal trend in ice volume to the inferred latest Mississippian stepwise building of ice sheets is suggested by a series of increasingly shorter lived and lower magnitude short-term lowstands superimposed on the mid-to-late Pennsylvanian sea level rise (Stage VI, Fig. 15). The inferred stepped buildup and contraction of Pennsylvanian ice sheets could record the stepwise development and breakdown of specific ice centers possibly involving climate threshold behavior associated with ice sheet hysteresis analogous to that of the early Cenozoic icehouse.

7.2 Global climate linkages

A shift from humid to semi-arid climates across the paleotropics during the mid-to-late Pennsylvanian has long been noted in sedimentologic and paleobotanical records (Phillips and Peppers, 1984; West et al., 1997; Hilton and Cleal, 2007; Kabanov et al., 2010), and more recently has been documented in high-latitude Gondwanan basins (Gulbranson et al., 2010). This period of widespread aridification coincided with a progressive restructuring of paleotropical floral ecosystems involving a shift from lycopsid- to tree fern-dominance in wetland habitats throughout Euramerica (Gastaldo et al., 1996; DiMichele et al., 2001; 2009; Cleal and Thomas, 2005) including the Donets Basin (Schegolev, 1975; Sachsenhofer et al, 2003). The cause of aridification, however, is less well understood, having been attributed to tectonic drift out of the paleotropics (Bless et al., 1984), tectonically induced changes in regional precipitation and drainage patterns (Rowley et al., 1985; Besly, 1987; Hilton and Cleal, 2007), an intense short-lived glaciation (Falcon-Lang et a., 2011), and global warming, in particular in the high-latitudes (Gonzalez, 1990; Durante, 1995), the latter being possibly greenhouse-gas forced (Cleal et al., 1999; DiMichele et al. 2009).

The stratigraphic distribution and aerial extent of coals and bedded evaporites in the Donets succession (Fig. 14) when compared to the onlap-offlap history provides insight into the temporal relationship between the regional climate and inferred glacioeustasy. Coal distribution indicates that everwet conditions, required to sustain peat-forming mires, were rapidly established in the region coincident with the onset of the Serpukhovian series of short-lived, high-magnitude onlap-offlap cycles and the inferred ephemeral glaciations. Peat-forming flora and humid conditions in the Donets Basin reached their acme during the inferred period of maximum development of Pennsylvanian ice sheets (Bashkirian through early Moscovian; Fig. 14). In the Donets Basin, the progressive decrease in coal extent and abundance, beginning in the middle Moscovian, coincided with the abrupt onset of bedded evaporate deposition and the turnover from protracted lowstand conditions of the early Moscovian (Stage V) to the onset of the long-term stepwise onlap and inferred contraction of Pennsylvanian ice sheets (Stage VI on Fig. 14). A penecontemporaneous shift from humid to semi-arid and more seasonal climate is recorded in several central European (Roscher and Schneider, 2006) and North American (Cecil et al., 2003; DiMichele et al., 2009) basins delineating the widespread geographic extent of this climate change. Late Paleozoic climate simulations (Poulsen et al., 2007; Horton et al., 2010) provide insight into this apparent high-low latitude climate linkage. These Pangaean simulations indicate a notable decrease in mean-annual precipitation and vegetation coverage over the continental tropics when atmospheric $p\mathrm{CO_2}$ rises from levels conducive to building and sustaining large ice sheets (≤560 ppmv) to CO_2 levels that lead to ice sheet contraction (<840 ppmv). Furthermore, these models reproduce the west-to-eastward progression in aridification revealed by paleotropical records (Cecil et al., 2003; Montañez et al., 2008; Bishop et al., 2010).

Higher frequency variations in the Donets coal and evaporite trends define shorter-term climate changes that correspond closely to the intermediate-scale onlap-offlap cycles superimposed on the mid-to-late Pennsylvanian rise (cycles 1-7 of Stage VI on Fig. 14). At the intermediate-scale (~0.8 to 1.6 my), wetter periods inferred from intervals dominated by widespread development of coals correspond to lowstands, whereas drier climate inferred from

