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Sequence Stratigraphy Enhancement of Biostratigraphic Correlation with Application to the Upper Cretaceous of Northern Siberia: A Potential Tool for Petroleum Exploration

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Abstract

Sequence stratigraphy can be used as a tool to bolster weak or low-resolution biostratigraphic correlation. On the basis of sequence stratigraphy, very high resolution correlations can be made if differences in local depositional and tectonic environments are taken into account. We have applied this tool to the Upper Cretaceous of northern Siberia, a frontier area with well-studied biostratigraphy, but with only feeble correlation with the Western world. The Upper Cretaceous biostratigraphy of northern Siberia can be defined on the basis of inoceramids, but this basis fails in detail both at the local level and for the purpose of interregional correlation. The situation can be remedied in part by the application of sequence stratigraphic concepts. These concepts have been developed primarily for passive margins and other rapidly subsiding basins, but with some modifications can be used to correlate depositional and eustatic events recorded in northern Siberian strata with those observed elsewhere throughout the world. The placement of biostratigraphic zonal and even stage boundaries in the Upper Cretaceous can be adjusted for northern Siberia in this way. Because this is the first sequence stratigraphic analysis of northern Siberian strata, it serves as a useful test of the applicability of sequence stratigraphy as a correlation tool. On the basis of sequence stratigraphic correlation, we demonstrate that correlation is greatly improved, not only in reliability but in resolution as well. On the basis of the results of this analysis, it appears that sequence stratigraphic correlation can be a generally useful tool in supplementing biostratigraphic correlation.

Introduction

STRATIGRAPHIC CORRELATION is crucial for petroleum exploration, particularly in frontier areas such as Siberia. The dating and correlation of geologic events generally is dependent on biostratigraphic control. There are constraints on biostratigraphic age based on ammonites, bivalves, and microfauna in Siberia, and these are correlated with the biostratigraphy of the Russian Platform and Western Europe. During certain time intervals, however, biostratigraphic correlation is difficult or of low temporal resolution. In these cases, sequence stratigraphic analysis can assist in correlation. In this paper, we present the first sequence stratigraphic analysis of Upper Cretaceous strata from Northern Siberia, based on a reference section exposed in outcrop at the mouth of the Yenisey River and Pyasina River Basin (Fig. 1). The reference section is augmented by many additional sections in the Ust'-Yenisey trough, and is consistent with Upper Cretaceous stratigraphy throughout Siberia.

It has been observed by many investigators that some unconformities appear to be globally synchronous, whereas others are not (Pitman, 1978; Parkinson and Summerhayes, 1985; Posamentier et al., 1988; Christie-Blick et al., 1990; Aubry, 1991). Unconformities that are observed only locally are generally attributed to the influence of local tectonics. Minor diachroneity between unconformities in different tectonic/depositional environments is attributed to differences in the relation between subsidence/sedimentation rates and eustatic variation rates. The slow subsidence/sedimentation rates inferred for northern Siberia during the Late Cretaceous allow us to

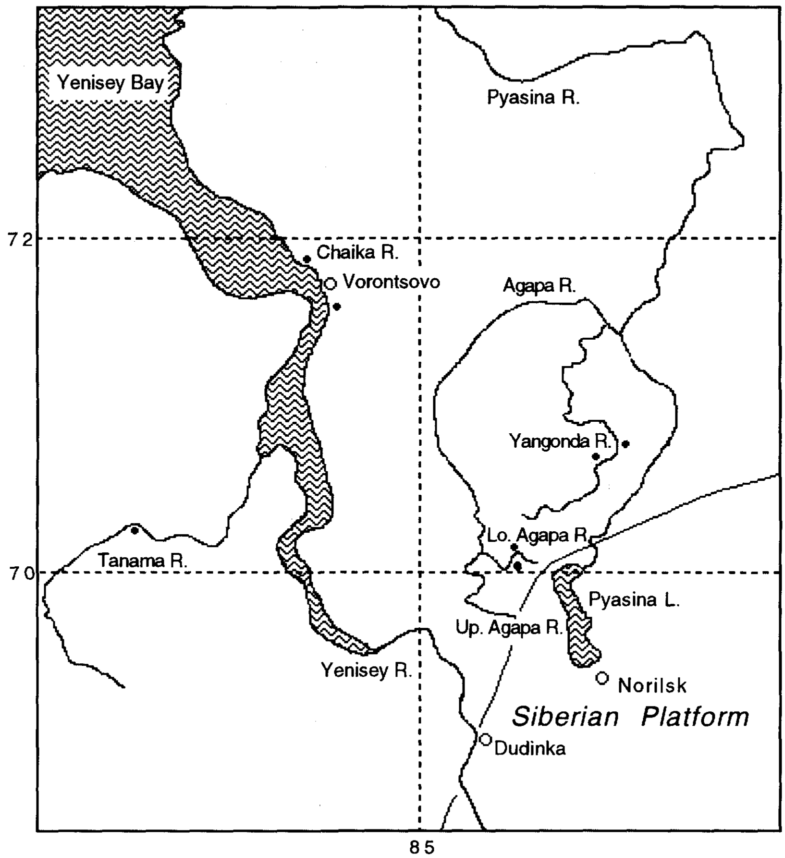

FIG. 1. Map of northern Siberia showing the localities from which the composite reference section is constructed.

determine precisely the relative timing of eustatic events and their associated depositional manifestations (facies shifts, unconformities, etc.).

