Glacioeustatic cycles in the Early Jurassic?

By **Klaus Brandt**, Tübingen

With 7 figures in the text

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Abstract: 10^5–10^6 y. eustatic cycles in the Sinemurian-Pliensbachian succession of Southern Germany and adjacent epicontinental areas are referred to changes in the volume of polar continental ice sheets, whose existence is indicated in Northern Siberia. This view is supported by a correlation between sea-level changes and palynological curves as well as by the occurrence of glendonites.

Zusammenfassung: Das Sinemurium und Pliensbachium Süddeutschlands und angrenzender epikontinentaler Gebiete ist gekennzeichnet durch eustatische Zyklen (Dauer 10^5–10^6 Jahre), die vermutlich auf Volumenänderungen von polarem Kontinentaleis in Nordsibirien zurückzuführen sind. Für diese Hypothese sprechen sowohl die Korrelation zwischen Meeresspiegelschwankungen und palynologischen Kurven als auch die Verbreitung von Glendoniten.

Introduction

Studies in the Lower Jurassic of England (HALLAM 1978, 1981a), France, and Germany (BRANDT 1985) show that these epicontinental sequences can be subdivided into a succession of shallowing-deepening cycles. The excellent biostratigraphic subdivision of the Jurassic in Western and Central Europe allows the correlation of these shallowing-deepening cycles at the precision of an ammonite subzone.

The sedimentary sequences of the South German and the Northwest German Basins record a history of continued subsidence throughout Triassic and Jurassic times. As sediment accumulation in the Lower Jurassic generally kept pace with basin subsidence, the average rates of subsidence can be calculated. Centres of subsidence (up to 5 cm/1000 y.) were located in the Northwest German Basin (Fig. 1), whereas subsidence rates in the South German Basin were comparatively low (up to 1 cm/1000 y.). Since no major tectonic events occured during Sinemurian and Pliensbachian times, the Northwest European epicontinental

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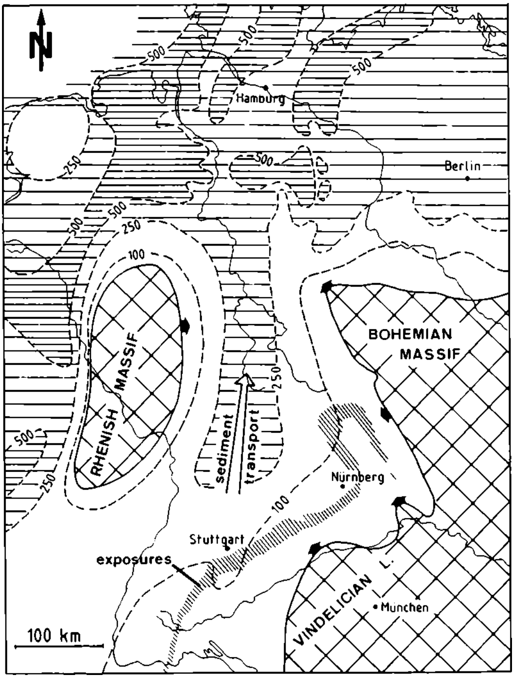

Fig. 1. Paleogeographical setting and isopachs of the Lower Jurassic in central Europe. Centres of sediment accumulation and subsidence were located in the Northwest German Basin. Black arrows = directions of terrigenous influx (main sources: BRAND & HOFFMANN 1963, ZIEGLER 1982).

basins (ZIEGLER 1982), and marine currents (e. g., tidal currents) were presumably only of minor importance (HALLAM 1981b, EINSELE 1985), the South German Basin represents a good example for studying the effects of ancient sea-level changes.

Shallowing-deepening cycles in the South German Basin

The Upper Sinemurian-Pliensbachian sequence in Southern Germany comprises a succession of claystones, marlstones, calcilutites, and calcarenites. Fig. 2A shows an idealized shallowing-deepening cycle. In the lower part of the cycle, silty clay and calcilutite are deposited below the effective wave base. Progressive shallowing, resulting in an increase in water energy, is indicated by winnowing of fine-grained sediment, and accumulation of coarse-grained, abraded components (bioclasts, intraclasts, and extraclasts). Widespread formation of glauconite and phosphorite typically occurs during these periods of extremely low net sedimentation rates.

