Eustatic Curve for the Middle Jurassic–Cretaceous Based on Russian Platform and Siberian Stratigraphy: Zonal Resolution[1]

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ABSTRACT

We have used the stratigraphy of the central part of the Russian platform and surrounding regions to construct a calibrated eustatic curve for the Bajocian through the Santonian. The study area is centrally located in the large Eurasian continental craton, and was covered by shallow seas during much of the Jurassic and Cretaceous. The geographic setting was a very low-gradient ramp that was repeatedly flooded and exposed. Analysis of stratal geometry of the region suggests tectonic stability throughout most of Mesozoic marine deposition. The paleogeography of the region led to extremely low rates of sediment influx. As a result, accommodation potential was limited and is interpreted to have been determined primarily by eustatic variations. The central part of the Russian platform thus provides a useful frame of reference for the quantification of eustatic variations throughout the Jurassic and Cretaceous.

The biostratigraphy of the Russian platform provides the basis for reliably determining age and eustatic events. The Mesozoic section of the central part of the Russian platform is characterized by numerous hiatuses. In this study, we filled the sediment gaps left by unconformities in the central part of the Russian platform with data from stratigraphic information from the more continuous stratigraphy of the neighboring subsiding regions, such as northern Siberia. Although these sections reflect subsidence, the time scale of variations in subsidence rate is probably long relative to the duration of the stratigraphic gaps to be filled, so the subsidence rate can be calculated and filtered from the stratigraphic data. We thus have compiled a more complete eustatic curve than would be possible on the basis of Russian platform stratigraphy alone.

Relative sea level curves were generated by backstripping stratigraphic data from well and outcrop sections distributed throughout the central part of the Russian platform. For determining paleowater depth, we developed a model specifically designed for this region based on paleoecology, sedimentology, geochemistry, and paleogeography.

The curve describes a series of high-frequency eustatic events superimposed on longer term trends. Many of the events identified from our study can be correlated to those found by Haq et al. (1988) and other sea level studies from other parts of the world, but there are significant differences in the relative magnitudes of events. Because the eustatic curve resulting from this study is based on a stable reference frame, the curve can be used in sedimentary basin modeling and as a tool for quantifying subsidence history from the stratigraphy of passive margins, basins, and other active regions.

INTRODUCTION

Eustasy is controlled by the relative volumes of the global ocean basins and global ocean water (Sahagian and Watts, 1991; Sahagian and Jones, 1993). Long-term relative sea level changes (>1 m.y.) have been observed qualitatively through their effects on the depositional patterns and shoreline processes of marine facies. However, quantification of eustatic changes has been hampered by

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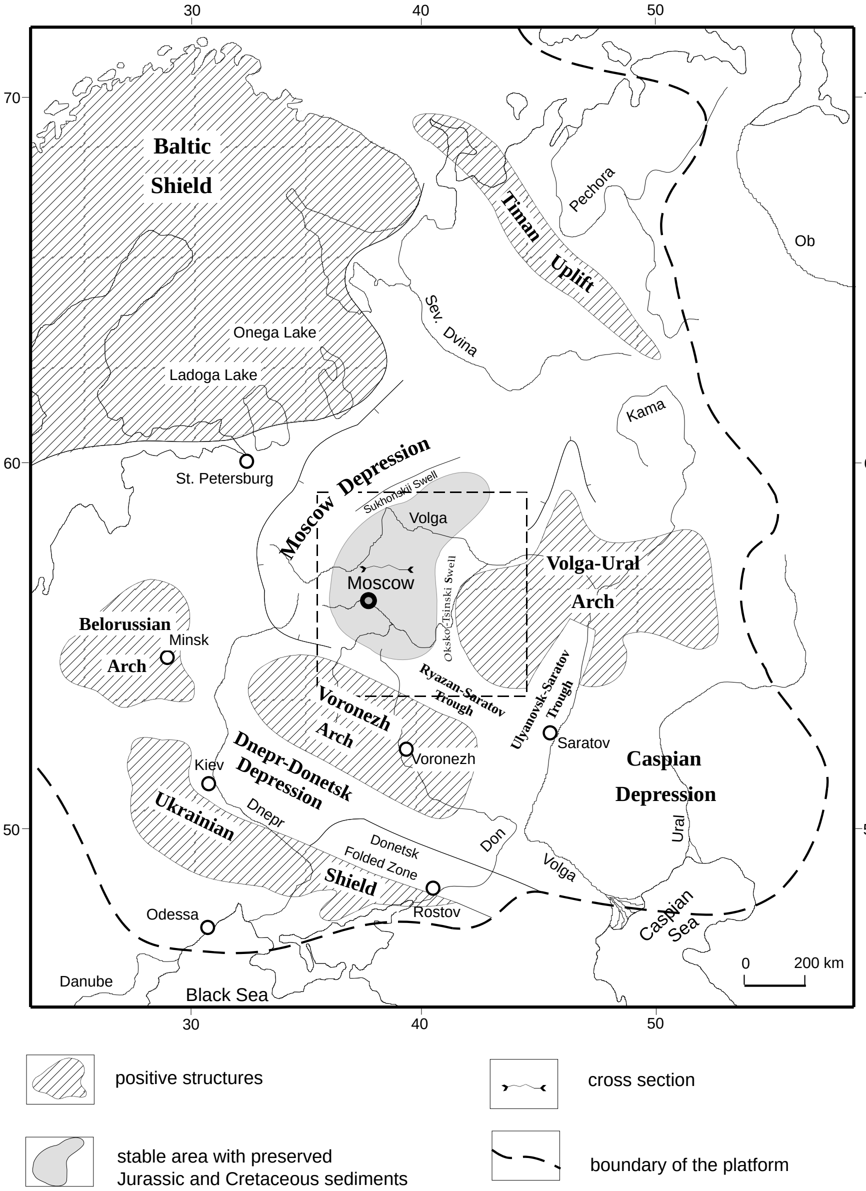


Figure 1—Sketch map of major structures of the Russian platform.

the lack of an adequate system of measure for this relationship. Although some workers have considered it impossible to accurately determine eustatic variations (Kendall and Lerche, 1988), other workers have suggested that a eustatic curve should ideally be based on the stratigraphy of a tectonically quiescent region for each time interval considered (Hallam, 1992). We have identified the central part of the Russian platform (Figure 1), based on its generally flat-lying and otherwise relatively undisturbed stratigraphy, as a useful reference for eustatic sea level quantification for the Middle Jurassic through the Cretaceous.

One way to observe sea level changes is through the effect on sedimentation patterns along continental margins (Vail et al., 1977; Jervey, 1988; Posamentier et al., 1988). Sea level changes can be estimated by applying backstripping techniques (Angevine et al., 1990). Because water-depth variations are an important term in backstripping analyses, eustatic variations can be quantified only to the resolution of the available paleodepth indicators, which are most reliable in shallow environments. In most tectonic environments, water depth is not solely dependent on eustasy (Baum et al., 1994), and in subsiding basins where subsidence depends on distance from a hinge, position also controls the relation between eustasy and water depth (Loutit et al., 1988). In this study, we examine the relationship between eustasy and sedimentation by quantifying water depth variations on a shallow platform sea.

Eustatic curves have been compiled in the past (Hallam, 1988; Haq et al., 1988; Harrison, 1988). Commonly, these curves have relied on methods of calculating tectonic activity (usually subsidence) to separate tectonic and eustatic signals reflected in stratigraphic sequences or paleohypsometric profiles (Greenlee and Moore, 1988). The errors inherent in these calculations of passive-margin subsidence histories (e.g., Watts and Steckler, 1979) may have been larger than the total sea level signal inferred on time scales of tens of millions of years. Thus, these curves have necessarily been qualitative, at best can be used for only short time intervals (<10 m.y.), and are limited by cumulative errors in subsidence calculations. By using an epeirogenically stable part of the lithosphere (central part of the Russian platform) as a reference frame, this limitation is eliminated because no discernible tectonic subsidence or uplift can be documented throughout the time of deposition, and only local and discrete activity has occurred since deposition. The stability and shallow-marine conditions of the central Russian platform throughout most of the Jurassic and Cretaceous make this region useful for detecting and quantifying eustatic variations. In addition, the Russian platform (Moscow depression) is unique because during its stable period it was very close to sea level, resulting in a relatively complete stratigraphic record compared to other areas thought to have been stable during the Mesozoic, such as North Africa and central North America (Sahagian, 1987, 1988).

TECTONIC SETTING OF THE RUSSIAN PLATFORM

The Russian platform is a large craton with an area of 5.5 million km^2 (Nalivkin, 1973). The platform generally consists of Precambrian crystalline basement and Phanerozoic cover. The accumulation of presently unmetamorphosed sediments began in the late Proterozoic (Riphean), about 1400 Ma, with the active formation of major aulacogens typical of the initial stages of platform development (Fedynsky et al., 1976). In the Vendian–Cambrian (650–550 Ma), the aulacogen stage terminated and sediments began to accumulate on the relatively flat-lying surface (compared to the modern basement relief) (Milanovsky, 1987). During the Paleozoic, significant subsidence and graben reactivation occurred throughout much of the platform, resulting in the deposition of thick sedimentary units. Some of the grabens were inverted in the late Mesozoic or early Cenozoic. The structure relevant to the present study is the Moscow depression, a subsiding graben complex with thick Paleozoic sedimentary fill in the central part of the Russian platform (Figure 1). The Mesozoic stratigraphy analyzed here is based on wells and outcrops on and near the extinct Moscow depression, referred to as the "Moscow syneclise" in the Russian literature.

By the Jurassic, the subsiding Moscow depression stabilized. This interpretation is supported by the uniformity and relatively thin nature of Mesozoic beds over great distances. For example, the Oxfordian shale facies between the Ryazan region and Unzha River sections (located about 600 km apart) displays similar isopachs down to the ammonite zone level. The thickness of the entire Mesozoic package increases in the marginal subsiding regions (e.g., Caspian depression, Dnepr-Donetsk depression).

The presence of a great number of unconformable surfaces and depositional hiatuses in the Jurassic–Cretaceous section of the Moscow depression represents additional evidence of stability. Due to very flat hypsometry and the lack of subsidence, even minor sea level falls could have caused submarine erosion or subaerial exposure, resulting in unconformities. In contrast, the more continuous deposition observed toward the southeast (lower Volga River region and Caspian depression) indicates significant subsidence and deeper water.

During the Mesozoic, limited reactivation of some aulacogen structures began on the Russian platform. However, the aulacogens in the Moscow depression apparently remained stable from the Middle Jurassic to at least the Santonian. Tectonic activity resumed during the Campanian–Paleogene in some regions that had been stable since the Jurassic. The inversion of Proterozoic graben structures occurred in the Oksko-Tsinski swell and Sukhonskii swell (Figure 1) through uplift of the axis zones. Some minor local movements also occurred in other parts of the previously stable area. All this resulted in local areas with different altitudes of Mesozoic strata; however, despite of the different vertical positions, the strata and facies are very uniform, even on the Oksko-Tsinski swell where the relief of Mesozoic surfaces reaches 160 m. This observation demonstrates the stability of the basin throughout deposition in the Mesozoic.

The interpretation that uniform sedimentation indicates stability is based on the assumption that the Russian platform did not rise or fall en masse. This assumption is supported by theoretical considerations and observations. The part of the Russian platform that is covered by flat-lying Mesozoic sediments is broader than the flexural half-wavelength of the lithosphere (Watts, 1989; Sahagian and Holland, 1993), so any point source of uplift or subsidence would be expected to lead to large-scale deformation, which is not observed. A broad source of epeirogeny, such as low-order geoidal variations, could affect the region's utility as a eustatic reference frame, but tomographic models suggest that this region has not experienced any significant variations in the relationship between dynamic topography and geoid since the Paleozoic (Gurnis, 1993). Consequently, we consider the Moscow depression as the most reliable sea level reference frame possible for the Jurassic and Cretaceous on an otherwise dynamic Earth. Although other regions on other continents suggest stability (Sahagian, 1987, 1988), the limited size and stratigraphic range make them inappropriate for constructing a eustatic curve for any appreciable interval in the Mesozoic.

PALEOGEOGRAPHY

Paleogeographic maps of the Russian platform have been compiled based on preserved stratigraphy (Naidin, 1959; Sazonov and Sazonova, 1967; Vinogradov, 1968; Naidin et al., 1986; Milanovsky, 1987). However, the extent of Mesozoic marine deposition was considerably greater than that of preserved strata because facies generally do not vary near the outcrop edge. Widespread post-Mesozoic erosion makes it difficult to make thorough paleogeographic reconstructions.