On the basis of our investigation, we can identify and quantify the magnitude of minor eustatic events. In northern Siberia, many of these minor events result in "forced regressions" (Posamentier et al., 1992) and type-I sequence boundaries as a result of the shallow environments of deposition and slow rate of subsidence. In addition to sequences, we can correlate major paleogeographic events such as the Early Turonian anoxic event (Schlanger and Jenkyns, 1976), and the accumulation of siliceous clays in the Santonian-Campanian. This sequence stratigraphic correlation serves to augment the biostratigraphic control and assists in Boreal-Tethyan correlation.

Stratigraphy

The most complete Upper Cretaceous section of east or west Siberia is exposed in the Ust'-Yenisey depression (Fig. 1). The most continuous and useful sections are exposed in the lower Agapa River (Upper Cenomanian-Lower Turonian), Yangoda River (Upper Turonian-Coniacian), and Tanama River (Santonian-Maastrichtian). Two small outcrops on the east bank of Yenisey Bay near the mouth of the Chaika River expose Upper Turonian, and just south of the village of Vorontsovo the Upper Coniacian is exposed. These latter sections are very important for correlation between the former sections, as they fill short gaps in the exposed succession (Zakharov et al., 1986, p. 82; Zakharov et al., 1989a; Zakharov et al., 1989b, p. 70).

Because the Upper Cretaceous section is exposed in several outcrops that contain overlapping portions of the section, we were able to construct a composite section based on biostratigraphic correlation of outcrops distributed within 150 km of a central point (Fig. 2). The Upper Cretaceous sediments were terrigenous and generally were deposited in shallow water environments. The strata are relatively thin (450 m for the entire section), and quite poorly lithified. Most of the section is composed of unconsolidated sediment with occasional lithified horizons that often represent sequence boundaries. In addition, glauconite and other iron and silicate minerals are abundant throughout the section, especially in the Upper Turonian, Coniacian, and Santonian. Widespread clay beds are useful for interregional correlation of sea level highstands (Lower Turonian, Turonian–Coniacian boundary, Campanian).

Stratigraphic units are areally extensive, having been deposited on a broad coastal shelf. No evidence exists for deltaic sedimentation (above the Lower Cenomanian), valley fill deposits, prograding units, or other localized depositional features. Consequently, it is inferred that facies variations and sequence boundaries represent the relationship between eustasy and subsidence, but are not controlled by local variations in sedimentation. In the reference area at the margin of the Ust'-Yenisey trough during the Late Cretaceous, subsidence appears to have been very slow and steady (as suggested by the thin and relatively uniform thickness of depositional units throughout the Upper Cretaceous). This is attributed to the influence of the relatively stable Siberian platform to which it is attached (Fig. 1). It is thus inferred that stratigraphic architecture was controlled primarily by eustatically forced transgressions and regressions (Posamentier et al., 1992) and their associated facies migrations.

The Upper Cretaceous sediments in the reference area of northern Siberia were deposited in a northeastern bay of the West Siberian Basin, at the present mouth of the Yenisey River. This region began gentle subsidence in the Middle Jurassic, and by the Late Cretaceous was very slowly and uniformly subsiding. The large oil-bearing Bazhenov formation was deposited in the Late Jurassic in the subsiding basin. Subsidence rates can be constrained by facies and stratal thicknesses, which are on the order of a few tens of meters per stage, or 1–5 m/m.y. The stratigraphy of the region suggests a terrestrial environment prior to a prominent transgression that began in the Late Cenomanian, establishing marine conditions with many fluctuations and with major eustatic peaks in the Early Turonian, Early Campanian, and Early Eocene.

The detailed stratigraphy of the region is described as follows (Fig. 2). The lowest member in the section is the continental Dolgan Member (part of the Uvat Formation) of Late Cenomanian age. It includes cross-bedded sands, coal seams, wood, and amber (with insects) and includes the first occurrence of *I. pictus* in the uppermost marine section. The overlying Dorozhkov Member with typical marine fauna (Upper Cenomanian–Lower Turonian) is composed mostly of clays, grading upward from basal sands and silts into anoxic black clays. The overlying Gazsale Member (Lower Turonian) is predominantly sand (and is one of the most important gas-producing horizons in West Siberia). The Dorozhkov and Gazsale members are parts of the Kuznetsov Formation, which extends throughout West Siberia and is part of a major transgressive-regressive cycle. The magnitude of eustatic rise responsible for this transgression has been estimated as 80 m on the basis of American stratigraphy (Sahagian, 1987; Ziegler et al., 1985; Vellamil and Arango, 1993).

The Nasonov Member corresponds with the Ipatov Formation (Upper Turonian–Upper Santonian), and is composed mainly of a shallow-water, poorly sorted sand facies. This part of the section is highly fossiliferous and includes numerous lithologic breaks, pebble horizons, glauconite group minerals, phosphatic beds, and concretions.

The Solpadayakha Member coincides with the lower part of the Slavgorod Formation (Campanian) in uneven unconformable contact with the underlying Nasonov Member. It is not known exactly how much time is represented in the unconformity because there is poor inoceramid zonation in the Campanian and the Lower Campanian may be partly or wholly absent, as is the case with part of the uppermost Santonian zone (*S. patootensis*). The Solpadayakha Member is composed predominantly of siliceous shales.