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intervals dominated by evaporites correspond to times of onlap. Feldman and others (2005) inferred a wet-dry climate cycle of similar temporal scale (~1 my) and relationship to sea-level from eight Midcontinent cyclothems corresponding to onlap-offlap cycle 6 in the Donets succession. They interpreted these intermediate-scale climate shifts as the primary control on development of incised valley networks and sediment flux in the Midcontinent region. Analogous (1 to 2 my) wet-dry cycles, characterized by a successive increase in the duration and intensity of the dry portion of each cycle, are recognized superimposed on the long-term Pennsylvanian aridification in several central and eastern Euramerican basins (Oplustil and Cleal, 2007). A linkage between mean-annual precipitation, seasonality and glacioeustasy is further suggested at the cyclothem-scale (100 to 400 ky). The stratigraphic position of 'everwet' coals between Vertisols (some calcic) and incised valley-filling fluvial sandstones, which formed during the buildup of ice sheets and sea-level drawdown, and transgressive marine limestones, which formed during deglaciation, suggest a turnover from seasonal sub-humid or semi-arid climate to everwet conditions *during* the glacial interval once maximum ice accumulation and the eustatic lowstand were reached. Taken together, these cyclothem-scale and intermediate-duration climate cycles suggest a likely teleconnection between high-latitude ice sheet behavior and low-latitude atmospheric dynamics - one that diverges from the 'arid glacial-humid interglacial' climate interpretations of some Carboniferous cyclothems (e.g., Tandon and Gibling, 1994; Falcon-Lang et al., 2009; 2011).

8. Summary

A hierarchy of stratigraphic sequences is recognized in the Carboniferous paralic succession of the Donets Basin on the basis of stratigraphic stacking patterns and basinwide architecture of marine to terrestrial facies assemblages. Documented shifts in base-level sensitive facies across 250 km of the depositional ramp define a 33 my record of onlap-offlap, resolved at the sub-400 ky scale, that includes superimposed short- and intermediate-scale fluctuations that fall within the Milankovitch frequency band. Comparison of Donets cyclothems with time-equivalent paleotropical successions and evidence for a relatively uniform subsidence history for the Donets Basin during the Pennsylvanian argues for a predominant eustatic influence on the onlap-offlap history.

Major lowstands and highstands inferred from the Donets succession correspond broadly with the timing of glacial maxima and minima inferred from the distribution of glacigenic deposits in high-latitude Gondwanan basins. Together, these records indicate a dynamic late Paleozoic sea-level and glaciation history characterized by stepped buildup and contraction of ice sheets, two intervals of early Pennsylvanian lowstand and maximum glaciation, and a protracted stepwise rise driven possibly by contraction of ice sheets during the mid-to-late Pennsylvanian.

The stratigraphic and aerial distribution of coals and evaporites in the Donets succession document a temporal relationship to inferred sea-level events at multiple time-scales. A shift from coal to evaporite dominance, interpreted to record the onset of aridification in the region, was coincident with the beginning of the inferred stepwise sea-level rise in the mid-to-late Pennsylvanian. Shorter-term variations in coal and evaporite distribution define higher frequency climate shifts that correspond to the intermediate-scale onlap-offlap cycles (~0.8 to 1.6 my) superimposed on the long-term sea-level rise. At this scale, wetter periods inferred from intervals dominated by widespread development of coals correspond to lowstands, whereas drier climate inferred from intervals dominated by evaporites correspond to times of onlap. Within Donets cyclothems, the stratigraphic position of coals and paleosols indicate a turnover from seasonal sub-humid or semi-arid climate to everwet conditions during the late lowstand once ice sheets reached their maximum accumulation. At all time-scales, inferred climate-glacioeustatic relationships suggest the existence of a mechanistic linkage between Pangaean tropical continental climate and high-latitude ice sheet dynamics.

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10. Figure Captions

Figure 1. Geographic (A), paleogeographic (B), and geologic (C) setting of the Donets Basin. (A) Rectangle outline delineates region shown in C. (B) Mollweide projection for ~300 Ma from Blakey (2008); circle is Donets Basin position and white dashed line is the paleoequator. (C) Study area (white rectangular outline) in Dnieper-Donets aulacogen (horizontal lined pattern).

Figure 2. Long-term cumulative accommodation curves for the Donets Basin. Curves defined using up-dip (light gray trendline) and down-dip cores (black trendline); see Fig. 3 for locations of wells. Age control based on high-precision ID-TIMS U-Pb dates on zircons obtained from tonsteins (diamonds) and biostratigraphy (circles) of major limestones in the Donets succession.

Figure. 3. Geologic map of study area showing locations of field sites (open squares) and subsurface cores (filled circles), including those used for up-dip (open circles) and down-dip (crosshatched circles) subsidence analysis. Transect line used to build across-depositional dip sections shown in Figs. 6, 9-12. Solid and dashed tie-lines show position of outcrop sections and core logs on transect line.