The low rate of deposition probably also favoured the formation of carbonate concretions. The concretions are generally uncompacted or only slightly compacted, as inferred by uncompressed burrows and fossils. The concretions were cemented during early diagenesis within a short distance – probably only decimeters or a few meters – below the sediment surface. Locally, further shallowing caused exhumation, transport, and accumulation of these concretions. Together with other coarse-grained fragments (fossils, lithoclasts) they formed "secondary hardgrounds", which were colonized by suspension-feeding borers and encrusting organisms.

A new phase of deepening is characterized by increasing contents of clay and calcilutite, and decreasing contents of fossils, intra- and extraclasts, glauconite, and phosphoritic concretions.

Fig. 2B shows a typical shallowing-deepening cycle in the Liassic of the South German Basin. Generally, only the deepening phase is preserved, whereas the sediments deposited during the shallowing phase were subsequently eroded. Thus, the erosion of the regressive sediments results in the formation of transgressive fining-up sequences. Reworked concretions and fossils at the base of the fining-up sequences, derived from the erosion of the underlying regressive sediments, suggest a substantial increase in water energy, probably caused by lowering of the storm-wave base during a sea-level fall.

In a shallow-marine environment, where sedimentation rate is higher than subsidence, and the depth range of storm waves remains constant, periods of

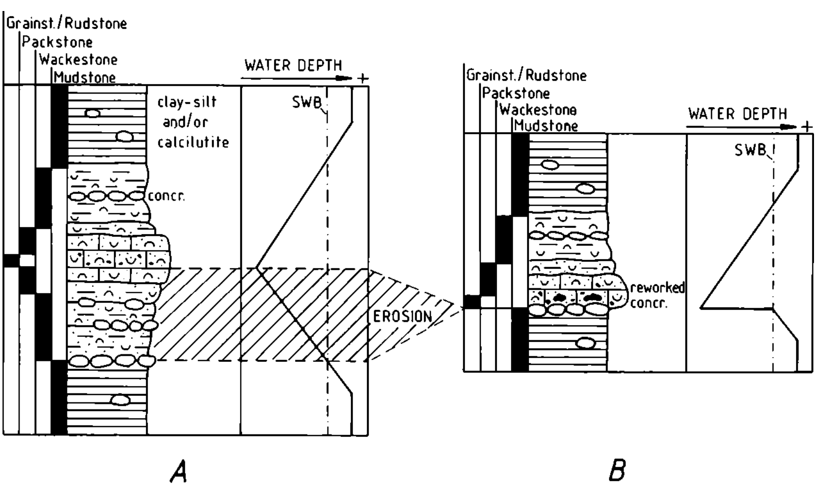

Fig. 2. Idealized (A) and typical shallowing-deepening cycle (B). Erosion of the regressive sediments caused the formation of fining-up/deepening-up cycles, which are characteristic of the Lower Jurassic sequence in the South German Basin. SWB = storm-wave base.

standstill during sea-level rise would presumably produce coarsening-up sequences, as shallowing is generally accompanied by an increase in water energy. Coarsening-up sequences are also expected to be formed during periods of decreasing rates of subsidence (assuming constant sea level and sediment supply) or during periods of increasing sediment influx (assuming constant sea level and subsidence). Therefore, the existence of widespread fining-up/deepening-up cycles in the Sinemurian and Pliensbachian, formed by deep erosion of the regressive sediments, indicates that drops of effective wave base – and sea level – actually occurred. Further, this interpretation implies that the rate of sea-level fall was higher than subsidence. A detailed study of the rather complicated interrelationship between rising and falling sea level, sediment supply, subsidence, and sedimentation at different locations within an epicontinental basin was carried out by EINSELE (1985).