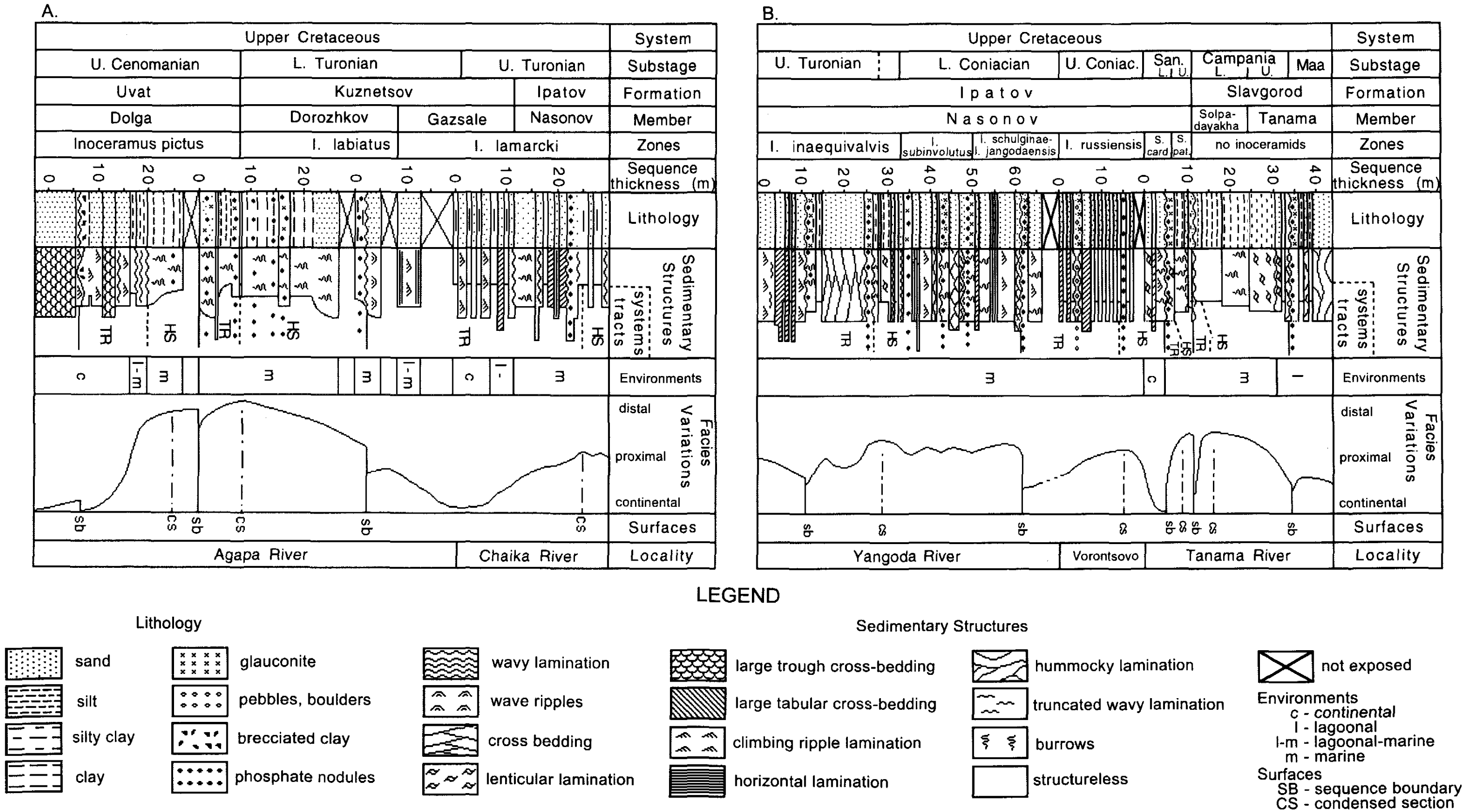

FIG. 2. Biostratigraphy and sequence stratigraphy of the Upper Cretaceous of northern Siberia (composite section). A. Upper Cenomanian to Upper Turonian. B. Upper Turonian through Maastrichtian. "Meters" indicates position of beds in outcrop section, and is reset at each outcrop in the composite stratigraphic section. The width of "sedimentary structures" indicates grain size (narrowest is clay, then silt, fine sand, medium sand, coarse sand, concretions). Sequences are separated by solid lines; systems tracts by dashed (TR = transgressive systems tract, HS = highstand systems tract). Facies variations are sensitive to distance from clastic source, water depth, and rate of clastic input into the system. The facies curve is not the same as the relative change in coastal onlap curves generated for passive margins by various investigators. The facies curve is based on environments of deposition (water depth) rather than on large-scale stratigraphic architecture. The inferred sequence boundaries and systems tracts are indicated. Sequences generally are bounded by type-I unconformities as a consequence of shallow depositional environments and slow rate of subsidence. Another consequence of this is that condensed sections occur in the lower part of highstand systems tracts rather than during transgressive systems tracts, as would be the case in a rapidly subsiding passive margin.

The uppermost formation in the Upper Cretaceous is the Tanama Member, which includes the Campanian–Maastrichtian boundary. The boundary between the Solpadayakha and Tanama members is not sharply defined, but is represented by a gradual gradation of clays to silts and finally sands. The boundary is defined on the basis of palynology. The Maastrichtian age of the upper part of the formation is indicated by the ammonites *Baculites anceps leopoliensis* Now. (a problematic subspecies) and *Tancredia americana* (Meek). The Tanama Member is composed primarily of sands, with silts and thin clay beds. The intercalation of sands and clays, along with the faunal composition, abundant trace fossils, and fragments of marine reptile skeletons, suggests a lagoonal environment of deposition.

