Choice of conodont *Idiognathodus simulator* (*sensu stricto*) as the event marker for the base of the global Gzhelian Stage (Upper Pennsylvanian Series, Carboniferous System)

We propose that the level at which the conodont species *Idiognathodus simulator* (Ellison 1941) (*sensu stricto*) first appears be selected to mark the base of the Gzhelian Stage, because we believe that this is the optimal level by which this boundary can be correlated. This taxon has a short range and a wide distribution, as shown by correlation of glacial-eustatic cycloths across the Kasimovian-Gzhelian boundary interval among Midcontinent North America and the Moscow and Donets basins of eastern Europe, based on scale of the cycloths along with several aspects of biostatigraphy. Outside of these areas, *I. simulator* (*sensu stricto*) is known also from other parts of the U.S., and is reported from the southern Urals and south-central China in its expected position between other widespread taxa. Its first appearance is consistent with the current ammonoid placement of the boundary (first appearance of *Shumardites cuvleri*), and it is also compatible with certain aspects of the distribution of Eurasian fusulinid faunas (e.g., lectotype of *Rausertites rossicus*).

**Introduction**

The Gzhelian Stage is the latest stage of the Pennsylvanian Subsystem and the Carboniferous System. The stage names originating in Russia are now used for the global stages of the Pennsylvanian because most aspects of their fusulinid faunas are similar enough at the generic level that these stages have been readily recognized across much of Eurasia, in contrast to the strongly provincial North American fusulinid faunas. However, on account of this general provinciality of the fusulinid faunas, conodonts are being utilized to mark the events that will be used to define the global stages within the Pennsylvanian, because some of their species are more widespread globally than those of the fusulinids. One such conodont is *Idiognathodus simulator* (Ellison 1941) (*sensu stricto*), which was named from Midcontinent North America, and is reported from the Moscow Basin of the Russian Platform (Barskov and Alekseev, 1975; Barskov et al., 1980), the Donets Basin of Ukraine, the southern Ural Mountains of Russia (Chernykh et al., 2006a, b; see also Heckel et al., 2005, 2007) at or near the classic base of the Gzhelian Stage, and in Guizhou Province in south-central China (Wang and Qi, 2002, 2003).

**Evolution of the base of the Gzhelian Stage**

The Gzhelian Stage was named by Nikitin (1890) from the village of Gzhe ~60 km east of Moscow, where it consists of an alternating succession of carbonates, shales, and sandstones. Its base was first defined by brachiopods, then variously recognized by different workers at the first appearance of the fusulinids *Rausertites stuckenbergii* (Rauser-Chernousouva 1938) and/or *R. rossicus* (Schellwien 1908) (see Ivanova and Rozovskaya, 1967). Later, Barskov and Alekseev (1975) and Barskov et al. (1980) proposed the conodont *Idiognathodus simulator*, which occurs with *R. rossicus* at Gzhe, to mark the base of the Gzhelian in the Moscow Basin, and more recently it has been used for this purpose in the southern Urals (see references in Chernykh et al., 2006a, b). Most recently, *I. simulator* has received close attention as the potential event level for the base of the global Gzhelian Stage (Villa and Task Group, 2005; Boardman et al., 2006), both because of its nearly pantropical distribution and because it appears at a level that is consistent with the ammonoid boundary (Bogoslovskaya et al., 1999; Boardman and Work, 2004).
Characteristics of *I. simulator* (sensu stricto)

Although originally named as a member of the troughed form genus *Streptognathodus* by Ellison (1941) and still regarded as such by some workers (e.g., Chernykh, 2005), this species is now regarded by many workers as a grooved descendent of similarly finely ridged species of *Idiognathodus* that dominate the deeper-water parts of middle and late Missourian (Kasimovian) cyclothems rather than of type *Streptognathodus* from the same strata (Barrick et al., 2004). The taxonomy of a lineage believed to lead to *I. simulator* (s.s.) in the southern Urals has recently been published by Chernykh (2005) and Chernykh et al. (2006a, b), who suggest an evolutionary succession at the Usołka section, from *I. praenuntius* (Chernykh 2005) in bed 4–1 through *I. simulator* in bed 4–2 to *I. auritus* (Chernykh 2005) in bed 5, in which *I. praenuntius* is considered its ancestor. Although the new taxa are defined only by dextral platform elements, Chernykh et al. (2006b) illustrated sinistral elements of *I. simulator* (s.s.).