During the Triassic, the Russian platform was a low-elevation plain with deposition of alluvial and lacustrine sediments. Shallow-marine sediments of Early and earliest Late Triassic age are present only in the Caspian depression (Milanovsky, 1987). In the Early Jurassic, marine transgressions from the Southern Tethyan basin are evident in the Black Sea depression, Dnepr-Donetsk depression, and Caspian depression. By the end of the Bajocian the central part of the Russian platform was a low-elevation plain with locally incised minor relief (Zhukov and Konstantinovich, 1951). The sites of minor relief were the site of the first Bajocian marine deposition, and after a period of incised valley fill, marine sedimentation spread uniformly over the region during the Callovian. Marine conditions subsequently dominated until at least the end of the Santonian and were interrupted only for relatively short periods during eustatic sea level drops. Thus, during the Jurassic–Cretaceous, the Russian platform was a shallow epicontinental sea that extended from Tethys to the Arctic with occasional marine connections to the west (Figures 2, 3). Marine deposition occurred with limited sediment supply from remote clastic sources. The lack of subsidence and the low sediment supply caused eustatic sea level to be the main factor controlling sedimentation. In our analysis, we use paleogeographic reconstructions as a secondary constraint for estimating paleowater depth.

STRATIGRAPHIC DATA

Middle Jurassic–Upper Cretaceous strata are widely distributed on the Russian platform. Many of the stratigraphic units in the Moscow depression are bounded both above and below by unconformities. The thickness of eroded sediments is impossible to calculate using methods such as vitrinite reflectance (Armagnac et al., 1989) because of the thin overburden. In this study, we have filled the gaps left by unconformities on the Russian platform with stratigraphic information from the more continuous stratigraphy of the neighboring subsiding regions, such as northern Siberia. Although these sections reflect subsidence, the time scale of variations in subsidence rate are probably long relative to the duration of the stratigraphic gaps to be filled, so the (constant) subsidence rate can be reliably calculated and filtered from the stratigraphic data (Sahagian and Jones, 1993). Northern Siberian stratigraphy has been treated elsewhere (Sahagian et al., 1994), and so will not be repeated here, but is available as supplementary information, along with other specific information, through the *AAPG Bulletin* Datashare service. The data from the western part of the nearby Ryazan-Saratov trough were incorporated directly for the lowermost Aptian and upper Bajocian–Bathonian because the similarity of overlying and underlying intervals to correlative intervals of the Moscow depression suggests no significant subsidence during the short incorporated intervals.

Biostratigraphic zonation is based primarily on ammonites, bivalves, forams, and palynomorphs (Sazonov, 1957; Gerasimov, 1962; Krymholts, 1972; Mesezhnikov, 1984; Naidin et al., 1984; Baraboshkin and Mikhailova, 1987; Mitta, 1993). The traditional approach taken by Russian geologists for subdividing Russian platform stratigraphy was strictly biostratigraphic at the stage and zone level (Sazonov, 1957; Gerasimov, 1971). More recently, Olferiev (Olferiev, 1986, 1988) subdivided units into formations based on lithostratigraphy (and constrained by biostratigraphy) and this is the approach of our study. Data were obtained for this study from wells, cores, and correlated outcrops throughout the central part of the Russian platform (Figure 4), where individual units are continuous over great distances, allowing relatively reliable correlation of sections (Sazonov, 1957; Gerasimov, 1962, 1969; Krymholts, 1972; Olferiev, 1986, 1988).

During times of lower sea level, the dominant clastic source was redeposition of previously deposited material (Gerasimov, 1962). Sediment recycling may have contributed to the broad distribution of sand

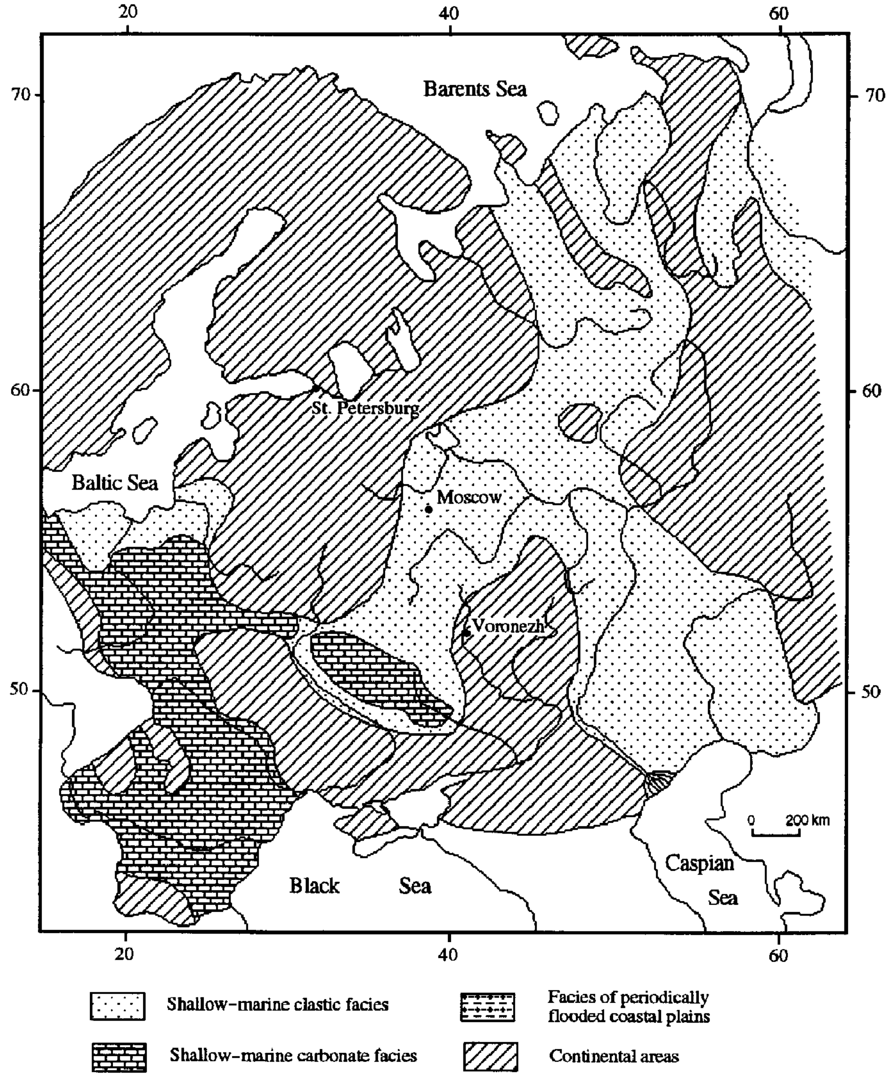


Figure 2—Late Oxfordian (*Amoeboceras alternans*) paleogeography of the Russian platform (after Sazonov and Sazonova, 1967).

across the Russian platform. Many examples have been found of fauna from several stages mixed together in redeposited strata on the Russian platform.

The stable region of the Russian platform (Moscow depression) includes the provinces of Moscow, Tver, Kostroma, Yaroslavl, Ivanovo, Vladimir, and Ryazan. Although individual stratigraphic sections preserve only portions of the Mesozoic section, a relatively complete composite section can be compiled from numerous sections throughout the stable region (Figures 5, 6). This composite section provides the most reliable framework for building a eustatic curve.

Jurassic

The average thickness of preserved Jurassic deposits is 120–140 m. The oldest marine section on the central Russian platform was traditionally considered to be Callovian, but more recently, upper Bajocian fauna, including *Parkinsonia doneziana Borissjak* and forams (*Lenticulina volganica*) were discovered in the basal oolitic sands of the Vyazhnevskaya Formation (Figure 5) in the western Ryazan Saratov trough (A. Olferiev, 1993, personal communication; Meledina, 1994). The upper portion of Vyazhnevskaya Formation consists of clays and is assigned to lower Bathonian (Figure 5). The conformably overlying middle to upper Bathonian Mokshinskaya Formation is represented by intercalated lagoonal and lacustrine sands, silts, and clays, and dated by forams, bivalves, and palynomorphs (Olferiev, 1986).

The Elatminskaya Formation is composed of a coarsening-upward succession of clays, silts, and sands. The contact between the Mokshinskaya and Elatminskaya formations is an erosional

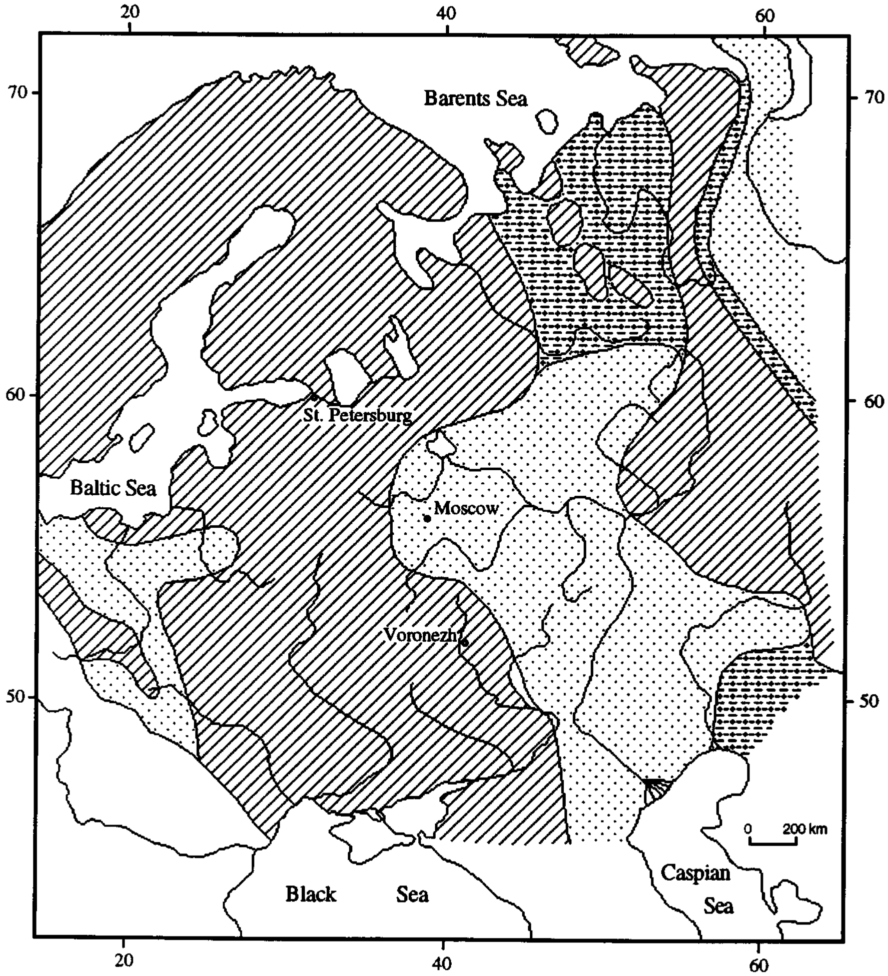


Figure 3—Hauterivian (*Speetoniceras versicolor*) paleogeography of the Russian platform (after Sazonov and Sazonova, 1967). See Figure 2 for legend.

unconformity overlain by an accumulation of belemnite fragments and pyritized wood. The Elatminskaya Formation has been considered a typical transgressive-regressive cycle (Olferiev, 1986). The lower part of the middle Callovian is represented by poorly sorted sands and silts with iron oolites of the overlying Kriushskaya Formation. The Kriushskaya is conformably overlain by clays with abundant bivalves *Posidonomya buchi* (*Roemer*) of the Velikodvorskaya Formation. The Kriushskaya is a transgressive deposit, whereas the Velikodvorskaya was formed during highstand and subsequent sea level fall (Olferiev, 1986). The overlying upper Callovian to lower Oxfordian Podosinkovskaya Formation consists of a basal oolitic marl overlain by light-gray clay. The contact between the Podosinkovskaya Formation and the Velikodvorskaya is unconformable in many locations.

The Podmoskovnaya Formation (middle to upper Oxfordian) is represented by fine-laminated bituminous clays and shales with abundant ammonite fauna. The erosional hiatus between the Podosinkovskaya and Podmoskovnaya formations is widespread, extending across and beyond the Moscow depression (Olferiev, 1986). The gray silty clays of the upper Oxfordian Kolomenskaya Formation conformably overlie the Podosinkovskaya Formation, but lenses of coarse sand and accumulations of bivalve and gastropod shells in the basal part suggest shallowing at the boundary of the two formations.

The Ermolinskaya Formation overlies the Kolomenskaya with an erosional unconformity in some places and conformably, but with evidence of shallowing, such as basal coarse-grained layers, in others. The formation is generally composed of dark-gray to black clays with abundant pyrite nodules and sparse fossils.