Biostratigraphy

In order to determine the timing of sea-level variations as recorded in the stratigraphy of West Siberia, it is necessary to correlate the biostratigraphy with other parts of the world. Because Tethyan biostratigraphic zonation (North America and Western Europe) is based on ammonites, there are some difficulties in zonal correlation between these areas and West Siberia, where ammonites rarely are found. However, good correlation can be obtained on the basis of inoceramids. Boreal Upper Cretaceous biostratigraphy has been studied in detail (Papulov and Naydin, 1979; Naydin et al., 1986, p. 262; Troeger, 1989) and is outlined below (Table 1). There are nine inoceramid zones established in the Upper Cenomanian through Upper Santonian. Inoceramids have not been identified in the Campanian and Maastrichtian strata (Zakharov et al., 1991). The cause of the early disappearance of inoceramids in West Siberia (and the Russian Platform) is not clear (but it is reminiscent of the disappearance of conodonts in this region two stages before extinction at the end of the Triassic).

For most reliable correlation between West Siberia and Western Europe, we correlate first with the Russian Platform, using biostratigraphy as a bridge to the west. The zonal scale of the Russian Platform for the Cenomanian–Santonian also is based on the succession of inoceramids, and the Campanian and Maastrichtian are based on belemnites. The duration of the inoceramid zonation on the Russian Platform, as in West Siberia, corresponds to substages. There is a very similar succession of inoceramids in West Siberia and the Russian Platform (Table 1). On this basis, we have good correlation between the two regions with identical index species, such as *Inoceramus pictus* (Upper Cenomanian), *I. labiatus* (Lower Turonian), *I. lamarcki* (Middle Turonian), *Sphenoceramus cardissoides* (Lower Santonian), and *S. patootensis* (Upper Santonian). For other times, correlation is achieved on the basis of simultaneously occurring species. An example of this is the occurrence of *I. russiensis* (West Siberia) in the *I. involutus* zone of the Russian Platform.

Correlation with Western and Eastern Europe is slightly more difficult because only a few zones coincide with the West Siberian sections. These include the boundary between the *I. pictus* and *I. labiatus* zones that defines the Cenomanian–Turonian boundary, the first appearance of *I. lamarcki* as the base of Middle Turonian, the first appearance of *S. cardissoides*, which defines the base of Santonian, and the *S. patootensis* zone (Upper Santonian). The other zones are correlated on the basis of occurrence of identical species in West Siberia, the Russian Platform, and Western and Eastern Europe, although the assemblages vary in composition between these regions. The most uncertain correlation occurs between the uppermost Turonian and Upper Coniacian. During this interval, there are few representatives of the *I. lamarcki* group, which is characterized by considerable morphologic variation within species.

There is a problem of correlation in the placement of the Santonian-Campanian boundary. Near the boundary, there is a very characteristic bed dominated by a certain bivalve, and known as the "*Pteria* Beds." D.P. Naydin (Naydin et al., 1984) placed the "*Pteria* Beds" in the Lower Campanian on the basis of forams. However, G.N. Papulov (Papulov, 1974, p. 176) considered them Upper Santonian on the basis of inoceramids. Unfortunately, there is no clear correlation between either the forams or the inoceramids to Western European and North American sections, so there can be no definitive placement of the stage boundary on these bases alone.

TABLE 1. Correlation Chart of Northern Siberia, Russian Platform, and Western and Eastern Europe, Based on Inoceramids

<table>
<tr><th rowspan="2">Stage</th><th rowspan="2">Substage</th><th colspan="4">Succession of inoceramids</th><th rowspan="2">Substage</th><th rowspan="2">Stage</th></tr>
<tr><th>Northern Siberia (Zakharov et al., 1991)</th><th>Russian Platform (Naydin et al., 1986)</th><th colspan="2">Western and Eastern Europe (Troger, 1989)</th></tr>
<tr><td rowspan="2">Maastrichtian</td><td>Upper</td><td rowspan="2">No inoceramids</td><td rowspan="2">No inoceramids</td><td colspan="2" rowspan="2">No inoceramids</td><td>Upper</td><td rowspan="2">Maastrichtian</td></tr>
<tr><td>Lower</td><td>Lower</td></tr>
<tr><td rowspan="2">Campanian</td><td>Upper</td><td rowspan="2">No inoceramids</td><td rowspan="2">No inoceramids
. . . .
Balticus[1]</td><td colspan="2">Regularis</td><td>Upper</td><td rowspan="2">Campanian</td></tr>
<tr><td>Lower</td><td colspan="2">Balticus[2]</td><td>Lower</td></tr>
<tr><td rowspan="3">Santonian</td><td>Upper</td><td>Patootensis</td><td>Angustus,[1] patootensis</td><td>Angustus,[2] pinniformis</td><td rowspan="3">Cardissoides</td><td>Upper</td><td rowspan="3">Santonian</td></tr>
<tr><td rowspan="2">Lower</td><td rowspan="2">Cardissoides</td><td rowspan="2">Cardissoides</td><td>Cordiformis</td><td>Middle</td></tr>
<tr><td>Undulatoplicatus</td><td>Lower</td></tr>
<tr><td rowspan="4">Coniacian</td><td rowspan="2">Upper</td><td rowspan="2">Russiensis</td><td rowspan="2">Involutus</td><td colspan="2">Subquadratus s.l.</td><td>Upper</td><td rowspan="4">Coniacian</td></tr>
<tr><td colspan="2">Koeneni/involutus</td><td>Middle</td></tr>
<tr><td rowspan="2">Lower</td><td>Schulginae/jangodaensis</td><td rowspan="2">Schloenbachi</td><td colspan="2" rowspan="2">Schloenbachi/ernsti</td><td rowspan="2">Lower</td></tr>
<tr><td>Subinvolutus</td></tr>
<tr><td rowspan="3">Turonian</td><td rowspan="2">Upper</td><td>Inaequivalves</td><td>Costellatus</td><td colspan="2">Costellatus</td><td>Upper</td><td rowspan="3">Turonian</td></tr>
<tr><td>Lamarcki</td><td>Lamarcki</td><td colspan="2">Lamarcki s.l.</td><td>Middle</td></tr>
<tr><td>Lower</td><td>Labiatus</td><td>Labiatis</td><td colspan="2">Labiatus s.l.
submytiloides/mytiloides</td><td>Lower</td></tr>
<tr><td>Cenomanian</td><td>Upper</td><td>Pictus</td><td>Pictus s.l.</td><td colspan="2">Pictus s. str.</td><td>Upper</td><td>Cenomanian</td></tr>
</table>

[1]Southern Urals (Papulov and Naydin, 1979).
[2]Species crosses Santonian-Campanian boundary.