In more basinal areas, well below storm-wave base, shallowing-deepening events can have effects which are the reverse of those in shallow areas. During transgressive phases most terrigenous sediments may be trapped in marginal shelf areas causing low deposition rates in basinal areas, whereas during regressions erosion on the shelf may cause high sedimentation rates in deeper offshore regions (EINSELE 1982, 1985). This example indicates that a simple lithostratigraphic correlation between sedimentary sequences of different basinal settings is not always possible, and that precise biostratigraphic correlation is of great importance in deciphering the relationships of sedimentary cycles in different marine environments.

VAIL et al. (1977, 1981) proposed eustatic curves, characterized by slow rises of sea level, minimal standstills, and very rapid, "geologically instantaneous" falls. As was pointed out by several authors (e. g. HALLAM 1984, MIALL 1984, EINSELE 1985) there is no reason for assuming such an asymmetrical mode of sea-level change. Yet, a remarkable point is the similarity between the Liassic shallowing-deepening cycles in the South German Basin (Fig. 2B) and the cycles proposed by VAIL et al. (1977, 1981), that suggest strong erosion of the regressive sediments, thus implying that the rates of sea-level fall were higher than the rates of subsidence.

Sea level changes in the Upper Sinemurian and Pliensbachian

Fig. 3 shows the relationship between rates of deposition, contents of carbonate, glauconite, phosphorite, Fe-oolite, and the proposed sea-level curve of the Upper Sinemurian-Pliensbachian sequence of the central Swabian Alb.

The sedimentation rates have been calculated using the time scale of VAN HINTE (1976). According to this time scale, 1 ammonite zone in the Lower Jurassic is on the average about equal to 1 m.y.

Since marine deposits of Lower Jurassic age are transgressive in many parts of

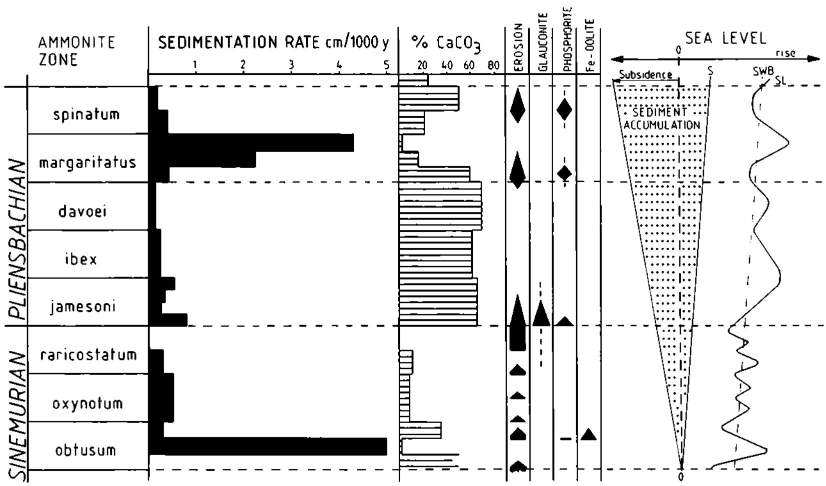

Fig. 3. Proposed sea-level curve for the Upper Sinemurian and Pliensbachian, related to rates of deposition, erosion, carbonate contents, accumulations of glauconite, phosphorite, and Fe-oolite of the central Swabian Alb (Kirchheim – Pliensbach area). S = sediment-water interface, SWB = storm-wave-base.

the world (Europe, Northern Asia, South America) an overall rise in sea level can be inferred. Upon this long-term deepening trend, shorter period sea-level changes, as described above, are superimposed. The similarity of the short-period sedimentary cycles throughout the early Jurassic indicates that, in spite of the overall sea-level rise and continuing subsidence, no long-term change in water depth occurred. Thus, it is to be assumed that normally the net sedimentation rates in the South German epicontinental sea were adjusted so as to maintain a state of equilibrium relative to the sea surface.