The upper Kimmeridgian has not been investigated in as much detail as have other parts of the Jurassic section because it has been almost completely removed by erosion, being adequately preserved in only several small areas in the Moscow depression. The Gorkinskaya Formation unconformably overlies

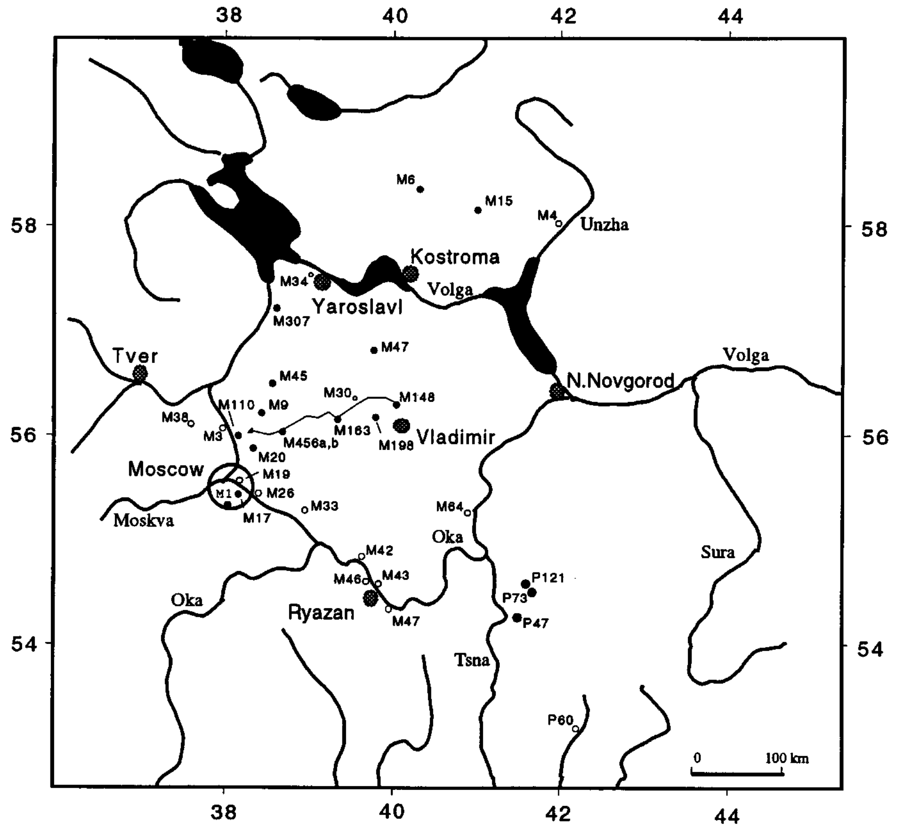


Figure 4—Locations of the main wells and outcrops used for the construction of the quantified eustatic curve.

the Ermolinskaya Formation and consists of dark clays with spongeolites and shell detritus.

The presence of biostratigraphically defined lower Volgian is reported only from the Kostroma province, where calcareous silty clays (3.5 m thick) have been encountered in wells. The age of the clay is indicated by forams (*Pseudolamarckina polonica* (*Biel. et Pos.*), *Planularia polenovae Kuzn.*, *Marginulina gluschisaensis Dain.*), but no ammonites have been encountered (Olferiev, 1986). Throughout most of the region, however, the middle Volgian overlies various Upper Jurassic strata with a significant erosional hiatus (Figure 5). The middle Volgian is widespread throughout the Moscow depression and is characterized by several marine facies that are represented by four middle Volgian formations (Figure 5). The fine-laminated bituminous shales and clays of the Kostromskaya Formation overlie a basal layer of coarse glauconite sands containing numerous redeposited phosphorite nodules with ammonites of different ages, including upper Oxfordian, Kimmeridgian, and middle Volgian. Note that there is no lower Volgian fauna present in this layer.

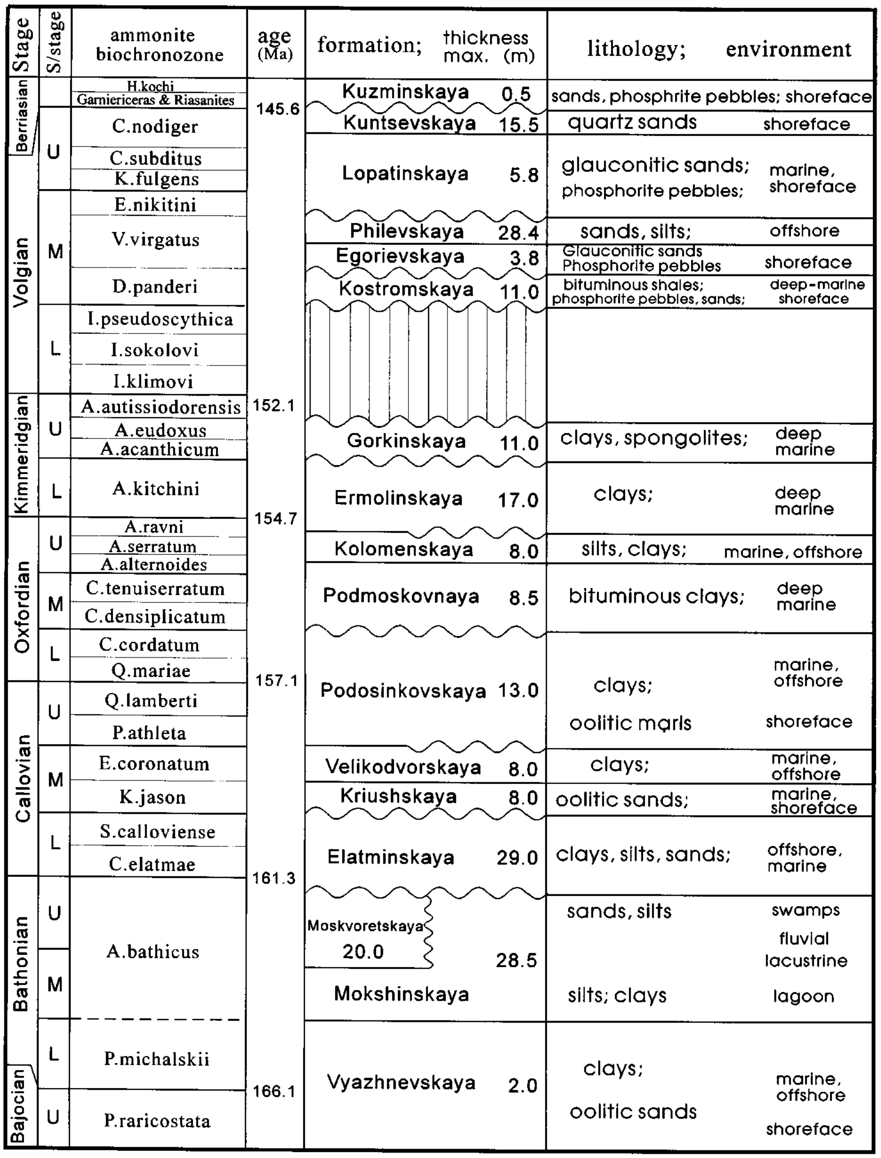


Figure 5—Middle and Upper Jurassic stratigraphy of the central Russian platform.

The Egorievskaya Formation that unconformably overlies the Kostromskaya Formation consists of fine-grained glauconite sands with phosphorite nodules and pebbles. The gray-black clay-rich sands and silts of the Philevskaya Formation overlie the Egorievskaya Formation with no sign of sedimentary interruption. The Egorievskaya is interpreted to represent transgressive deposition, and the Philevskaya highstand and regressive deposition (Olferiev, 1986).

The Lopatinskaya Formation unconformably overlies the Philevskaya and is represented by very homogeneous gray-green fine quartz-glauconite sands with an abundance of sandy phosphorite nodules in the upper part. The top of the Jurassic section is observed in outcrop in the vicinity of Moscow, and consists of a thick section of white, fine, well-sorted quartz-glauconite sands with phosphorite pebbles of the Kuntsevskaya Formation (Gerasimov, 1969).

Cretaceous

Cretaceous strata of the Moscow depression have an average thickness of 260–290 m. The section includes several significant erosional hiatuses (Figure 6) that developed local relief that was filled during subsequent transgressions (Figure 7). The marine Cretaceous of the Russian platform began in the Berriasian (Ryazanian). The terms “Ryazanian” and “boreal Berriasian” are used synonymously in the

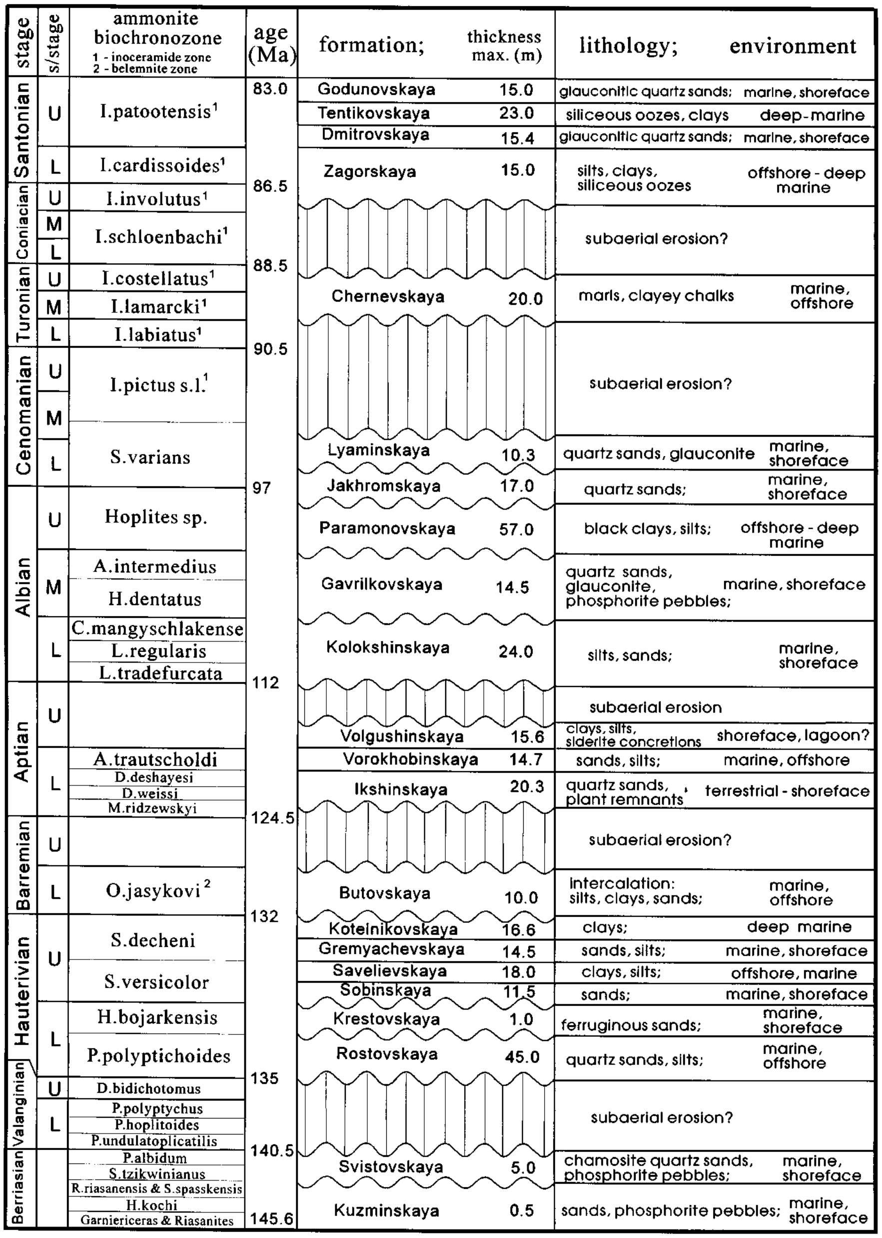


Figure 6—Cretaceous stratigraphy of the central Russian platform.

Russian literature. The relationship of boreal Berriasian biozones to Tethyan biozones and the position of the Jurassic-Cretaceous boundary is a separate issue that has been debated for over 30 yr (Krymholts, 1984) and will not be addressed in this paper.

The most complete sections of the Berriasian are in the southern part of the Moscow depression in the Oka River basin. At this locality, the lower Kuzminskaya consists of two beds of phosphorite sandstone separated by chamosite sands, all of very shallow marine facies (Figure 6). The Svistovskaya Formation in some places unconformably overlies the Kuzminskaya Formation. The Svistovskaya Formation is represented by chamosite sands with abundant phosphorite concretions and pebbles in the lower part (Olferiev, 1988).