Sequence Stratigraphy

Sequence stratigraphic concepts have proved extremely useful in understanding the relationship between eustatic variations and stratigraphic architecture (Pitman, 1978; Pitman, 1979; Pitman and Golovchenko, 1983; Posamentier and Vail, 1988; Galloway, 1989; Jordan and Flemings, 1991). Accordingly, we have applied sequence stratigraphic techniques to the problem of northern Siberian stratigraphy in an attempt to better constrain the timing of eustatic events and their correlation with events recorded in other parts of the world. The stratigraphic sequences of the Upper Cretaceous section in Northern Siberia are clearly observable in the field. There are interfingering continental, estuarine, near-shore, and open marine facies. The strata are composed of terrigenous sands, silts, and clays that generally are unlithified (Zakharov et al., 1986, p. 82; Zakharov et al., 1989a; Zakharov et al., 1991).

In northern Siberia, shallow hypsometry caused minor eustatic variations to create high-frequency sequences (Mitchum and Van Wagoner, 1991; Van Wagoner et al., 1991). The facies variations recorded in depositional sequences are most clearly recorded in areas experiencing shallow-marine deposition (Mitchum and Van Wagoner, 1991). In regions of deep water, however, small eustatic variations (which cause facies changes in shallow water) are not recorded because distal clays are deposited in any case. Thus, if the paleohypsometry of the region of deposition can be inferred, the clarity of high-frequency sequences can be used as an auxiliary method of water-depth estimation. Indeed, observations from northern Siberia indicate that during times of shallow water (0–50 m) the facies variations caused by a 20-m eustatic change are recorded clearly, for example, but as water depth increases (50–100 m), these facies variations become damped, and in deep water (>100 m), the eustatic variations are not reflected in observable lithofacies variations.

The relatively flat hypsometry of the reference area during the Late Cretaceous is reflected in the rate of shoreline migration during the Late Cenomanian to Early Turonian transgression. A sea level rise of 80 m during this transgression (Ziegler et al., 1985; Sahagian, 1987; Vellamil and Arango, 1993) is interpreted to have caused a southward migration of the shoreline of the West Siberian Sea of 2000 km over a period of 1.5 m.y. This rate implies an average shoreline migration of 1.3 m/yr in this region.

The sequences observed in northern Siberia include condensed sections and are bounded by type-I sequence boundaries. Type-II sequence boundaries are not observed, possibly because of the shallow hypsometry of the depositional system and the proximal location of the reference area. The reference area was on the edge of the Siberian Platform and was topographically higher than most passive margin settings. As a result, lowstand systems tracts are not observed in the section, as lowstand deposition would have occurred farther seaward only. Thus lowstand time is hidden in type-I sequence boundaries, between which are alternating transgressive and highstand systems tracts. Condensed sections occur in the lower part of highstand systems tracts, rather than in the transgressive systems tracts. This important difference between northern Siberian and passive margin stratigraphy reflects the very slow rate of subsidence in northern Siberia. In the extreme case of no subsidence at all, as in the Russian Platform (Sahagian and Jones, 1993), condensed sections would occur in sediments deposited at the highest point of relative sea level, which would correspond to the highest point in eustatic sea level. Because there is some subsidence in northern Siberia and accommodation is at least partially filled with sediments, the condensed sections occur earlier in the highstand systems tracts, but later than would be expected in a passive margin environment. This interpretation is contrary to the definition of the relation between condensed sections and systems tracts and is a result of the relatively slow rate of sedimentation and subsidence.

We now describe the stratigraphy and depositional environments of individual sequences observed in the reference area, stage by stage. The Upper Cenomanian and Lower Turonian section is exposed at the Agapa River (Fig. 1). This section reflects a prominent marine transgression, and subsequent major regression, and includes two distinct sequences. At the base of the section is the sandy top of a previous sequence and type-I sequence boundary.[1] The first complete sequence in the reference section is entirely in the *Inoceramus pictus* zone and begins with continental deposits grading into several high-frequency sequences of shallow marine sands in the transgressive systems tract. These grade into silts and silty clays higher in the section, with a diverse marine fauna in the highstand systems tract. This sequence is less striking in its internal facies variation, and is thinner (20 m) than the underlying sequence.

The next sequence is 30 m thick and includes the Cenomanian-Turonian boundary in the condensed section, which represents the deepest-marine part of the entire Upper Cretaceous section in northern Siberia. Above this is a set of parasequences reflecting shallowing marine conditions, but with very little accumulation (only 13 m of sediments during a shallowing of at least 30 m). It is composed of a set of parasequences, which become progressively thicker and more clearly defined higher in the section (toward the top of the *I. labiatus* zone), in an almost mirror image of the underlying transgressive systems tract. The next sequence starts out marine, then grades into lagoonal and eventually continental deposits, then back through lagoonal into marine again, culminating in a condensed section at the lowest point in the highstand systems tract. The transgressive systems tract includes a progradational parasequence set leading to continental deposition (rather than an unconformity and sequence boundary), followed by a retrogradational parasequence set leading to marine deposition and culminating in a condensed section at the base of the highstand systems tract.[2] This sequence has the highest ratio of deposition to accommodation rates found in the reference section, and consequently has a condensed section in the relatively lowest position in the sequence. Notwithstanding, the ratio is lower than that typical of a passive margin, wherein the condensed section normally is found even lower, in the transgressive systems tract.