Recent study in Midcontinent North America (Barrick, Heckel, and Boardman, 2008) shows that *I. simulator* (s.s.) is characterized by a distinctly asymmetrical pair of sinistral and dextral Pa elements (Figure 1). The holotype, from the Heebner Shale of the Oread cyclothem (Figure 2), is the more distinctive sinistral element (Figure 1, specimen 5). This element is more strongly curved inward (caudally) such that the reverse ridges are at an oblique angle to the line of the blade, with a strongly eccentric groove close to the inner (caudal) margin. The adcarinal ridges are short and flare outward away from the carina and blade in the anterior (ventral) direction. The dextral element (Figure 1, specimen 6) is straighter with a less well developed eccentric groove, but the adcarinal ridges are similarly short and flaring outward away from the blade. The probable ancestor to *I. simulator* (s.s.) was termed *I. aff. simulator* by Barrick et al. (2004), and is now named *I. eudoraensis* by Barrick, Heckel and Boardman (2008). It has a less asymmetrical pair of Pa elements in which the sinistral element is much less curved inward (caudally), and both elements have longer adcarinal ridges that run parallel to the blade rather than flare outward (Figure 1, specimens 1, 2). *I. eudoraensis* dominates the Eudora Shale of the second major cyclothem [Stanton] below the Oread cyclothem, which contains the holotype and first appearance of *I. simulator*. Rare specimens that appear transitional from *I. eudoraensis* to *I. simulator* occur in the Greta Shale (Figure 1, specimen 3; dextral only) of the South Bend intermediate cyclothem and the Little Pawnee Shale (Figure 1, specimen 4) of the major Cass cyclothem between the Stanton and Oread cyclothems (Figure 2). Although Chernykh et al. (2006b) stated that *I. aff. simulator* (now *I. eudoraensis*) most probably belongs to *I. praenuntius*, this cannot be certain until the more distinctive sinistral element is studied. It is possible that *I. praenuntius* is a transitional species distinct from both North American species, considering that *I. eudoraensis* first appears in the Stanton cyclothem, 4 major to intermediate cyclothems and about 100 m below the first appearance of *I. simulator* in the Midcontinent, whereas *I. praenuntius* first appears only 20 cm below the first appearance of *I. simulator* at Usolka in the southern Urals (Chernykh et al., 2006b).

Value of *I. simulator* for global correlation

Across central North America from Texas through the Midcontinent to Illinois, *I. simulator* (s.s.) appears within a consistent homotaxial succession of conodont species above a likely ancestor *Eudoraen- sis* (Boardman et al., 2006). Accompanying *I. eudoraensis* in the Stanton (Midcontinent), Merriman-Upper Winchell (Texas) and Little Vermillion (Illinois) cyclothems is the first appearance of *Streptognathodus firmus* Kozitskaya 1978, followed by upward *S. pawhuskaensis* (Harris and Hollingworth 1933) in the South Bend and Lower Ranger (Texas), then *S. zethus* Chernykh and Reshetkova 1987 in the Cass (Midcontinent) and Omega-Bonpas (Illinois), (not yet certain in the Colony Creek in Texas), which marks the base of the regional Virgilian Stage (Figure 3). *I. simulator* (s.s.) appears above *S. zethus* in the Oread (Midcontinent), Finis (Texas), and Shumway (Illinois) cyclothems and is followed upward by co-occurrence of *L. tersus* Ellison 1941 and *S. ruzhencevi* (Kozur 1976) in the Lecompton (Midcontinent), Necessity (Texas), and Bogota (Illinois) cyclothems. The ammonoid succession is strongly consistent with the conodont succession in the Midcontinent and Texas, where the ancestral shumarditid *Pseudaktubites stainbrooki* (Plummer and Scott 1937) and *Vidrioceras conlini* Miller and Downs 1950 appear with the first appearance of *S. zethus* in the Cass, and in the Lower Colony Creek at the base of the regional Virgilian Stage (Figure 3). Above this, *V. uddeni* Böse 1919 appears with *I. simulator* in both the Oread and Finis, along with the earliest *Shumardites* (*S. cuyleri* Plummer and Scott 1937) accompanying it in the Finis (Boardman et al., 1994; Boardman and Work, 2004). The first occurrence of these two ammonoids along with *I. simulator* in the Finis Shale is a key point for global correlation because the evolving ammonoid zonation initiated by Ruzhencev (e.g., 1965) regarded the appearance of these two genera to characterize the *Shumardites-Vidrioceras* Genozone, which now corresponds to the base of the Gzhelian Stage (Bogoslovskaya et al., 1999; Boardman and Work, 2004). The appearance of the older ammonoids with *S. zethus* defines the *Pseudaktubites stainbrooki-Vidrioceras conlini* Subzone (emended from Boardman and Work, 2004), which lies at the base of the regional Virgilian Stage. In both the Moscow and southern Urals region of Russia, *I. simulator* occurs above *S. zethus* and below *S. vitali* Chernykh 2002. We recognize that the two cyclothems of lesser scale in the Midcontinent (Amazonia, Toronto) and Texas (Upper Colony Creek, Vermilion Creek) below the Oread cyclothem (in which *I. simulator* and its accompanying ammonoids occur) and above the Cass-Lower Colony Creek cyclothem (in which *S. zethus* and its accompanying ammonoids occur) lack the