Remarkable are the high sedimentation rates (4–12 cm/1000 y.) in the *obtusum* Zone and the upper *margaritatus* Zone, which compare well to deposition rates on modern shelves. During both periods, dark, monotonous clays were deposited, showing no signs of erosion. It can be concluded that they were deposited below storm-wave base during periods of high sea level. Another major deepening event occurred at the base of the Pliensbachian (*jamesoni* Zone). All three deepening events can be correlated with marine transgressions on the Armorican Massif and the Massif Central. Reworked layers at the base of the *jamesoni* Zone, the lower *margaritatus* Zone and the upper *spinatum* Zone, documenting lowstands of sea level have been traced in the South German, Northwest German, Paris and Aquitaine Basins. A more detailed description of the shallowing-deepening cycles in the Sinemurian-Pliensbachian sequence of Southern Germany is given by BRANDT (1985).

A major limitation in the eustatic interpretation of these shallowing-deepening cycles is the difficulty of extending this correlation to other continents, where biostratigraphic zonation is less detailed. Nevertheless, transgressive Lower Jurassic sequences are recorded from South America (HILLEBRANDT 1971) and Japan (HIRANO 1971, 1973) with sedimentary cycles similar to the cycles described in Europe.

The duration of the short-period eustatic cycles in the Sinemurian and Pliensbachian ranges from several hundred thousand years to 2 million years. According to the classification proposed by VAIL et al. (1977) and MIALL (1984), they represent 3rd and 4th order cycles.

As the amplitude of the Lower Jurassic sea-level fluctuations is unknown, it is not possible to determine the rate of sea-level change. However, some general remarks concerning the minimum speed of sea-level change can be made. Deepening can only occur when the rates of sea-level rise and subsidence are higher than the rate of sediment accumulation. In the South German and the Northwest German Basins reworked layers, formed above storm-wave base, are conformably overlain by thick claystone sequences (*obtusum* and *margaritatus* Zone), deposited below storm-wave base. Therefore, the rate of sea-level rise and subsidence combined must have been significantly higher than the sedimentation rates (4–12 cm/1000 y.) during these intervals. As the average rate of subsidence in the South German Basin was relatively small (< 1 cm/1000 y.), the minimum speed of sea-level rise necessary to cause deepening during these intervals must have been in the order of several cm/1000 y.

Causes of sea-level changes in the Lower Jurassic

Eustatic oscillations in sea level have been attributed to a variety of processes, such as waxing and waning of continental ice sheets, variations in sediment flux, crustal shortening, desiccation and flooding of small ocean basins, changes in the volume of the mid-oceanic ridge system, or continuing differentiation of lithosphere (PITMAN 1978, DONOVAN et al. 1979).

Of these processes probably only two were capable of causing multiple 3rd and 4th order eustatic fluctuations:

- Changes in the volume of the mid-oceanic ridge system, either due to variations in the rates of seafloor spreading, or variations in the length of the ocean ridge system. According to calculations by PITMAN (1978), a change in the rate of seafloor spreading of 3 cm/y. at a 40 000-km-long ridge could cause a maximum rate of sea-level change of 1 cm/1000 y.
- Waxing and waning of polar continental ice caps. Total melting of all present continental ice would cause a sea-level rise of 65–80 m. Since part of this rise in sea level would be compensated for by isostatic adjustment of the oceanic crust, the sea-level rise relative to the continents should be 40–50 m (PITMAN

1978). During Pleistocene glacial periods the approximate sea-level fall is estimated at about 100 m below present sea level (DONOVAN et al. 1979). Thus the maximum amplitude between the Pleistocene glacial epochs and total melting of all land ice is about 150 m. The average rate of the Holocene sea-level rise is about 10 m/1000 y.

The calculations by PITMAN (1978) indicate that the maximum rate of sea-level change caused by volume changes of the oceanic ridge system is not fast enough to account for the formation of the short-term oscillations described in this paper. As was pointed out by VAIL et al. (1984), the only known mechanism that produces rates of sea-level change, sufficiently high to cause formation of 4th order eustatic cycles is continental glaciation. Eustatic fluctuations due to volume-changes of the continental ice are by 3 orders of magnitude faster than sea-level changes due to changes in the volume of the oceanic ridge system.