The marine sands in the upper part of the transgressive systems tract (*I. lamarcki* zone) represent the beginning of a general Late Turonian marine transgression that continues into the *I. inaequivalvis* zone (Fig. 2A) and includes three sequences. The nature of the upper marine part of the transgressive systems tract is similar to that of the Upper Cenomanian, beginning with fossiliferous sands with the first appearance of dinoflagellates, and grading into silts and clays. However, it differs from its Cenomanian counterpart in that it is thinner, more glauconitic, and contains more pronounced boundaries between parasequence sets. The deepest-water deposits are represented by sandy clays (rather than the silty clays of the Cenomanian-Turonian). These differences suggest that the Late Turonian transgression did not reach the water depth of the Earlier Turonian because of a lesser rate and magnitude of eustatic rise. The upper marine part of the transgressive systems tract includes several parasequences of approximately equal facies variation. This is in contrast to the Cenomanian-Turonian transgressive systems tract, in which successive parasequences (and parasequence sets) became more subdued, with progressively smaller internal facies variations. The character of these Upper Turonian parasequences of the Chaika River section is interpreted to represent a slow transgression during which deposition was able to keep pace with long-term eustatic rise (+ subsidence), so that each successive parasequence set was deposited in the same range of water depth and facies (aggradational stacking). In the lower part of the transgressive systems tract, aggradation exceeded accommodation, and coastal-continental deposition took place. A condensed section occurs in the lower part of the Nasonov Member. Above the condensed section, the highstand systems tract grades from clay to sand before reaching the sequence boundary ten meters above the base of the *I. inaequivalvis* zone.

The next sequence includes the Turonian-Coniacian boundary, and begins with a transgressive systems tract consisting of parasequences of sand and lagoonal clays. The highstand systems tract is represented by clays and a condensed section just below the Turonian-Coniacian boundary. The highstand systems tract is represented by slightly shallowing

[1]Only the top of this unit is shown in Figure 2A.

[2]An unconformity and thus sequence boundary in the unexposed section beneath the continental deposits cannot be ruled out, but we do not place one there, as this would imply an unlikely and ad hoc scenario of continental deposits overlying an unconformity.

progradational parasequence sets. The parasequence sets are similar in thickness and lithology throughout the Lower Coniacian.

The top of the Lower Coniacian and all of the Upper Coniacian consists of a single sequence that begins with transgressive highly fossiliferous glauconite sands with phosphatic nodules, followed by silty clays representing deeper water, and finally regressive sands in the Lower Santonian (Fig. 2B). The sequence ends at a type-I sequence boundary. The transgressive systems tract is composed of a progradational parasequence set underlying an aggradational parasequence set of alternating sands and clays. The highstand systems tract also consists of alternating sands and clays, culminating in highly bioturbated sands with climbing ripple laminations before a type-I sequence boundary. The uppermost Coniacian is not exposed in outcrop in the Yenisey River region, but can be observed at the Synya River in the subpolar Urals.

The Coniacian at the Synya River is represented there by shallow-facies sands with numerous minor unconformities. There are phosphatic beds in the lower part and calcareous sands with a diverse assemblage of bivalves, brachiopods, and forams in the middle part of the Coniacian. There are three very thin and incomplete sequences that are composed of glauconitic sands, with no silt or clay facies represented. The sequences are bounded by unconformities that may represent erosional hiatuses during which large portions of the sequences were removed (if they ever were deposited). The lower and middle parts of the section represent two sequences bounded by minor unconformities. A third sequence begins in the Coniacian and continues into the Santonian, as is observed in the reference section. This is the largest of the three sequences (15 m) in the Synya River section, and includes the Coniacian-Santonian boundary, which is biostratigraphically well constrained.

The upper part of the Lower Santonian and the entire Upper Santonian of northern Siberia are represented by a single sequence. It includes two aggradational parasequence sets of similar thickness and characteristics (Fig. 2B). Each begins with highly fossiliferous glauconite sands grading into silts, and ending again with sands. This pattern suggests a slow rise in sea level, with deposition keeping pace with accommodation (slow long-term eustatic rise + subsidence). The upper parasequence set is capped by sands that include *Sphenoceramus* cf. *lingua* (uppermost Santonian). The prominent unconformity in the Upper Santonian (Fig. 2B) in the Ust'-Yenisey depression may include some time represented by strata at the Synya River, but the detailed subzonal correlation is not clear. The capping unconformity represents a significant hiatus, with perhaps as much as two zones of the lower Campanian missing. During this extended time of exposure, the uppermost part of the Santonian sequence may have been eroded, as well as any of the lowest Campanian as may have been deposited.