The Valanginian is absent in most of the Moscow depression. Thin fragments of lower Valanginian are found in only two places, the Kostroma province and the northern part of the Oka-Don lowland (Ryazan province) where it unconformably overlies the Svistovskaya Formation. Because there is no useful Valanginian section, we do not discuss Valanginian stratigraphy of the Russian platform, and filled this gap using the more

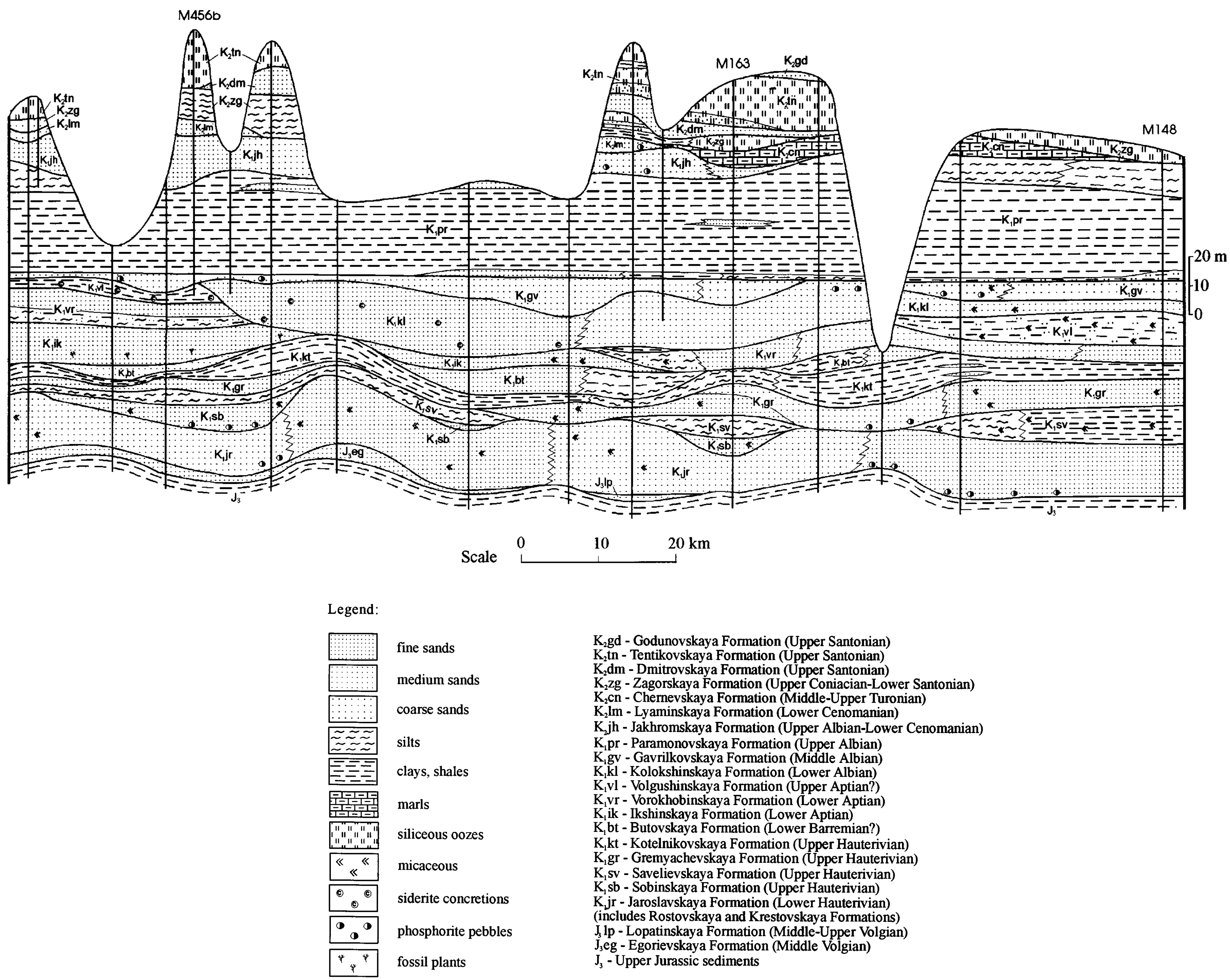


Figure 7—Cross section of Cretaceous strata of the central Russian platform.

complete northern Siberian sections along the Boyarka River (Zakharov and Judovnyi, 1974).

The overlying Hauterivian section is very well represented in the central part of the Moscow depression (Moscow and Vladimir provinces) and is divided into six formations. The Rostovskaya Formation (Figure 6) is composed of predominantly fine-grained quartz sands and sandstones that overlie various Cretaceous and Jurassic strata with an erosional unconformity. The thin Krestovskaya Formation is composed of ferruginous sands. The thin layer of poorly sorted coarse sand indicates shallowing that occurred at the beginning of Krestovskaya deposition. A subsequent sea level fall resulted in an extensive erosional unconformity throughout the entire Moscow depression at the lower Hauterivian–upper Hauterivian boundary.

The overlying four formations reflect the transgression of the late Hauterivian sea. The basal beds are composed of sands of the Sobinskaya Formation that fill depressions and the incised valleys of the eroded surface. The overlying clays and silts of the Savelievskaya Formation and shoreface sands and silts of the Gremyachevskaya Formation spread more uniformly across the region. The dark-gray clays and silts of the Kotelnikovskaya Formation are the most widespread, and probably represent the highest sea level stand in the uppermost Hauterivian. Sands and silts of the lower Barremian Butovskaya Formation conformably overlie the Kotelnikovskaya formation. The upper Barremian is absent from the Moscow depression and represents an erosional hiatus throughout the region.

The earliest marine Aptian sediments in the central part of the Russian platform are documented in the western Ryazan-Saratov trough where unsorted sands and silts fill incised valleys. The Aptian in the Moscow depression includes three formations. The deepest formation is the Ikshinskaya, which unconformably overlies Carboniferous, Jurassic, and Lower Cretaceous strata. The Ikshinskaya is composed of quartz sands with abundant fossil flora, and grades upward from terrestrial to lagoonal, and finally to marine sediments. The Ikshinskaya gradually transitions to the Vorokhobinskaya Formation, which is composed of offshore marine sands, silts, and clays. The overlying upper Aptian Volgushinskaya Formation is composed of shoreface to lagoonal clays and silts with siderite concretions. The Volgushinskaya includes Aptian–Albian spore and pollen assemblages and is assigned to the upper Aptian based on its position in the section. Significant regression occurred in the second half of the late Aptian that resulted in erosion of the upper contact of the Volgushinskaya Formation. The marine uppermost Aptian is present only in the Caspian depression and some small areas of the eastern part of the Ulyanovsk-Saratov trough, and represents an erosional hiatus throughout most of the Russian platform (Sazonova, 1958), suggesting one of the most significant sea level falls of the Lower Cretaceous on the Russian platform.

The lower Albian is represented by the Kolokshinskaya Formation of light-purple silts and sands with ammonites and palynomorphs (Baraboshkin, 1992). The unconformably overlying middle Albian Gavrilkovskaya Formation is composed of offshore-marine glauconite quartz and fine and medium sands with phosphorite nodules. Shallowing and subaerial exposure occurred in the uppermost middle Albian, as is indicated by an unconformity and mud cracks at the top of the Gavrilkovskaya Formation.

The clays of the Paramonovskaya Formation consist of three parts from base to top: (1) intercalations of sands and silts with basal coarse sands, (2) massive silts and black clays, and (3) silts and sands. The Paramonovskaya Formation is the thickest Lower Cretaceous unit preserved in the Moscow depression (up to 57 m thick) and represents the time of highest Early Cretaceous sea level. The upper Albian age of the Paramonovskaya is indicated by radiolarians and forams. The green-gray fine glauconite shoreface sands of the Jakhromskaya Formation overlie the Paramonovskaya clays with an erosional unconformity having relief of up to 20 m. The Lyaminskaya Formation consists of shoreface fine glauconite quartz sands with quartz gravels and phosphorite pebbles. In some places, the Lyaminskaya overlies the Jakhromskaya with some evidence of erosion (Olferiev, 1988).

A large stratigraphic gap includes the middle Cenomanian to lower Turonian. The gap is manifest as an erosional unconformity throughout the Moscow depression, but has been identified as a condensed section on the Voronezh arch and the eastern Ulyanovsk-Saratov trough (Naidin, 1981). The middle–upper Turonian overlies the unconformity and consists of marls of the Chernevskaya Formation. Another gap exists in the lower Coniacian (Figure 6). We have bridged both of these gaps with stratigraphic data (Zakharov et al., 1989a, b) from the Ust-Yenisey depression of northern Siberia (Sahagian and Jones, 1993; Sahagian et al., 1994).

The upper Coniacian Zagorskaya Formation unconformably overlies the Albian, lower Cenomanian, and middle–upper Turonian. In the western Moscow depression (Moscow province), the Zagorskaya is composed of intercalated quartz glauconite shoreface sands and silts with radiolarians. To the east (Vladimir province), this formation consists of offshore and deep-marine silicic clays, tripoli, and silts with radiolarians of late Coniacian and early Santonian age. The unconformably overlying Dmitrovskaya Formation consists of quartz glauconite shoreface sandstone. The Tentikovskaya Formation also overlies an erosional unconformity, and is composed of offshore to deep-marine silts and siliceous oozes. The Upper Cretaceous section of the Moscow depression is capped by the quartz glauconite sands and sandstones of the Godunovskaya Formation that unconformably overlies the Tentikovskaya Formation. The Godunovskaya Formation is preserved only in the central part of the Moscow depression. The Godunovskaya's age is uncertain, but it is conditionally placed in the upper Santonian based on its stratigraphic position. The Campanian and Maastrichtian are absent from the Moscow depression, probably due to subsequent (until present) subaerial erosion.

WATER DEPTH SCHEME

Water depth is an important component in reconstructing past sea level variations, but it is difficult to estimate paleowater depth accurately for backstripping analyses. In the case of extremely slow subsidence and deposition rates, water depth variations may be the sole expression of eustasy. Thus, a basis is necessary for the most accurate estimate of water depth, particularly when, as is usually the case on the Russian platform, water depth variations for a given interval are of greater magnitude than sediment thickness of the same interval.

Determining Paleowater Depth

Many different methods have been attempted for reconstructing paleowater depth, but none are universally applicable (Hallam, 1967a; Eicher, 1969; Benedict and Walker, 1978; Clifton, 1988; Brett et al., 1993). Most analyses use some form of geologic data (lithological, chemical, paleontological, etc.) and their typically associated water depths in modern marine environments. However, no universal model exists that takes into account all environmental factors, nor is there a generally accepted scheme for shallow shelf environments. Consequently, any attempts to apply water depth schemes based on modern conditions to paleowater depth are limited by the differences in the relationships between water depth and the geologic indicators used to estimate it. To accurately determine paleowater depth, one must account for all possible factors, including types and rates of sedimentation, climate, bottom geometries, and tectonic conditions, on the basis of all available geologic data.

Paleobathymetric Model for the Jurassic and Cretaceous Seas, Central Russian Platform

A few workers have attempted to estimate paleodepth on the Russian platform (Sazonov and Sazonova, 1967). However, these attempts have involved very low (100 m) depth resolution. For example, Sazonov and Sazonova (1967) grouped all Jurassic and Cretaceous facies of the entire Russian platform into two "magnafacies," one in shallow water (0–100 m) and one in deep water (100–200 m). In our analysis, we attempt to obtain the maximum possible depth resolution by developing a consistent quantitative model of water depth for the central Russian platform.

The paleodepth model for Jurassic and Cretaceous seas of the Russian platform is summarized in Figure 8. The model is based on the depths that correspond to deposition of different kinds of sediments, formation of sedimentary structures, mineralization, different kinds of taphonomic conditions, trace fossil distribution (ichnofacies), and bottom communities.

Contrasting levels of wave activity due to different geographic conditions in different basins result in significant variations in depth indicators. Wave base, however, remains at a depth of one-half the wavelength. On the basis of several factors (e.g., size, shape, depth, etc.), the Russian platform sea can be compared to the present Baltic Sea. Observational and theoretical studies indicate that Baltic storm wave base is 20–30 m (Zakharov, 1966). Mild Jurassic and Cretaceous climates may have had winds weaker than present winds (Hallam, 1967b). In addition, a climatic model for the Kimmeridgian–Volgian (Moore et al., 1992) shows relatively low annual wind activity for the region of the Moscow depression. As such, we take Jurassic and Cretaceous fair-weather wavelength on the Russian platform to be 20 m (wave base of 10 m). The maximum wavelength for major storms would have been 40 m (wave base 20 m). Fair-weather wave base (5–15 m, depending on local conditions), can be considered to divide sand-dominated shoreface sediments from mud-dominated offshore sediments (Walker and Plint, 1992). We thus define a relationship between lithology and water depth in our model.