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**Figure 1** Photographs (25X) of Pa elements of *Idiognathodus simulator* (Ellison 1941) (sensu stricto) and related forms from older units in Midcontinent North America (see Figure 2 for stratigraphic position).

1. *Idiognathodus eudoraensis* [sinistral, holotype of new species], Eudora Shale of Stanton cyclothem, Oklahoma.
2. *Idiognathodus eudoraensis* [dextral], Eudora Shale of Stanton cyclothem, Kansas.
3. *Idiognathodus eudoraensis* [dextral, probably transitional to *Idiognath-odus simulator*], Grotna Shale of South Bend cyclothem, Kansas.
4. *Idiognathodus eudoraensis* [sinistral, transitional to *Idiognathodus simulator*], Little Pawnee Shale of Cass cyclothem, Kansas.
5. *Idiognathodus simulator* [sinistral, holotype], Heebner Shale of Oread cyclothem, Kansas.
6. *Idiognathodus simulator* [dextral], Heebner Shale of Oread cyclothem, Nebraska.

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in all regions. Correlation of the Oread with the deeper water facies in which these taxa are typically found, but this problem is inherent on shelves in the strongly...

Figure 2  Middle Missourian through early Virgilian major (upper case) and intermediate (lower case) cyclothem succession in Midcontinent North America, and correlative cyclothems elsewhere, showing stratigraphic occurrences (in bold face) of Idiognathodus simulator (s.s.), its probable ancestor, I. eudoraensis, transitional forms, and related species (in bold face). Also shown are units containing its possible precursors, the I. magnificus lineage in North America and I. toretzianus in eastern Europe. See Figure 3 for detail on correlation. Simulator group lineages seem to have non-continuous occurrences, because they are confined to offshore facies, which occur only in major cyclothems and one intermediate cyclothem, all of which are separated from one another by disconformities in Midcontinent, Moscow, and Donets basins. Cyclothems are not recognized in southern Urals at Usolka section, where other species related to I. simulator have been described by Chernykh (2005).

deep water facies in which these taxa are typically found, but this problem is inherent on shelves in the strongly glacial-eustatically controlled cyclic succession in this part of the Pennsylvanian.

Basis for correlation of cyclothems
In the revised ICS guidelines for establishing global chronostratigraphic boundaries, Remane et al. (1996) emphasized that correlation of the strata encompassing a boundary interval must precede the definition of the boundary by the marker event of optimal correlation potential selected for establishing a GSSP. The generally acknowledged difficulty in global correlation of Pennsylvanian strata because of geographic provincialism is now being alleviated by recognition of the general glacial-eustatic control over the marine cyclolithems separated by terrestrial deposits and exposure surfaces that characterize Pennsylvanian stratigraphy in shelf regions. The Middle to Late Pennsylvanian succession of widespread marine cyclothems recognized in the Midcontinent has been correlated across large parts of the United States (Boardman and Heckel, 1989; Heckel, 1994, 2002; Ritter et al., 2002), using the distinctive successions of conodont faunas within the successive cyclothems (Barrick et al., 2004). Recognizing the global control of glacial eustasy, modern Russian stratigraphers have now identified the exposure surfaces separating cyclothems in the Moscow region and have begun to correlate the cyclothems across the Russian Platform (e.g., Kabanov, 2003; Kabanov and Baranova, 2007). Cyclothems can also be recognized in the Donets Basin of Ukraine and adjacent Russia, where marine carbonates and shale alternate with terrestrial clastics and coal. Recent progress in working out the conodont successions in North America (Barrick et al., 2004) and eastern Europe (Goreva and Alekseev, 2006; Alekseev and Goreva, 2007) has shown that while a fair amount of provincialism exists, there are levels where distinctive taxa are found across most of these regions. Therefore we have established a correlation of the glacial-eustatic cyclothems across the Kasimovian-Gzhelian boundary interval among these regions where they are recognized (Heckel et al., 2007), and compared it with the biostratigraphic succession in the western slope of the southern Urala where the distinctive sinistral element of I. simulator has been illustrated by Chernykh et al. (2006b), but cyclothems are not yet recognized.