Figure 4. Correlation of Kalinovo (KV) field section with the 'C. Kalinovo' core drilled ~4 km to the NE of the field site. Tie lines correlate major limestones (upper case "O" with numbers) and coals (black bands in delta-top facies denoted by lower case 'o' and numbers). "A" through "F" to the right of the C. Kalinova core log correspond to photographs in Fig. 5.

Figure 5. Field photographs of representative lithofacies, Donets Basin. (A) Laminated and fissile mudstones: marine facies assemblage; hammer handle for scale. (B) Wavy, nodular-bedded carbonate mudstone/wackestone: marine facies assemblage. (C) Planar-tabular cross-bedded sandstones with intercalated laminated to thinly bedded siltstones and fine-grained sandstones: marine facies assemblage. Scale bar is 30 cm. (D) Silty, laminated mudstones with coaly partings and overlying intercalated, ripple-laminated siltstones and fine-grained sandstones: delta-top facies assemblage. (E) Cross-bedded fluvial sandstones; eroded base of channelized sandstone at waist level: terrigenous facies assemblage. (F) Polymict pebble conglomerate with fine-grained arkosic matrix; basal fluvial lag: terrigenous facies assemblage.

Figure 6. Cross-platform correlation of Gzhelian and Moscovian decameter-scale cyclothems based on biostratigraphically constrained major limestones (P4, M7, M8) and coals (m5-3, m6-2; coals shown as black bands). Upper transect exhibits progradational architecture for two evaporite-bearing Gzhelian cyclothems; lower transect shows down-dip seaward thickening of two retrogradational Moscovian cyclothems. SB = sequence boundary; MFS = maximum flooding surface; TS = transgressive surface.

Figure 7. Typical Pennsylvanian cyclothem types, Donets Basin. Up-dip and down-dip positions of correlated cyclothems illustrate cross-ramp variations in the facies assemblages (FA) of the three types of cyclothems: retrogradational (Serpukhovian C interval), aggradational (Bashkirian G interval), progradational (Moscovian K (lower) and Gzhelian P (upper) intervals).

Figure 8. Depositional model for sequence development during a relative sea-level (base-level) cycle, Donets Basin. (A) Paleosol formation, fluvial incision, and progradational fluvial deposits associated with accommodation minima and early stage of eustatic lowstand (black region on curve). Subaerial exposure associated with development of the sequence boundary (SB) can span the period from onset of forced regression following the highstand peak to the sea-level minimum. (B) Aggradational coastal plain developed during landward retreat of river systems due to increasing accommodation provided by the compound effects of slowing rate of sea-level fall and subsidence (late lowstand; black region on curve). (C) Retrogradational marine-dominated system associated with peak accommodation during eustatic rise (TS to MFS). Following C, an aggradational-to-progradational deltaic system comparable to phase B developed during progressively decreasing rates of accommodation of the highstand.

Figure 9. Sub-seismic scale cross-sections of Moscovian sequences and composite sequences constructed across ~225 km of the Donets depositional ramp. Upper cross-section of strata between the M1 and L1 limestones; lower cross-section of strata between the L1 and K1 limestones. Composite sequence boundaries (bold black lines) are characterized by widely developed incised surfaces and paleosols. Widths of individual facies on the stratigraphic column represent their lateral extent across the Donets ramp. Sets of sequences build into 'composite sequences' which further build into 'long-term composite sequences.'

Figure 10. Chronostratigraphy (B) and onlap-offlap curve (C) for Moscovian sequences and composite sequences of the K1-M1 interval (A) shown on Fig. 9. (B) Horizontal bars show lateral extent of fluvial sandstones, marine limestones and transgressive sandstones. Symbols show up-dip and down-dip positions of pinning points, described in text. (C) Best estimate of onlap history shown by 5-point running mean of pinning points (bold trendline); muted fine trendline connects all pinning points.

Figure 11. Sequence stratigraphy, chronostratigraphy, and onlap-offlap curve for the mid-Carboniferous boundary interval drawn down-dip (left to right) across ~150 km of the Donets depositional ramp. (A) Cross-section drawn for strata between the D1 and E1 limestones. Mid-Carboniferous boundary shown as heavy dashed line. Strata adjacent to and on top of the paleotopographic high are erosionally truncated at the boundary. Tie-lines between cross-section and chronostratigraphic diagram and temporal positions of key facies and pinning points on chronostratigraphic diagram as for Fig. 10. (C) Best estimate of Serpukhovian-Bashkirian onlap-offlap history shown by same line patterns as in Fig. 10.