Structural evidence may provide important information for paleodepth reconstruction, especially for shallow-marine environments (Clifton, 1988). Sedimentary structures closely connected to wave activity include cross-bedding, swaly cross-stratification, and various types of wave ripples above fair-weather wave base. Parallel laminations and hummocky cross-stratification are predominant below fair-weather wave base, and fine laminations of sediments rich in organic carbon are normally found below storm wave base (Walker, 1984).

Oolites are chemically formed in warm, oxygen-saturated, turbulent shoreface water above fair-weather wave base and are most abundant in depths of less than a few meters (Kump and Hine, 1986). The abundance of iron oolites and oolitic

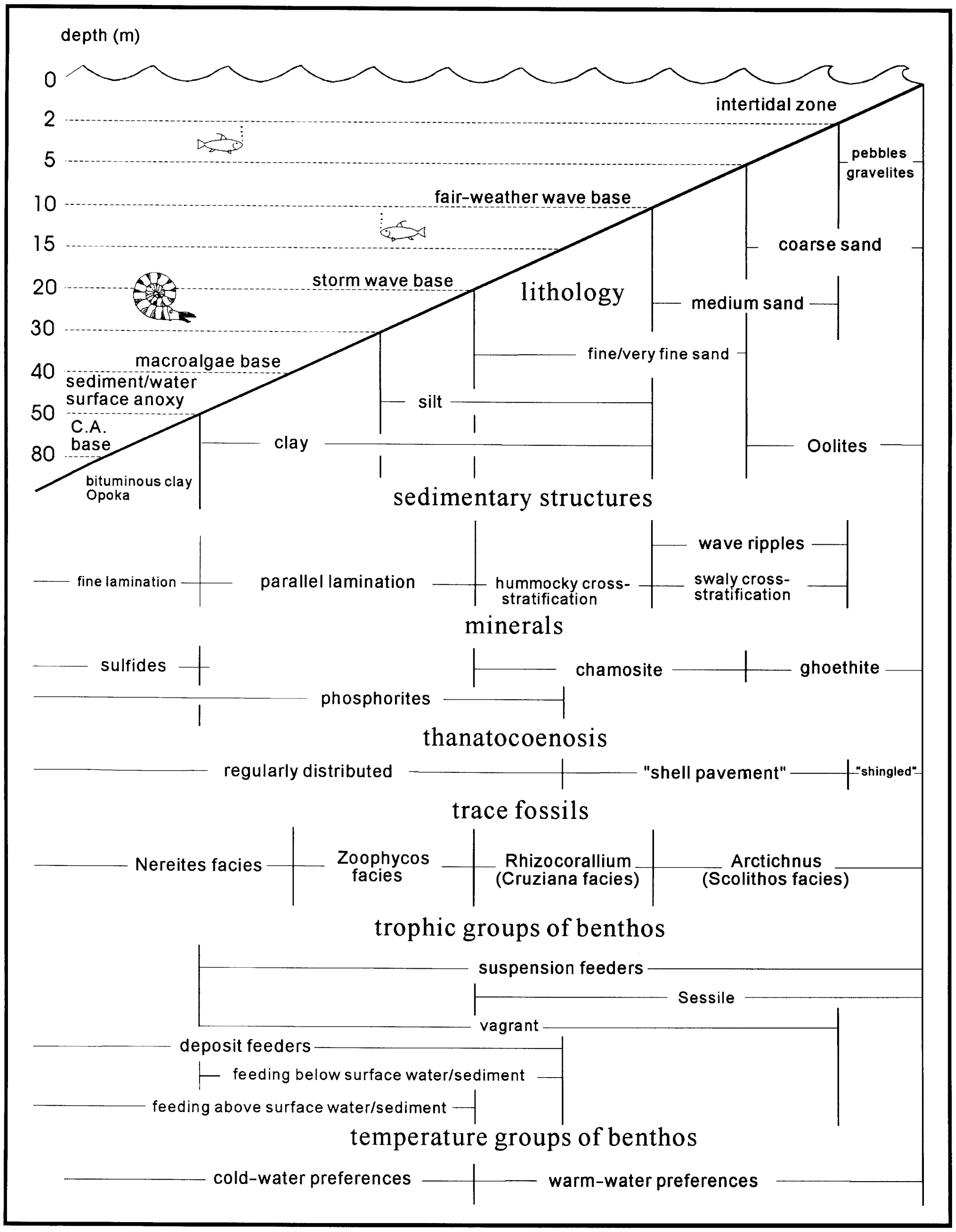


Figure 8—Paleodepth model for Jurassic and Cretaceous seas of the central Russian platform.

marls in Jurassic and Cretaceous strata of the Moscow depression makes them an exceptionally useful paleobathymetric indicator.

Authigenic minerals (particularly iron group minerals and phosphates) form at specific depths. Ghoethite in tropical seas is formed in extremely shallow (0–10 m) water. Chamosite forms in shallow (10–50 m) very warm (up 20°C) and active water. Glauconite is deposited at the deeper part of the shelf (150–250 m) at temperatures below 15°C (Porrenga, 1967). Most recent investigators have interpreted a shallow-water origin for phosphorites (30–150 m) (Bushinski, 1964; Bromley, 1967; Benedict and Walker, 1978). Carbon is of particular interest as a paleodepth indicator because it is well preserved in anoxic sediments (Black Sea, Mediterranean Sea depressions, Norway fjords). Carbon is usually reduced with Fe^{+2} (marcasite, pyrite), which is present in sediment and is well preserved in rocks. The presence of sulfides in rocks indicates relatively deep water conditions (below storm wave base).

Benthic communities are useful depth indicators. Regular patterns emerge in the range of modern marine benthic communities with respect to the alternation of the suspension feeders and deposit feeders throughout the shelf zone (Zenkevitch, 1977). Two zones of suspension feeders can be defined parallel to the shoreline in turbid water along typical continental margins: one zone in shallow water near the shoreline, and the other zone in considerably deeper water at the shelf–slope boundary (shelf break). Deposit feeders, however, are concentrated in oxygen-poor water on the deeper shelf and slope (Zenkevitch, 1977). No strict bathymetric control exists for the distribution of modern bottom communities in boreal seas, but suspension feeders are generally found in the nearshore and deposit feeders offshore.

Trace fossils are used widely for paleodepth interpretation (Seilacher, 1967; Ekdale, 1988). Four ichnofacies are identified from the shoreline seaward, and include *Scolithos, Cruziana, Zoophycos,* and *Nereites*. The only two trace fossil facies that have been considered as being depth constrained are the shallow-water *Scolithos* facies and the deeper water *Nereites* facies (Seilacher, 1967). Other types of ichnofacies can be found at different depths. In our model, we use the approximation suggested by Walker and Plint (1992).

Taphonomic data based on marine invertebrates is useful for quantitative paleobathymetric interpretation for depths of from 0 m to fair-weather wave base. Depth is indicated by preservation, separation, selection, and orientation of hard parts of these animals (bivalves, brachiopods, ostracods) (Yanin, 1983). Taphonomic investigation of bivalves in Peter the Great Bay of the Sea of Japan shows the following results. At depths of 0–5 m the species from different communities are mixed, the shells are broken, and there are shell banks. At depths of 5–15 m, valves are separated and moved from life position. Occasionally, the shells accumulate in spots and lenses. At depths greater than 15 m entire shells are buried in life positions (Evseev, 1981). Two types of accumulations are formed above fair-weather wave base. The “rose-type” or “shingled” accumulation is formed at the surf zone above 2.0 m water depth (Zakharov, 1966, 1984). This type consists of a nested and vertically oriented accumulation of large valves. “Shell pavement” accumulations are formed at between 2 and 15 m water depth by separate valves of bivalves (or brachiopods) that are convex upward and lying in close contact with a cobblestone appearance (Maksimova, 1949).

We assume that the maximum depth of the light penetration to support macroalgae is 40 m and that temperature decreased with depth in the Mesozoic seas; however, microalgae (e.g., calcareous cyanophycean) depths can reach 80 m. These assumptions are based on low water clarity in the Russian platform seas interpreted from terrigenous fine-grained sedimentation that predominated throughout the Jurassic and most of the Cretaceous.

Subaerial unconformities were assumed to represent at least some time of 0 m water depth (exposure), unless further sea level fall could be estimated on the basis of the amplitude of subaerial incision.

Our generalized scheme is adapted for “normal” shallow-marine systems and cannot be accurately applied to deltas, lagoons, estuaries, etc., and is subject to the vagaries of bottom relief, currents, variations in sediment supply, and other factors. Clearly, all local environmental factors must be taken into account before the model is applied. Because this paleodepth model was specifically constructed for the Moscow depression epicontinental sea, it should not be applied to other environments and hypsometries, or errors will result. However, the methods by which the model was constructed can be applied to other times and places, and can be used to develop models specific to other basins or platforms.

DATA ANALYSIS

Data analysis consisted of two main parts: geological analysis (isopach, lithology, facies, subsurface geometry, areal distribution, paleodepth interpretations, etc.) and backstripping. We studied over 50 wells and outcrops from this region and 32 wells were specifically used for constructing the composite curve (Figures 4, 9). We carefully examined five main regional stratigraphic profiles and series of lithologic-paleogeographic maps and analyzed subsurface stratal geometries and facies distributions throughout the region. Part of the regional profile IV-IV is shown in Figure 7. The results of the geological analysis were a database for use in backstripping routines that are used to construct sea level curves.

Backstripping involves three primary variables obtained from stratigraphic data: (1) thickness of each sedimentary unit, (2) reconstructed depositional water depth, and (3) lithology. Our simple Airy backstripping routine accounted for compaction and loading of sediments and water (Watt, 1988; Angevine et al., 1990; Sahagian, 1993). Coefficients from Angevine et al. (1990) were used for decompaction. A potential error can arise from assigning compaction coefficients to poorly sorted units with variable grain size, such as sandy shales or silty sands. However, the thin nature and minimal overburden of Mesozoic strata make decompaction and associated potential errors relatively small. Because thicknesses of individual depositional units were relatively constant across the stable part of the Russian platform, a distance greater than the lithospheric flexural wavelength, Airy isostatic response to lithospheric loading is interpreted to

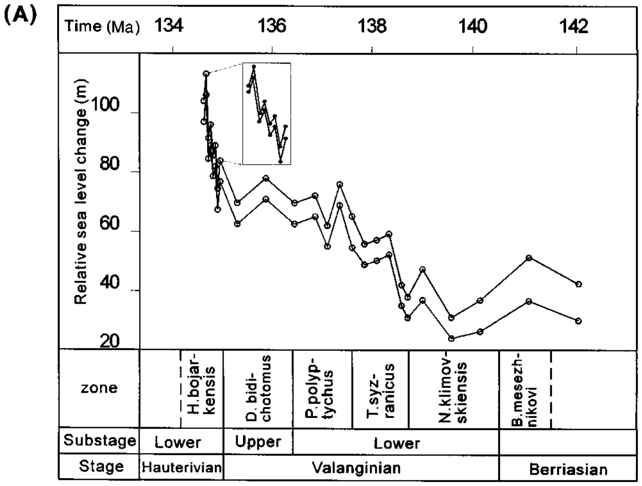
Series	Stage	Substage	Section used	Source
Upper Cretaceous	Santonian	Upper	M163,M47,M1	P121 (Lasitsy), M456 (Varavino), M45 (Skovorodino), M1(Teplyi Stan), M17 (Kolomenskaya), M307 (Uglich), M163 (Savelievo), M20 (Tsernskoe), M148 (Shikhobolovo), M15 (Galich), M110 (Paramonovo), M3 (Volgusha), M47 (Yuriev-Polskii), M6 (Yurino), M198 (Boristsevo), M34 (Krest) - from "CentrGeologia" technical reports (unpublished)
		Lower	M9,M1,M456a	
	Coniacian	Upper	M9,M1,M456a	
		Middle	Yangoda River	
		Lower	Yangoda River	
	Turonian	Upper	M47,M163,M1	
		Middle	M47,M163,M1	
		Lower	Agapa River	
	Cenomanian	Upper	Agapa River	
		Middle	----------	
		Lower	M1,M456a,M163	
Lower Cretaceous	Albian	Upper	M1,M456b,M198,M110	
		Middle	M1.M38,M3,M9	
		Lower	M163,M30,P60,M3	
	Aptian	Upper	M1,M456b,M148	
		Lower	P121,P73,M1,M456b,M20	
	Barremian	Upper	----------	
		Lower	M1.M20	
	Hauterivian	Upper	M163,M1,M456b,M307	
		Lower	M456b,M15,M163,M34,M6	
	Valanginian	Lower	Boyarka river	Yangoda River - Zakharov et al., 1989b
		Upper	Boyarka river	Agapa River - Zakharov et al., 1989a
	Berriasian		M33,M46	
Upper Jurassic	Volgian	Upper	M33,M19,M26,M17	M38 (Gavrilkovo), M3 (Volgusha) - Baraboshkin and Mikhailova, 1987
		Middle	M4,M456b,M33,M19	
		Lower	----------	M30 (Eza), M60 (Vorona) - Baraboshkin, 1992
	Kimmeridgian	Upper	M456b,M17,M45	P73 (Lasitskyi ovrag) - Sazonov and Sazonova, 1967
		Lower	M456b,M4,M17	
	Oxfordian	Upper	M456b,M4,M45,M17	M34 (Krest) - Ivanov, 1968
		Middle	M456b,M4,M43,M45	Boyarka River - Zakharov and Judovnyi, 1974
		Lower	M42,M456b,M4,M43	
Middle Jurassic	Callovian	Upper	M64,M42,M456b,M4	M46 (Kuzminskoe) - Mesezhnikov et al., 1979
		Middle	M64,M42,M456b	
		Lower	P121,M64,M4	M33 (Lopatino), M19 (Khodynka) - Gerasimov, 1972
	Bathonian	Upper	P121,P47	
		Middle	P121,P47	M64 (Elatma), M42 (Alpatievo), M4 (B.Korovitsa), M43 (Novoselki), P47 (Prosandeevka) - Sazonov, 1957
		Lower	P121,P47	
	Bajocian	Upper	P121	

Figure 9—Stratigraphic data sources used for constructing the quantified eustatic curve. Numbered sections include both well and outcrop data. See Figure 4 for locations.

have been maintained. The compaction of the relatively thicker Paleozoic section is considered to be unaffected by the thin Mesozoic–Cenozoic overburden. Backstripping resulted in a series of relative sea level curves.