To establish the most reasonable correlation, the following assumptions of Heckel et al. (2005, 2007) apply: [1] Because they are glacial-eustatic, the scale of each cyclothem, that is, its relative lateral extent and water depth attained, should be roughly the same globally compared to that of the adjacent cyclothems. This assumes that local differential tectonism acts too slowly (1–2 m.y.) to mask the pattern in the more frequent fluctuations in sea level (20–400 k.y.) that resulted in the particular succession of major, intermediate and minor cyclothems, which is well documented in Midcontinent North America and correlated into Texas (Boardman and Heckel, 1989) and the Illinois and Appalachian basins (Heckel, 1994, 1999, 2002). This should be true for the cratonic Midcontinent and Russian Platform, but may be less so in the Donets Basin where tectonic forces may have affected the strata during deposition in the aulacogen. [2] Major cyclothems with the greatest lateral extent of marine facies and the deepest-water facies on the shelves should be the most readily correlated, both because they contain deeper-water fossils as well as shallow-water fossils, and because they would have allowed the greatest interchange of conspecific organisms across the inundated shelves of the pantropical realm. [3] Conodonts and ammonoids are the primary fossils used to correlate the cyclothems because they were likely largely pelagic, whereas the benthic and more provincial fusulinids are used only secondarily. [4] Major cyclothems are recognized in the Midcontinent by means of their conodont-rich dark phosphatic shale facies that resulted from water deep enough and far enough from shoreline to significantly reduce detrival dilution. Major cyclothems are recognized in the Moscow Basin of the Russian Platform and in the Donets Basin also by means of greatest conodont abundance, which similarly reflects decreased sediment dilution in the deepest-water facies. In the Moscow Basin these facies are often shaly limestones (sometimes with tempestite beds) in contrast to the adjacent purer, shallower-water limestones (Kabanov et al., 2006). In the Donets Basin, these facies are usually in the non-algal limestone beds.

Correlation of cyclothems across Kasimovian-Gzhelian boundary interval
Using these guidelines, and including the north-central Texas succession for its ammonoid information, the following correlations are made across the Kasimovian-Gzhelian boundary interval (Figure 3): The major North American Midcontinent Oread cyclothem and Texas Finis cyclothem are correlated with the major Upper Rusavkino cyclothem of Russia and Donets Basin Limestone O., based on the first appearance of the distinctive conodont Idiognathodus simulator (s.s.) in all regions. Correlation of the Oread with the Finis cyclothem is strongly supported by the first appearance of the ammonoid Vindriceras uddeni in both (Boardman and Work, 2004). Two major cyclothems below this correlated cyclothem, the Midcontinent Stanton and Texas Merriman-Upper Winchell cyclothems...
are correlated with the Russian Troshkovo cyclothem, based on the first appearance of *I. eudoraensis*, the probable ancestor of *I. simulator* (s.s.). The major cyclothem between these two correlated cyclothems, the Midcontinent Cass cyclothem is correlated with the Lower Colony Creek cyclothem of Texas by the appearance of the ammonoids *Vidrioceras conlini* and *Pseudaktubites stainbrooki* in both, and with both the Middle Rusavkino cyclothem of Russia and Donets Limestone O6 by the first occurrence of the conodont *Streptognathodus zethus* in both. The next major cyclothem above the Oread–Upper-Rusavkino–O6 cyclothem, the Midcontinent Lecompton and Texas Necessity cyclothems are correlated by the first appearance of *S. ruzhencevi* and *S. vitali*, along with the presence of *I. tersus*, and these two cyclothems are correlated with the Amerevo cyclothem of Russia by the appearance of *S. ruzhencevi* and *S. vitali*.