Figure 12. Sequence stratigraphy, chronostratigraphy, and onlap-offlap history for the uppermost Moscovian to lower Gzhelian interval drawn down-dip (left to right) across ~200 km of the Donets ramp. (A) Upper cross-section of strata between the O1 and P1 limestones; lower cross-section of strata between the N1-8 and O1 limestones (note overlap between cross sections). (B) Tie-lines, horizontal bars and pinning points on chronostratigraphic diagram as for Figs. 10 & 11. (C) Best estimate of Moscovian to early Gzhelian onlap-offlap history.

Figure 13. Upper Carboniferous relative sea level curve and relationship to cyclothem types, limestone marker beds, and hierarchy of sequences. Generalized stratigraphic column keyed to Figs. 9-12. Time-scale of Davydov et al. (2010) with most recent estimates of Pennsylvanian North American stage boundaries (M. Schmitz and V.I. Davydov, unpublished data); position of ID-TIMS U-Pb ages from Donets tonsteins shown on 'Russian Stages' column. Cyclothem type defined on the basis of four or more consecutive sequences. Best estimate of relative sea-level (5-point running mean) shown by trendline. Gray shading indicates geographic edge of the dataset used in this study. Position of limestone marker beds on relative sea-level curve indicated by red dashed lines. Light and bold gray tie lines link individual composite sequences and longer-term composite sequences to excursions on the curve, respectively.

Figure 14. Donets onlap-offlap history correlated to Moscow Basin curve (Alekseev et al., 1996), temporal and spatial distribution of coals and evaporites in the Donets succession, and best estimates of ages of high-latitude glaciations. Time-scale, U-Pb ages, limestone marker beds, and trendline as in Fig. 13. Blue shading indicates periods during which offlap extended past the '100 km' point on the Donets transect; blue hachured interval delineates period of stable higher sea-level with superimposed third-order lowstands that extend beyond the 100 km point on the Donets ramp. Sea-level stages (I-VII and intermediate-scale cycles (1-7 in Stage VI) as discussed in text (Section 6.). Coal and evaporite abundance shown as: 1 = present across 1-15 km of Donets depositional ramp; 2 = present across 16-50 km; 3 = present across 51+ km. Blue bars and vertical lines on far right are estimates of duration and uncertainties, respectively, of glacial periods in northwestern Argentina (Gulbranson et al., 2010), eastern Australia (Fielding et al., 2008), Kalahari-Karoo Basin, southern Africa (Isbell et al., 2008; Stollenhofen et al., 2008) and Parana Basin, Brazil (Holz et al., 2008; 2010; Rocha-Campos et al., 2008) as well as of sea-ice development in the high northern paleolatitudes of Siberia (Epshteyn, 1981). The Permo-Carboniferous succession of the Parana Basin records up to nine cycles of glacial advance-retreat (Holz et al., 2008) grouped into three glacial periods represented by the dark blue bars. No connotation of absolute duration is represented by the length of dark blue bars with unconstrained uncertainties (denoted by a '?'; see Section 7 for details). Hachured bars indicate poorly constrained temporal distribution of ice sheets within that interval.

Figure 15. Heirarchy of Donets sequences and their correlation to previous studies and Midcontinent cyclothems. Stratigraphic section shown for interval of correlated Donets and Midcontinent successions. Limestone marker beds and Donets sequences (right side) presented as 'major', 'intermediate', and 'minor'. 'Major' cyclothems are defined in the Midcontinent succession by the presence of widespread deeper-water conodont-rich shales and associated limestones; 'minor' cyclothems are marine beds of lesser extent that represent a reversal of sea-level trend, usually within a larger marine unit (Heckel, 1994). Limestones in sequences not formally named by Makarov (1982; 1985), shown in brackets, are coded to the nearest underlying limestone with a 'b' suffix. Gray dashed tie-lines indicate Heckel et al.'s (2007) correlation of Donets limestone marker beds to the Midcontinent cyclothems. Gray shading delineates the grouping of Donets sequences into composite sequences (this study), and the proposed equivalence to Midcontinent 'major', 'intermediate', and 'minor' cyclothems. Superscript '+' indicates the presence of additional minor cyclothems in the Midcontinent record and '*' denotes less confident correlation between the two regions (Heckel, 2008; Heckel et al., 2007). Comparison of cyclothem groupings of the two regions and the Donets onlap-

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offlap history suggests at least 15 additional correlations between cyclothems of the two regions that were not directly correlated by Heckel et al. (2007). Comparison to Izart et al's (1996; 2003; 2006) composite sequences and elementary sequences shown to the right. Bold gray lines bracket LTCS defined in this study.