At the base of the Campanian in the Yenisey region (Tanama River), there is an unconformity during which there was a significant faunal and lithologic event (Fig. 2B). Lithologically, there was a change from fossiliferous green sands and silts to black siliceous clays containing exclusively dinoflagellates. The nature of this unconformity is consistent throughout West Siberia, the Urals, and the northern margin of the Siberian Platform. The next sequence starts with very thin basal sands grading rapidly into siliceous clay (with radiolarians, diatoms, sponges, and dinoflagellates). A very thin (2 m) transgressive systems tract lies immediately above the unconformity. The overlying black siliceous clays of the highstand systems tract represent an anoxic event and include a condensed section present throughout the entire region. Because the water depth was probably fairly deep, it is impossible to quantify precisely. Above the siliceous clay, there are silty clays grading into sands, indicative of a shallowing trend throughout the Campanian, with a shallowing lagoonal facies culminating in an unconformity at the Campanian-Maastrichtian boundary. Shallow lagoonal clays and muds alternating with cross-bedded sands continue throughout the rest of the preserved Maastrichtian section. This is the upper limit of the exposed section in the reference area.

The sequence stratigraphy of the north Siberian sections can be compared to the observations of Haq et al. (1988) as well as to other sequence stratigraphic analyses throughout the world. There are three very prominent, easily distinguished events in the Upper Cretaceous that allow direct sequence stratigraphic correlation between northern Siberia, Western Europe, and North America. These include a condensed section at the base of the Lower Turonian, a major regressive event in the Upper Turonian (sequence boundary at 90 Ma in the *I. inaequivalvis* zone) as well as the following transgression, and a regressive event at the end of the Santonian. We have taken care not to overcorrelate events observed in northern Siberia and those depicted by Haq et al. (1987, 1988); there are so many minor events that, given a small allowance for dating errors, virtually any correlation can be made (Miall, 1992). Consequently, the present study is concerned only with the most major and widespread sequence boundary-defining events.

The three major events described above can be seen clearly on Figure 2. Between these major markers, a large number of minor events can be identified, many (but not all) of which correlate with the Western Interior (of the United States), Canada, and the North Sea (Zakharov et al., 1991), and with events identified by Haq et al. (1988). The correlation of northern Siberian Late Cenomanian and Turonian events with those in Haq et al. (1988) was described in Sahagian and Jones (1993) and shows a close match in the timing and number of eustatic events between 92 and 89 Ma, but with slightly differing relative magnitudes.

The biostratigraphic zonation of the Turonian of northern Siberia has been divided classically into an upper and lower substage. However, in North America and Western Europe, there are three substages in the Turonian. On the basis of sequence stratigraphic correlation, we can subdivide the northern Siberian Turonian into three substages as well. The base of the middle Turonian would thus be five meters above the unconformity in the *I. labiatus* zone, and the top would be 12 m above the base of the Chaika River section in the *I. lamarcki* zone. With this scheme, the Middle Turonian would include the Gazsale Member of the Kuznetsov formation. However, this cannot be documented on the basis of inoceramids or any other macrofauna. The Gazsale Member contains only pollen and spores, and is interpreted to be in part terrestrial.

The sequence stratigraphy of the Upper Turonian and Coniacian of West Siberia can be resolved into several parasequences. Specifically, there are 10 definable parasequence sets between the base of the *Inoceramus lamarcki* zone and the top of the *S. cardissoides* zone (Fig. 2). In other parts of the world, the subtle structure of the three sequences in that time interval is not as clear. The relatively shallow water depths and gentle hypsometry in the region throughout that time may be responsible for enhanced sensitivity of West Siberian sequences to small eustatic variations.

In the Campanian, there is poor biostratigraphic control in West Siberia. The biostratigraphic ages are based on palynological studies, as there are no diagnostic megafauna (such as inoceramids) available. However, in the middle Campanian, there is a prominent unconformity at 80 Ma evident in both Siberia and the West (Fig. 2). In this case, sequence stratigraphic correlation may enhance the correlation between Siberian and European biostratigraphy. A similar approach has been taken for the Western Interior of the United States (Hancock and Kauffman, 1989).

The above observations suggest a very close correlation between sequences observed in West Siberia and those observed in Europe and North America. This consistency enhances our confidence in the timing of the observed eustatic events. For quantification of eustatic variations, the Siberian data must be tied to the Russian Platform (Sahagian and Jones, 1993), in order for a more detailed quantitative eustatic curve to be constructed. This is beyond the scope of the present paper.

Relation of Biostratigraphy and Sequence Stratigraphy

Correlation of depositional sequences in certain intervals may help constrain the placement of zone or stage boundaries where there is no clear biostratigraphic control. An example of the utility of sequence stratigraphic techniques in helping to clarify biostratigraphic zonation is in the Upper Turonian and Lower Coniacian. The uppermost beds exposed at the top of the Chaika River outcrops include sands that previously had been dated as Lower Coniacian on the basis of endemic inoceramids (Zakharov and Khomentovskiy, 1989). However, the correlation of these local inoceramid species with Western European zonation is not clear. It is possible to modify the local inoceramid zonation in order to place the sands in the Upper Turonian, but there is considerable biostratigraphic uncertainty. On the basis of sequence stratigraphic correlation with other parts of the world, a strong argument can be made for the latter interpretation. The stratigraphy indicates a transgression after the continental part of the Chaika River section and a pattern of three distinct sequences through the Upper Turonian and Coniacian. If the chronostratigraphy of Haq et al. (1987, 1988) is accepted for correlation with Western European and North American biostratigraphy, then the pattern of sequences suggests a Late Turonian age for the aforementioned transgressive sands, and placement of the Turonian-Coniacian boundary (dashed) at the condensed section in the Yangoda River outcrops as indicated in Figure 2B. The first appearance of diagnostically Coniacian inoceramids is 5 m above the condensed section in the Yangoda River section. On this basis, the Coniacian normally would be defined as starting at that point, following the usual rules of biostratigraphy. However, the beds between the condensed section and the first appearance of *I. (V.) subinvolutus* lack inoceramids altogether, so they could have been deposited in Lower Coniacian time. Figure 2B depicts the strict biostratigraphic definition of the boundary, but for correlation with the rest of the world, the boundary should be placed at the condensed section.