The upward succession of 5 intermediate and major cyclothems below the Stanton–Troshkovo cyclothem (Figure 3) and above the Dennis–Upper Neverovo–O2 cyclothem in North America (Cherryvale, Dewey, Iola, Wyandotte, Plattsburg) lines up well with position with only the third cyclothem upward (minor Presnya) not at the same relative scale as its positional equivalent (Iola) in North America (see also Heckel et al., 2007). The Donets conodont succession below I. simulator in Limestone O6 is less well known than it is in Russia, but so far appears to be dominated by *S. firmus* and *I. toretzianus* Kozitskaya 1978, both long-ranging forms that were named from this area. *S. firmus* appears abruptly in the Midcontinent in the upper Eudora Shale (Stanton cyclothem) by migration, and extends upward to the Oread. The Donets succession contains *S. zethus* and *I. eudoraensis* recently discovered in Limestone O5, which allows correlation with the Cass and Middle Rusavkino, but the Donets units below this are correlated mainly by position and scale. Below O5, the downward succession of three major Donets cycles (O4, O43, and O41) line up well with the three major cyclothems in North America (Stanton, Iola, and Dewey, respectively), providing a more reasonable correlation of these higher Donets cycles than shown by Heckel et al. (2005), since the more recent discovery of the first *I. simulator* (s.s.) in Donets cycle O6, rather than in O7 as previously thought. Thus, even if the correlation of the Oread–Upper Rusavkino–O6 cyclothem were not based on the first appearance of *I. simulator*, the overall correlation framework of nearly all the major middle and late Kasimovian and early Gzhelian cyclothems based on cyclothem scale and first conodont and ammonoid appearances still provides the most reasonable framework possible (Figure 3). Above O6, correlation of the Donets succession is less certain because O6 contains a continuation of the older *S. firmus–I. toretzianus* fauna, while O7 contains the first appearance of *I. tersus*, which first appears in the Midcontinent in the Oread and dominates the next three intermediate
to major cyclothems upward to the Lecompton (and the Necessity in Texas), above which it is absent. Therefore, O7 is provisionally correlated with the Lecompton–Necessity cyclothem (and by extension with the Amerevo of Russia) because of the presence of I. tersus. This places O7, equivalent to either of the two intermediate cyclothems between the Oread and Lecompton in the Midcontinent (Clay Creek or Spring Branch), but until Gzhelian conodont faunas of the Donets Basin are better known, we cannot rule out the possibility that O6 might correlate with the Lecompton–Necessity–Amerevo cyclothem, while O7 is younger. O7 also contains the holotype of S. luganicus Kozitskaya 1978 and other simulator-like forms that we term I. cf. simulator, which resemble similar forms in strata younger than bed 4-2 at Usolka in the southern Urals.

Among fusulinids, Rauserites rossicus first appears with I. simulator in the Upper Rusavkino at the Gzhel section near Moscow (Figure 3), source of the recently designated lectotype (Isakova and Ueno, 2007). Current work reports R. rossicus similar to the Gzhel lectotype from Donets Limestone O7, which by conodont data is younger than the Upper Rusavkino, and more primitive R. rossicus from Limestone O8, which is older than the Upper Rusavkino, although all 3 morphotypes are close enough to be considered subspecies of the same species. Recent choice of the lectotype from Gzhel facilitates the usage of R. rossicus to identify the base of the Gzhelian in facies where I. simulator is not found. This has been current practice in many areas, such as Arctic Russia where R. rossicus appears at or above the base of the Gzhelian (see Remizova, 2006). Among other fusulinids, Jigultites makkalensis Davydov 1986, which is considered Gzhelian, is reported to appear in Donets Lime stone O8, and with I. simulator in bed 7 at the Nikolsky section in the southern Urals (see below). Thus some fusulinid species, as currently designated, apparently are not sufficient for accurate cyclothem-level correlation, although their appearance may indicate a position close to the level of I. simulator. Therefore, we rely on the conodonts and ammonoids along with cycle scale as the primary basis for the cyclothem correlation shown in Figure 3.

Correlation of the successions in which cyclothems are not identified is based mainly on the succession of conodonts, again using fusulinids where they appear helpful. In the Dalniy Tyukals-2 section of the southern Urals, the upward appearances of S. zethus and I. eudoraensis in bed 42, of I. simulator in bed 46, and of the fusulinid Rauserites stuckenbergi in bed 47, indicate correlation of this part of the succession, respectively, with the Cass–Middle Rusavkino–O8 cyclothem, the Oread–Upper Rusavkino–O6 cyclothem, and the Lecompton–Amerevo cyclothem (Figure 3). In the nearby Usolka section of siliceous carbonates, the presence of type S. zethus in bed 4-1 (along with type S. praenuntius, another possible ancestor of I. simulator), and I. simulator (s.s.) in bed 4-2, suggest correlation of this part of the section with the Cass–Middle Rusavkino–O5 and Oread–Upper Rusavkino–O6 cyclothems, respectively. In the detrital siliciclastic Nikolsky section not far away, the presence of both S. firmus and S. pawhuskaensis in bed 5, the appearance of I. simulator in bed 7, the appearance of R. stuckenbergi in bed 10 and the appearance of S. vitali in bed 12, suggest correlation of this part of the succession, respectively, with the South Bend cyclothem of the Midcontinent, the Oread–Upper Rusavkino–O6 cyclothem, and the Lecompton–Amerevo cyclothem, although bed 12 could be younger.