The individual relative sea level curves from each well or section were compared to check for inconsistencies. Most curves coincided, indicating close agreement in timing and magnitude of sea level variations. Minor deviations were examined and the supporting data were scrutinized. Variations between curves were generally caused by uncertain depth interpretations, erosion, and minor variations of sedimentation rates. Despite the minor differences, general agreement between the wells and outcrop sections analyzed supported our interpretation of a stable region in the Russian platform, and further validated its use as a reference frame for eustatic quantification.

We incorporated data from northern Siberian sections to fill gaps in the Russian platform stratigraphy by matching highstands in the two regions



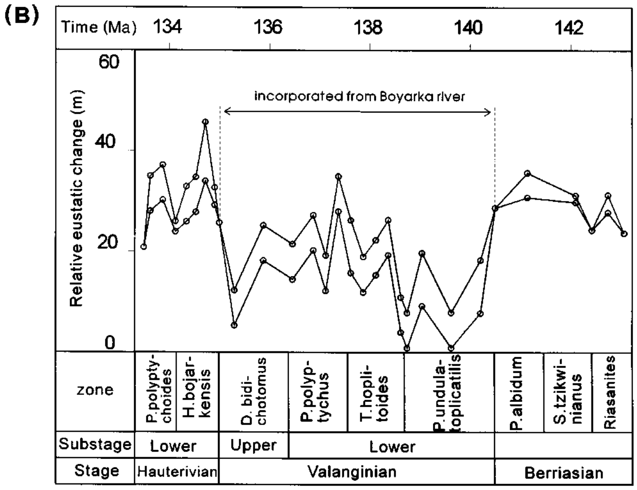


Figure 10—Example of incorporation of Siberian (Boyarka River) stratigraphic data to fill Valanginian unconformity of the Russian platform. (A) Relative sea level curve for Boyarka River section. (B) Boyarka River data incorporated into Russian platform curve. Incorporation was accomplished by matching the elevations of the highstands in the two regions immediately before and after the Russian platform unconformity. Note that higher order cyclicity is superimposed on Hauterivian sea level rise in the Boyarka River section.

immediately before and after each Russian platform unconformity. To accomplish this, we backstripped the appropriate intervals of northern Siberian data to generate relative sea level curves. This procedure accounted for sediment fill, compaction, loading, and water depth variations and loading, and resulted in the sum of tectonic subsidence and eustasy (Steckler and Watts, 1978; Angevine et al., 1990). The relatively short durations of the intervals made it possible to assume that Siberian subsidence rates were constant within the intervals (usually <5 m.y.). Thus, the tectonic subsidence defined a straight-line trend, the deviations from which could be attributed to eustatic variations. To merge Russian platform and Siberian data, we chose highstand tie points in the Russian platform eustatic curve immediately before and after each hiatus to be filled, and correlated them to their northern Siberian equivalents. The correlations were based on biostratigraphic control at biostratigraphic zonal resolution. For example, for the Valanginian hiatus, we correlated highstands in the upper Berriasian ammonite zone *Peregrinoceras albidum/Bojarkia mesezhnikovi* and lower Hauterivian zone *Homolsomites bojarkensis* (Figure 10). The difference in sea level rise in this interval between the two curves was attributed to northern Siberian subsidence, and the slope defined by this difference was subtracted from the northern Siberian stratigraphic data. This procedure resulted in a subsidence-corrected northern Siberian sea level curve. Once this was obtained, we could simply use the northern Siberian data to fill the gap in the stratigraphy of the Moscow depression to complete the missing intervals in the eustatic curve.

SEA LEVEL CURVE

Constructing the Quantified Eustatic Curve

On the basis of stratigraphic continuity and reliable geologic age control, the relative sea level curves from two wells, M1 (Teplyi Stan) and M456 (Varavino), were chosen as a frame for the eustatic curve. Data from the various other well, core, and outcrop sections of the Russian platform were incorporated both as a check for consistency and as a source for additional stratigraphic detail. The final eustatic curve was constructed as a composite of the individual relative sea level curves (Figure 11) using the Harland time scale (Harland et al., 1990). The thickness of the error band reflects uncertainties in water depth analysis as well as other smaller factors. The data for upper Bajocian–Bathonian and two zones of the basal Aptian were taken from the western Ryazan-Saratov trough region of the Russian platform (Figure 1). We filled the gaps caused by the most prominent unconformities (Valanginian, upper Cenomanian–lower Turonian, lower Coniacian) with north Siberian data. Upper Barremian and upper Aptian sediments are absent throughout most of the Russian platform (Sazonov and Sazonova, 1967) and are also poorly controlled biostratigraphically or are completely absent in Siberian sections. These intervals, in addition to the lower Volgian and middle Cenomanian, are shown with dashed lines on the eustatic curve (Figure 11).

Relation of the Eustatic Curve to Present Sea Level

Although we find stratigraphic evidence for stability of the Moscow depression throughout Mesozoic deposition, we also find evidence of significant post-Santonian rejuvenation of pre-Mesozoic structures. Consequently, we do not use the present elevation of the central Russian platform strata as an absolute measure of eustatic change after the Mesozoic, but restrict its use to the variations within the Mesozoic. To tie the Mesozoic curve to present sea level and set the elevation scale in Figure 11, we had to choose a point that can be considered as having been stable throughout the Cenozoic. On the Paleozoic Voronezh arch (Figure 1), the top of the Cenomanian is flat-lying at 214–225 m above present sea level across a region spanning 250 km and trending northwest-southeast (Blank et al., 1992). However, south of the Voronezh arch is the Dnepr-Donetsk depression, in which the Cenomanian has subsided by 500–600 m. North of the Voronezh arch, the base of the Aptian lies at an elevation of 260–270 m, indicating significant uplift that caused erosion of the Cenomanian strata. This setting compromises the reliability of the Voronezh arch for tying the Mesozoic to present sea level.

A region in Minnesota (United States) also has flat-lying Cenomanian–Turonian strata and has been inferred to be tectonically stable since that time (Sloan, 1964; Sleep, 1976; Sahagian, 1987). The region extends through Minnesota and into Iowa, and may have extended across an eroded or non-deposited region as far as Tennessee (Marcher and Stearns, 1962). There is no evidence for any epeirogenic activity in the region aside from glacial rebound and regional erosion (Sahagian, 1987). However, the limited stratigraphic range of these deposits (only Cenomanian–Turonian) does not allow construction of a continuous Mesozoic sea level curve. If the elevation of the Minnesota strata is used as a baseline, with the elevation of the Cenomanian–Turonian highstand at 270 m above present sea level (Sahagian, 1987), 160 m should be added to the arbitrary elevation scale in Figure 11. The shape and magnitude of variations within the eustatic curve in Figure 11 were determined solely on the basis of Russian platform stratigraphy (with some short sections from Siberia). The Minnesota horizon can be used only for placing the zero point of the elevation scale (vertical axis) relative to present sea level.

Comparison with Other Sea Level Curves

Several sea level curves in recent decades have been based mainly on the stratigraphy of passive margins or otherwise-subsiding basins. The most cited curve is that of Haq et al. (1987, 1988). This curve, however, has been criticized by some workers (Sloss, 1991; Miall, 1992) for not taking sufficient account of the tectonic and sedimentary processes that dominate the mainly passive margin environments upon which it was based. Nevertheless, the curve was based on a large body of stratigraphic and biostratigraphic data, and provides an interesting comparison for the eustatic curve generated from the Russian platform (Figures 12, 13). The most obvious result of this comparison is that both curves have similar long-term trends. Haq et al. (1988) indicated a general sea level rise from the Bathonian (Middle Jurassic) to the Volgian (Late Jurassic) punctuated by several sea level falls. We obtained a similar pattern (Figure 12), although the magnitude of the long-term rise is less than that indicated by the Haq et al. (1988) curve. Both curves indicate a long-term lowstand in the Berriasian and Valanginian and sea level rise in the Hauterivian that continued to a maximum in the early Turonian.

We also found similarities and some significant differences between the curves at a finer scale, particularly with respect to magnitude of eustatic events. The Bathonian portions of both curves are almost identical, showing slow eustatic fall, and the similarity continues through the Upper Jurassic. Although the number of small-scale eustatic events is similar in the two curves, we found some discrepancies in the timing of events at the biostratigraphic zonal level, possibly owing to biostratigraphic correlation uncertainties.

We found significant discrepancies in the Berriasian–Valanginian interval. A sea level fall at the Jurassic–Cretaceous boundary caused a regional erosional unconformity throughout the Moscow depression; however, the Haq et al. (1988) curve showed a sea level highstand at this time. Furthermore, we found no evidence for the major sea level drops of more than 100 m indicated by Haq et al. (1988) at 128.5 and 126 Ma on either the Russian platform or the more continuous record of west Siberia [note different time scales on our quantified eustatic curve (Figure 11) and Haq et al. (1988) curves].

In the Cretaceous, both our eustatic curve and that of Haq et al. (1988) show a general lowstand in the Valanginian. On our quantified eustatic curve (Figure 11), the Valanginian lowstand is followed by early Hauterivian eustatic rise with a magnitude of at least 30 m. After a sea level fall at the end of the early Hauterivian, there is another rise of at least 60 m in a time interval of at most 2 m.y. The total magnitude of sea level change during the Hauterivian is estimated to have been at least 60 m between a low in the uppermost Valanginian to a high in the basal Barremian. This generally agrees with the results of Haq et al. (1988), who place a lowstand in the Valanginian and a highstand in the basal Barremian, but the curves differ in detail.

There is little agreement between the two curves for the Barremian–Aptian interval. For the Albian both our curve and the Haq et al. (1988) curve indicate an overall sea level rise with a highstand in the upper Albian. In the Upper Cretaceous, both curves agree with respect to a few important events, but again show different amplitudes that include middle Cenomanian and middle Turonian sea level falls, and a maximum highstand just after the Cenomanian–Turonian boundary.

Hallam (1988) obtained an Upper Jurassic curve similar in general form to ours, but again the curves differ in detail. For example, Russian platform and Siberian data do not reflect important sea level falls during the basal Callovian and basal Oxfordian. Hallam (1988) summarized transgressive/deepening events recorded on various continents and regressive/shallowing events of regional importance in Europe. Note that most of these events correspond to those of our quantified eustatic curve and include transgressive episodes from the late Bajocian, late Bathonian, early Oxfordian, middle Oxfordian, late Oxfordian, early Kimmeridgian, and middle Volgian. Regressive events occurred during the latest early Callovian, latest early Oxfordian, latest middle Oxfordian, and early Kimmeridgian (submutabilis zone).

In their general trend, our results agree particularly well with those of Weimer (1984) (using the Obradovich and Cobban time scale) for the Upper Cretaceous of the United States Western Interior. Our quantified eustatic curve includes some high-frequency oscillations that do not appear on the Weimer (1984) curve, but at the level of major events, the agreement is excellent.