Another problematic issue is the boundary between Campanian and Maastrichtian. In northern Siberia, biostratigraphic control is very poor in these stages. While some forms of *Baculites* have been found in the Tanama Member, it is not clear if these are related to *Baculites anceps leopoliensis*, which occurs in the Maastrichtian of Greenland (Birkelund, 1965, p. 192). There have been some palynological studies on the northern Siberian Campanian and Maastrichtian strata (Lebedeva, 1991). However, the results do not indicate a clearly defined stage boundary. The Tanama and Solpadayakha members have been divided on the basis of lithology alone. The poor biostratigraphic resolution can be augmented by sequence stratigraphic correlation. There is a prominent upper Lower Campanian unconformity throughout northern and western Siberia, as well as in North America and western Europe. We correlate the unconformity at the base of the Solpadayakha Member with the prominent upper Lower Campanian event at 80 Ma indicated by Haq et al. (1988). Thus, the lower Lower Campanian is absent from the northern Siberian section, and the upper Lower Campanian is represented by clays grading into silty clays, and finally silt beneath the sands of the Tanama Member. There is no clear evidence for an unconformity at this time in the Tanama River section, but the base of the sand correlates to the unconformity at 75 Ma of Haq et al. (1988), so that the boundary between Lower and Upper Campanian is at the Solpadayakha-Tanama Member boundary. The uppermost Campanian lies between the base of the sand and the unconformity in the Tanama Member. We correlate the unconformity to the event at 71 Ma in the chronostratigraphy of Haq et al. (1988). Above this unconformity are Maastrichtian lagoonal and shoreface deposits, but it is not clear at what time marine conditions end on the basis of northern Siberian stratigraphy.

An additional issue in the relationship between sequence and biostratigraphy is the relative position and biostratigraphic boundaries and sequence architectural features. In West Siberia, zonal boundaries correspond with condensed sections and/or parasequence set boundaries in the lower part of the Upper Cretaceous (Upper Cenomanian through Upper Santonian), but the correspondence is less clear in the upper part of the Upper Cretaceous (Campanian-Maastrichtian). There are coinciding boundaries that divide each of the biostratigraphic stages (Cenomanian-Campanian). In addition, there are numerous boundaries that correspond to biostratigraphic zonal boundaries. In the Campanian, the pattern of correspondence breaks down, and the major sequence boundary of the middle Campanian cannot be identified with any specific biostratigraphic zone boundary. While there may be a correspondence with Tethyan faunas, it is not observed in the Boreal faunas (Haq et al., 1987), and cannot be determined on the basis of north Siberian biostratigraphy.

There has been some speculation regarding the meaning of the relation between sequences and extinction events that define biostratigraphic boundaries. If the biota are sensitive to sea level and associated depositional variations, then sea-level events (which define sequence boundaries) may cause the extinctions that define the biostratigraphic boundaries (Hallam, 1989). This may have been the case in the lower part of the Upper Cretaceous. However, if the biota are largely independent of sea level and sedimentation, but rather depend on climate (Stanley, 1988; Simms, 1989), correspondence would not be expected between sequence and biostratigraphic boundaries, as observed in the upper part of the section.

An additional basis for correlation of stratigraphic units is strontium isotopic variations. As the Sr-stratigraphic timescale is developed in more detail, it will become a very useful tool for interregional correlation, because the variations in Sr isotopic composition of sediments is taken to reflect global changes in ocean chemistry. The $^{87}Sr/^{86}Sr$ ratio increased in the Cenomanian and Turonian, then decreased until the Maastrichtian (McArthur, 1991; McArthur et al., 1993). It may be possible to augment sequence stratigraphy for the correlation of the Campanian-Maastrichtian boundary, for example, based on Sr isotopes where biostratigraphic constraints are poor. This is beyond the scope of the present work, but may become an increasingly important tool in the future.

Conclusions

This first attempt to combine biostratigraphic and sequence stratigraphic analyses in northern Siberia has resulted in correlations of variable precision and detail in the Upper Cretaceous. The biostratigraphy of northern Siberia can be defined on the basis of exposed Upper Cretaceous outcrops near the mouth of the Yenisey River and Pyasina River basin. This section provides the most detailed and complete stratigraphic framework available in the Boreal realm of Eastern Europe and Siberia. The Upper Cenomanian, Turonian, Coniacian, and Santonian sections provide very detailed biostratigraphy as well as sequence stratigraphy, with resolution of zones, sequences, and parasequences usually better than 1 m.y. The resolution of the Campanian and Maastrichtian is less, both sequence and biostratigraphically, often exceeding 1 m.y. On the basis of Northern Siberian stratigraphy, seven sequences have been identified in the Upper Cenomanian through Santonian. These correlate closely to sequences found in Western Europe and North America. Campanian and Maastrichtian sequences also can be correlated with the West, but because there are only two of them, the resolution is less. Likewise, in the lower part of the section there is a detailed zonation of inoceramids, but the upper part of the section is poorly controlled.

The Siberian sequence and biostratigraphy readily can be correlated with that of the Russian Platform, and sets the stage for the development of a detailed quantified eustatic sea level curve. The correlation of northern Siberian biostratigraphy with Tethyan counterparts is more problematic. This is the subject for additional future research, and it is anticipated on the basis of our preliminary results that sequence stratigraphic correlation will be a generally useful tool in supplementing biostratigraphic correlation.

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