In south-central China, Idiognathodus simulator has been reported (as Strepognathodus simulator) from a narrow stratigraphic interval in the Nashui section near Luodian in Guizhou Province (Wang and Qi, 2002, 2003). There it defines the S. simulator Zone, which lies between two locally named zones, but is appropriately positioned between two zones that are based on middle Mississippian/Kasimovian species below and late Gzhelian species of Strepognathodus above.

Conclusions

The relative ease of correlation of the Oread–Upper Rusavkino–O6 cyclothem by means of the first appearance of I. simulator [s.s.] in all regions above strata that contain the first appearance of S. zethus (the Cass–Middle Rusavkino–O5 cyclothem) and I. eudoraensis (the Stanton—Troshkovo cyclothem) indicates that this appearance would provide a good marker event for defining the base of the Gzhelian Stage (Figures 2, 3). The appearance with I. simulator in this cyclothem in Texas of the earliest species of Shumardiites, S. cuvieri, serves to keep the base of the Gzhelian at its proper position in terms of the recently emended ammonoid zonations of Boardman et al. (1994) and Bogoslovskaya et al. (1999). The appearance of the lectotype of the fusulinid Rauserites rossicus with I. simulator in the Moscow region and forms similar to R. rossicus above I. simulator in the Donets Basin, indicate that morphotypes of this fusulinid should aid in identifying this boundary in Eurasia.

Ironically, the widespread exposure surfaces that help to expedite correlation will make the selection of GSSPs (which require continuous sedimentation) difficult in the shelf regions where the cyclothems are well defined. However, the correlation of sections in which cyclothems are not recognized into this cyclothem framework should allow the possibility of selecting a GSSP in a section of continuous sedimentation that can be correlated globally (at least in the pantropical belt), if several conditions are met (Heckel et al., 2007): [1] Cyclothems are not recognized because the section was deposited at greater water depth below sea-level lowstand; [2] the section contains a complete succession of fossils that occur also in the more shelfward regions where the correlation framework is recognized; and [3] the section is on a slope gentle enough that the continuity is not interrupted by debris flows that may have eliminated a significant amount of strata or mixed biotas of different ages. The Usolka section near Krasnosouski in the southern Urals may provide the requisite characteristics for defining a GSSP for the Kasimovian-Gzhelian boundary at this level (Chernyk et al., 2006a, b), as it appears to be a slope deposit, but it must undergo further thorough lithic and biostratigraphic study to confirm its potential as a candidate. In addition, the Nashui section near Luodian in south-central China also is a slope deposit (Wang and Qi, 2003), and it also will undergo further detailed lithic and biostratigraphic study for its consideration as a candidate for the GSSP.

Acknowledgments

Among the authors, Heckel coordinated and compiled information from all authors and established the correlations; Barrick and Boardman provided conodont information for the Midcontinent; Work and Boardman provided ammonoid information for the Midcontinent and perspective on ammonoids reported elsewhere; Alekseev and Goreva provided information for correlations in the Moscow region and Dalniy Tyukals in the Urals; Isakova provided information on critical fusulinids in eastern Europe; Nemyrovska provided conodont and cycle-scale information for correlations in the Donets Basin; Ueno provided fusulinid information for the Donets Basin; Villa chaired the task group that is dealing with this stage boundary, and provided perspective on fusulinid information. We thank all other members of the SCCS Task Group on the Kasimovian-Gzhelian Boundary for providing information, thoughtful correspondence and discussions at meetings, particularly V.I. Davydov and V.V. Chernyk who provided information on fusulinids and conodonts in the Usolka and Nikolsky sections in the southern Urals, and along with H.C. Forke, made helpful comments on the manuscript; other task group members include A. V. Dzhenchuraeva, B. Fohrer, O.L. Kossovaya, L.L. Lambert, C.A. Mendez, M.L. Martinez Chacon, L.C. Sanchez de Posada, S.T. Remizova, E. Sammankassou, and G.P. Wahlman.
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