DISCUSSION

The relationship between eustatic variations and sedimentation is quite different for cratonic areas than it is for passive margins. This difference is a result of contrasting geometries (hypsometries), sedimentation rates, and tectonics. High rates of subsidence and sediment supply on passive margins result in relatively continuous deposition of thick (>100 m) sedimentary units. Shoreline shifts are primarily caused by variations of rates of eustatic change, and relative sea level change can be interpreted through change of coastal onlap. However, even though eustatic change is generally considered as the main factor that drives coastal onlap shifts, transgressions and regressions on passive margins remain very sensitive to subsidence and sedimentation rates. For example, Pitman (1978) demonstrated that on passive margins, transgressions and regressions may occur as a result of variations in the rate of sea level fall, which may result in potential error in reconstructing eustasy on the basis of changes in coastal onlap unless the time and space distribution of tectonic subsidence is known. This problem does not arise in cratonic regions such as the Moscow depression, which lacks discernible syndepositional tectonics and has extremely slow sedimentation rates. In these environments, transgressions and regressions are driven only by eustatic rise and fall, respectively.

An important difference in the phase relationship between eustasy and shoreline shifts (transgressions-regressions) exists between passive margins and cratonic basins. Angevine et al. (1990) showed that maximum regression may occur anywhere from the point of maximum rate of eustatic fall to lowstand, depending on tectonics and geometry. This results in different timing of shoreline shift episodes in different basins caused by the same eustatic change. Angevine et al. (1990) calculated that for third-order eustatic variations, transgressive/regressive episodes may vary in timing by as much as 2.5 m.y. in different basins, resulting in uncertainties of dating eustatic events inferred from subsiding basins, but are avoidable only in the unusual case in which the time and space distribution of tectonic subsidence rate is well documented for the period of deposition. Some workers have argued that the most meaningful way to view subsidence, eustasy, and sedimentation on passive margins is on the

Figure 11—Quantified eustatic curve for late Bajocian–Santonian. The time scale is from Harland (1990). The elevation scale is arbitrary, with 0 set at the lowest point on the curve. The position of the curve relative to present sea level can be established if one can identify a frame that has been stable between the Mesozoic and the present. A baseline in Cenomanian–Turonian strata of Minnesota is considered best suited for this purpose, and indicates that 160 m should be added to the eustatic scale (see discussion in text). The width of the band defined by high and low estimates reflects the various sources of error in the analysis, including interpretations of water depth, decompaction, lithology, stratal thickness, and correlation. Subaerial unconformities are assumed to represent at least some time of 0 water depth (exposure), and are indicated by convergence of high and low estimates. The curve represents eustasy to the extent that the Russian platform frame of reference is sensitive to the relationship between ocean basin volume and ocean water volume.

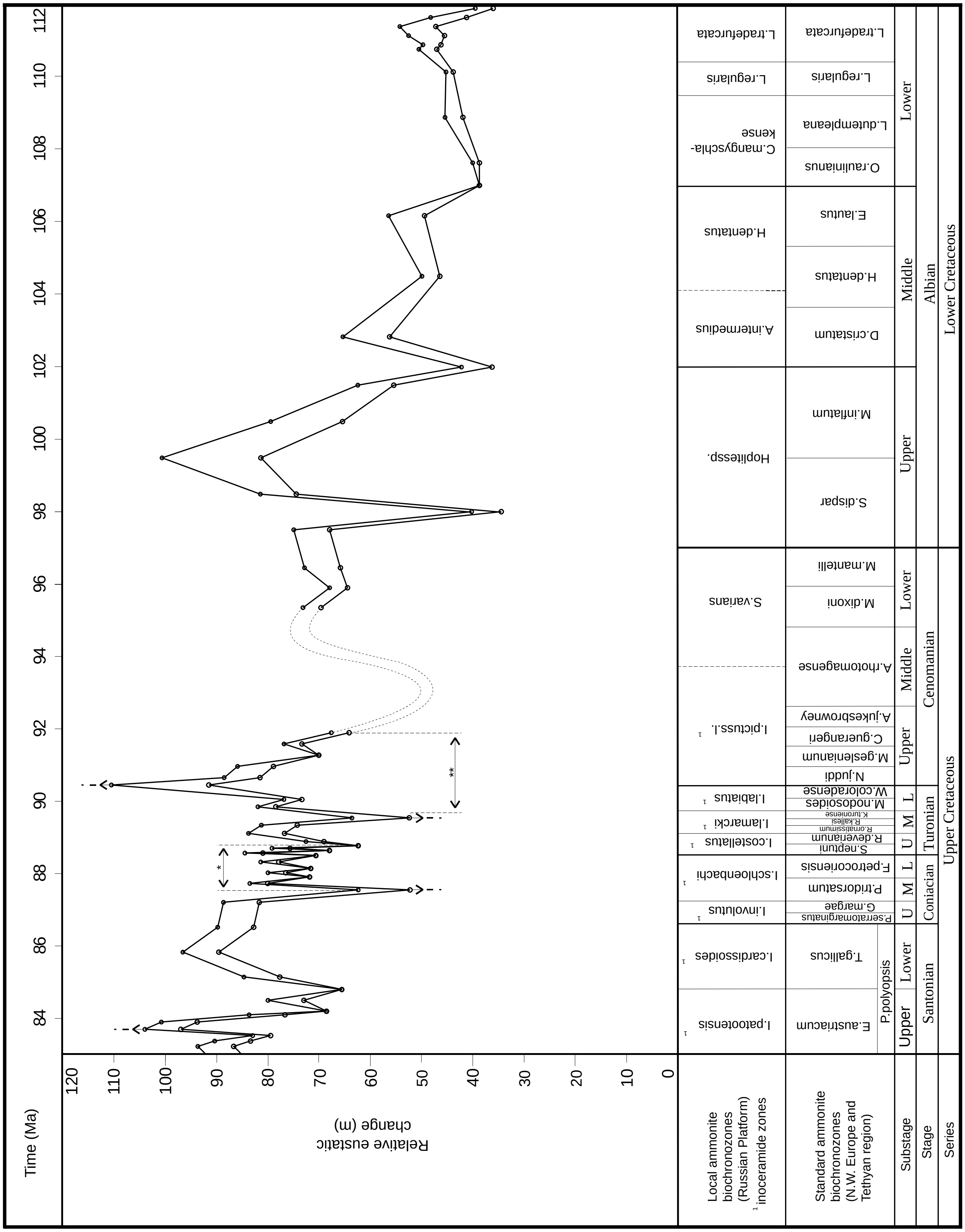

Time (Ma)
Relative eustatic change (m)
Local ammonite biochronozones (Russian Platform) ¹ inoceramide zones
Standard ammonite biochronozones (N.W. Europe and Tethyan region)
Substage
Stage
Series
I.patootensis
I.cardissoides
I.involutus
I.schloenbachi
I.costellatus
I.lamarcki
I.labiatus
I.pictuss.l.
S.varians
Hoplitessp.
H.dentatus
A.intermedius
C.mangyschlakense
L.regularis
L.tradefurcata
E.austriacum
T.gallicus
P.polyopsis
P.serratomarginatus
G.margae
P.tridorsatum
F.petrocoriensis
S.neptuni
R.deverianum
R.ornatissimum
R.kallesi
K.turoniense
M.nodosoides
W.coloradense
N.juddi
M.geslenianum
C.guerangeri
A.jukesbrowney
A.rhotomagense
M.dixoni
M.mantelli
S.dispar
M.inflatum
D.cristatum
H.dentatus
E.lautus
O.raulinianus
L.dutempleana
L.regularis
L.tradefurcata
Upper
Lower
U
M
L
Middle
Santonian
Coniacian
Turonian
Cenomanian
Albian
Upper Cretaceous
Lower Cretaceous

Figure 11.

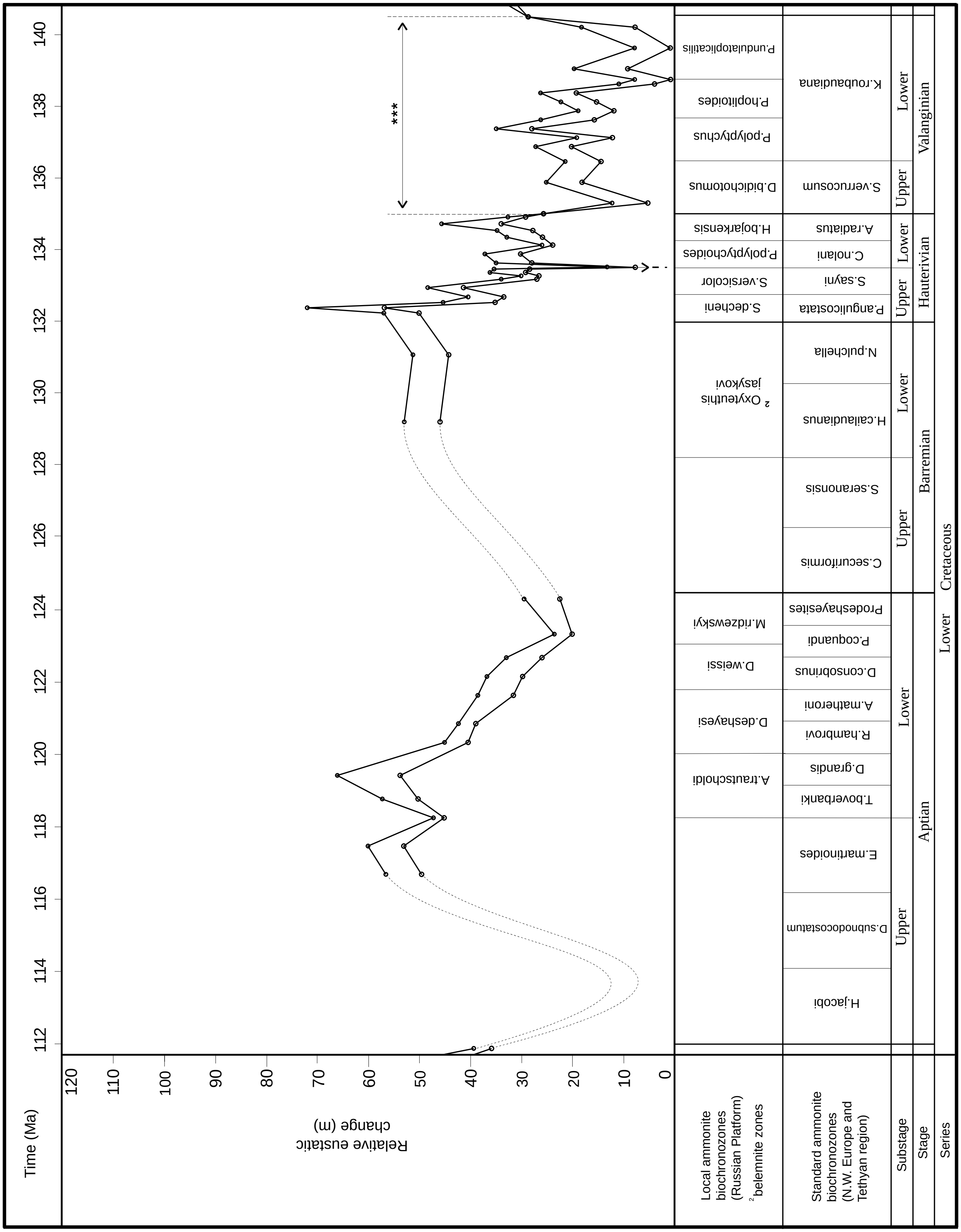


Figure 11—Continued.

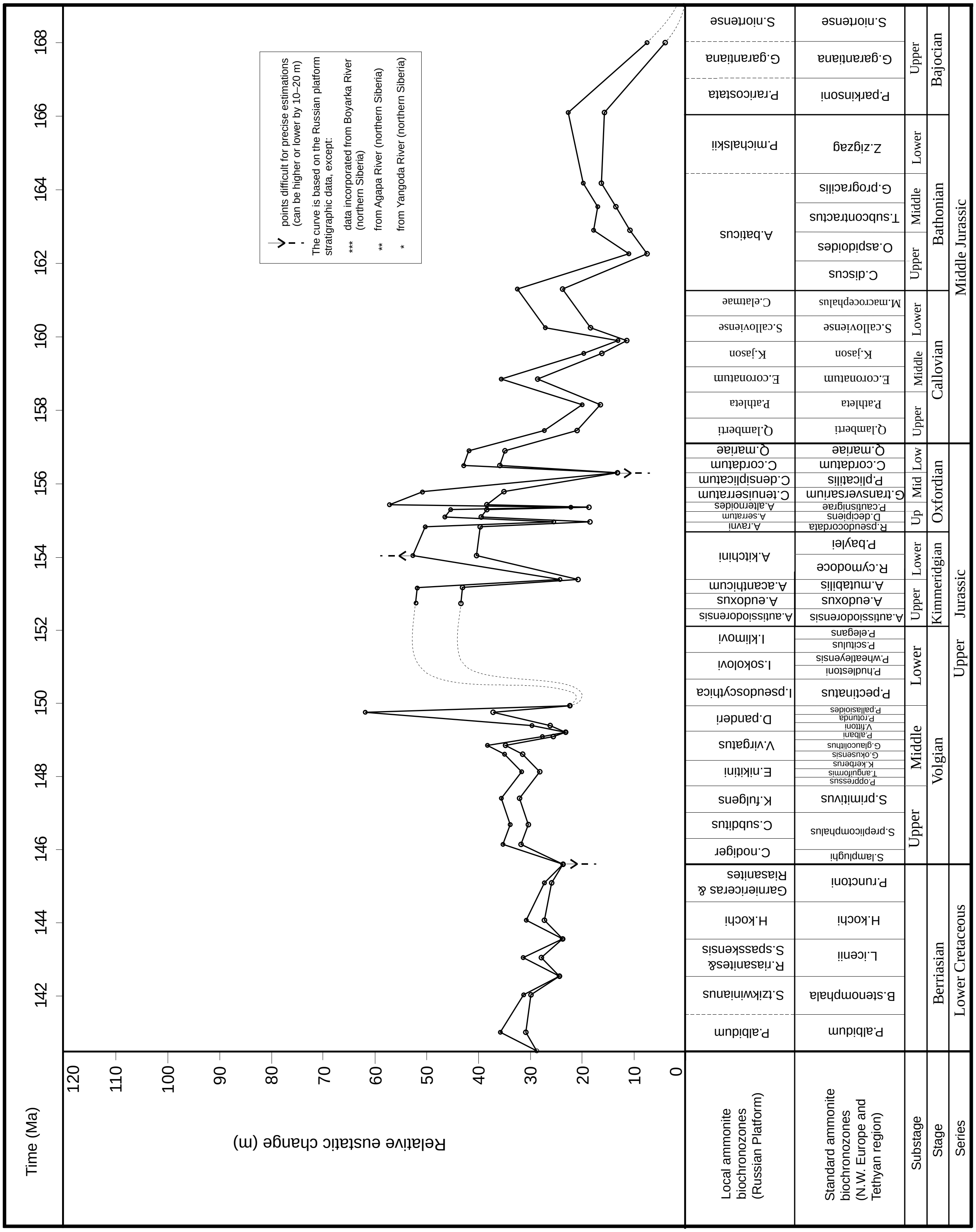


Figure 11—Continued.

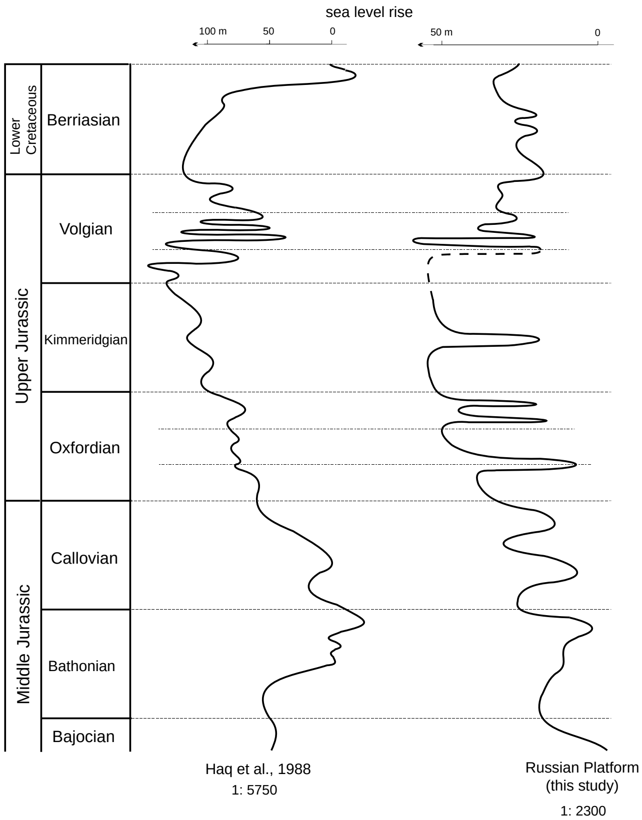


Figure 12—Comparison of Jurassic results of our study with those of Haq et al. (1988). Amplitudes from Haq et al. (1988) are 240% greater than those established on the basis of Russian platform stratigraphy (rescaled for illustration purposes).

basis of rates rather than amounts (Pitman, 1978; Posamentier et al., 1988; Christie-Blick, 1990). However, if the rate of subsidence is zero and the rate of sedimentation is low, as on the Russian platform, it may be useful to consider amounts of eustatic change instead.

The tectonic stability and very slow sedimentation rates of the Moscow depression make a phase relationship such that eustasy and shoreline shifts change in parallel. Thus, assigning eustatic events to stratigraphic elements observed on the Russian platform is much more precise than would be possible on passive margins. Another advantage of the Russian platform is its well-documented ammonite biostratigraphy (for most of the section), which provides the most reliable correlation possible.

Potential errors in eustatic reconstructions arise from different sources on passive margins and stable cratons (e.g., Moscow depression). On passive margins, large potential errors may occur from subsidence, sedimentation, and water depth (all terms of the backstripping equation), whereas erosion is a negligible factor compared to sedimentary thicknesses. On the Russian platform, potential errors may occur from estimating water depth and erosion, with smaller errors arising from minor variations of sedimentation. These errors can be minimized by the use of multiply redundant stratigraphic data.

The greatest potential source of error for eustatic reconstruction based on the stratigraphy of the Moscow depression arises from paleodepth interpretations. This is a universal problem, but compared to other basins, the Moscow depression is well suited for paleodepth analysis as a result of shallow water, and thus relatively precisely estimable paleodepths. Unlike previous sea level analyses based on passive margins, in which potential errors from estimating thermotectonic subsidence are so great that water depth variations are small in comparison, in our analysis these same water depth variations are the largest potential sources of error and have been carefully accounted for to achieve the greatest eustatic interpretive reliability.

Erosion in the Moscow depression resulted in very limited distribution of certain stratigraphic units, making it more difficult to constrain paleodepth estimates on the basis of paleogeography and stratal geometry. The areal extent of younger sediments on the Russian platform is more limited than that of older sediments due to extensive postdepositional (including Quaternary) erosion. For example, Upper Cretaceous strata are only locally preserved, although there is ample evidence that indicates deposition throughout most of the Late Cretaceous. Thus, our facies analysis and sea level curve based on the Russian platform are more precise for earlier times than for later. The lack of proximal margins (shoreline deposits) of many units due to erosion also results in difficulties with paleogeographic control for units deposited during highstands of sea level. During significant regressions, the Russian platform was completely exposed, resulting in unconformities due to erosion or nondeposition. Thus, the least accurate depth estimates are for times of extremely high or extremely low sea level. During highstands, the deep water is difficult to quantify, and the proximal margins of highstand deposits are generally eroded. During lowstands, previously deposited sediments may be eroded. Incorporating intervals from Siberian basins can fill the gaps, but represent an additional potential source of error. Nevertheless, the magnitude of this error is only a few meters, whereas the error for eustatic reconstructions from passive margins or subsiding basins (with kilometers of subsidence and sedimentation) can be considerably greater.

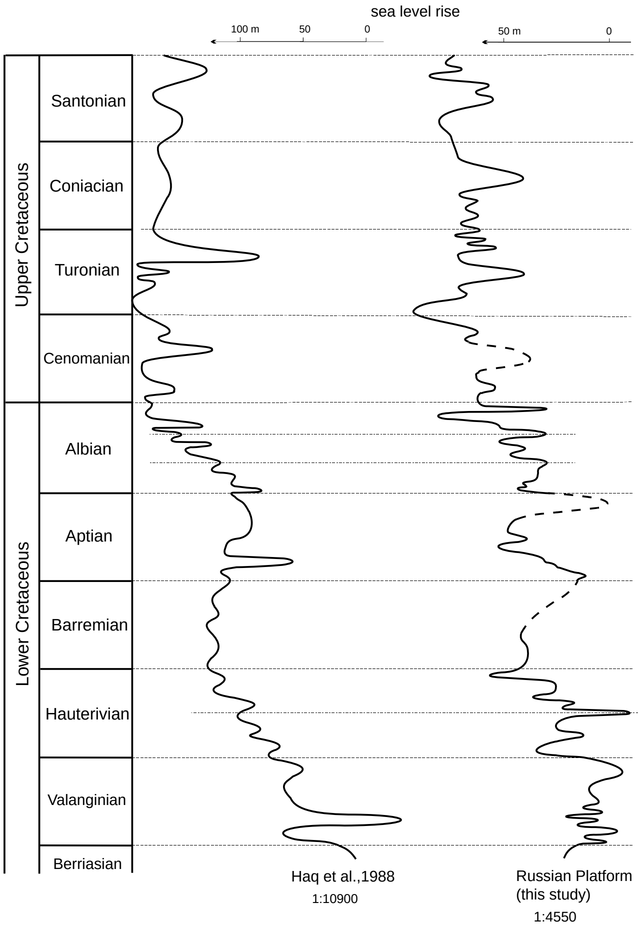


Figure 13—Comparison of Cretaceous results of our study with those of Haq et al. (1988). Amplitudes from Haq et al. (1988) are 250% greater than those established on the basis of Russian platform stratigraphy (rescaled for illustration purposes).

The quantification of eustatic variations on time scales of less than 1 m.y. bears on the issue of rates and causes of eustatic changes. Because we use stratigraphic techniques, deposition rates must be considered minimum estimates. Thus, rates of sea level rise are minimal. During the late Hauterivian, sea level rose by at least 60 m in at most 2 m.y. This rate of greater than 30 m/m.y. is normally considered greater than that attributable to the mechanisms accepted for causing sea level variations during the Mesozoic. In the absence of major continental ice sheets (Barron et al., 1981; Barron and Washington, 1985), the mechanisms for large, rapid eustatic variations are poorly understood. Some explanations have been offered that may bear on the problem (Karner, 1986; Cloetingh, 1988; Jacobs and Sahagian, 1993), but no single mechanism has been accepted that can account for the inferred magnitudes and rates.

CONCLUSIONS

The Russian platform provides a stable frame of reference for the quantification of Mesozoic eustatic changes. Our quantified eustatic curve so constructed should be more reliable than curves inferred from passive margin and subsiding basin stratigraphies because of better tectonic control. In our analysis, our largest source of error is paleodepth, which is relatively well constrained due to shallow water depths. Other, larger sources of error, such as thermal subsidence or sedimentation rate variability, are eliminated by the stable tectonic environment of the Russian platform. A well-established biostratigraphic framework, based mostly on ammonites and good correlation with western Europe, makes it possible to accurately assign ages to the interpreted eustatic events. The relatively small potential errors result mainly from paleodepth interpretations and erosion.

The fortuitous hypsometry and elevation of the Russian platform during the Mesozoic led to shallow-marine deposition useful for accurately determining paleowater depth. However, these same conditions also led to the development of many unconformities throughout the Jurassic and Cretaceous sections. The largest of these stratigraphic gaps (zone-to-substage duration) have been filled with stratigraphic data from adjacent subsiding regions with more continuous sections.

The quantified eustatic curve shows a general eustatic rise from the Middle Jurassic through the Upper Cretaceous, punctuated by many higher order events. The highest sea level was reached in the basal Turonian at an elevation of 270 m above present sea level (using Minnesota as a datum). Comparison of the quantified eustatic curve with other published sea level curves shows low-order similarities, but many differences at a higher order. In many cases, events can be correlated between curves, but magnitudes are different.

The quantified eustatic curve may be a useful tool applicable to any basin globally. The West Siberian basin may be a particularly well-suited case for initial application because of its well-established interregional biostratigraphic correlation with the Russian platform. Our eustatic curve (Figure 11) can be applied to problems of basin subsidence and basin modeling where eustatic input is necessary. Thus, our curve may potentially be used as a tool to (1) estimate the influence of local factors (subsidence and sedimentation rates) by removing the eustatic signal from stratigraphic data, (2) improve geological correlation (where there is poor biostratigraphic control), and (3) constrain the eustatic parameter for computer models of basin sedimentation. By subtracting the eustatic signal from backstripping results from any basin, tectonics and sedimentation can be quantified at a resolution and reliability previously unattainable. This improved data source may lead to a better understanding of depositional and thermal histories of specific sedimentary basins.

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