Up to now many authors have assumed that no polar ice caps existed during the Jurassic (e. g. SCHWARZBACH 1974, FRAKES 1979, HALLAM 1981b), and that mountain glaciation was volumetrically insignificant. Therefore, a glacioeustatic interpretation of the short-period sedimentary cycles in the Lower Jurassic would not be possible. For this reason it seems appropriate to briefly reconsider the geological data which led to the assumption of an equable, icefree climate in the Jurassic.

Paleoclimate and paleogeography in the Early Jurassic

Paleotemperature data

Oxygen-isotope studies in the carbonates of Jurassic belemnite rostra (FRITZ 1965, STEVENS 1971, STEVENS et al. 1971) yield significantly higher sea-water temperatures than do exist at present in comparable latitudes. However, large variations in the oxygen-isotope values make the usefulness of this method for the Jurassic questionable (FRAKES 1979). Several reasons may be responsible for conflicting Jurassic paleotemperature data:

(1) The $^{18}O^{\circ}$ content of the Jurassic oceans is not known. EPSTEIN et al. (1953) estimated that a variation in salinity of 1 ‰ would be accompanied by 1° C error in temperature determinations from shells in isotopic equilibrium with the paleo-ocean water. Therefore, the observed changes in $\delta\,^{18}O^{\circ}$ may record variations in salinity – and ice volume – rather than variations in temperature. For the Pleistocene, VAN DONK (1976) estimated that "at least 90 percent of the changes in the isotopic composition are attributable to variation in the isotopic composition of ocean water, which is due to the waxing and waning of large continental glaciers".

(2) It is not known whether Jurassic belemnites secreted their carbonate in isotopic equilibrium with ocean water. SCHOPF (1980) noted that "isotopic frac-

tionation values have been reported which are species-specific and which are distinct from values of local waters".

(3) It is not known whether growth of the belemnite rostra took place during the entire year or only during the warm summer seasons.

(4) The primary isotopic composition of oxygen in the carbonate shell has to be preserved, which is difficult to verify for Mesozoic carbonates (HOEFS 1980).

The problems described suggest that the paleotemperature data for the Jurassic cannot be regarded as reliable indicators of average annual temperatures. According to FRAKES (1979), undetected alteration or paleosalinity effects generally tend to raise the initial temperatures.

Paleontologic data

Fossil plant remains found in Jurassic deposits of the Canadian Arctic Archipelago, Greenland, Spitsbergen, and Antarctica are generally considered to evidence temperatures in high latitudes which were significantly higher than at present (SCHWARZBACH 1974, DONN 1982). However, considering the different latitudinal position of continents in the Jurassic due to plate motions, the paleobiological evidence from these areas is far less spectacular. According to paleogeographic reconstructions of SMITH et al. (1977), and BARRON et al. (1981) the North Pole was situated in North-eastern Siberia during early Jurassic times. Thus, Greenland, Spitsbergen, and the Canadian Arctic Archipelago lay approximately between 40° and 70° N in the Pliensbachian (Fig. 4). Since modern woodlands extend beyond 70° N in Northern Asia, fossil plant remains from these regions cannot be regarded as evidence of a warmer climate in high latitudes during the Lower Jurassic.

Annual growth rings are common in Jurassic fossil woods of Eurasia (VAKHRAMEYEV 1964), thus seasonality is implied. FRAKES (1979) suggested that seasonal variations in rainfall might have caused the construction of the growth rings. However, this seems rather unlikely because coal-formation in the Jurassic was very widespread in Asia (Fig. 4), indicating a humid climate (SCHWARZBACH 1974). A comparison with the distribution of recent peat deposits indicates that peat formation in semiarid zones with seasonal rainfalls is insignificant. Thus it can be concluded that a clearly defined seasonal climate prevailed during the Lower Jurassic in Northern Asia, with low temperatures during a considerable part of the year.

The assumption that the Jurassic had a warm and equable climate was partly based on the widespread distribution of terrestrial or marine fossils, such as ferns (BARNARD 1973) or bivalves (HALLAM 1981b). However, it should be noted that occurrences of species, considered to be indicative of tropical or temperate climatic conditions in high latitudes, are always restricted to certain portions of the Jurassic sedimentary sections in these areas. Therefore, they document warm cli-

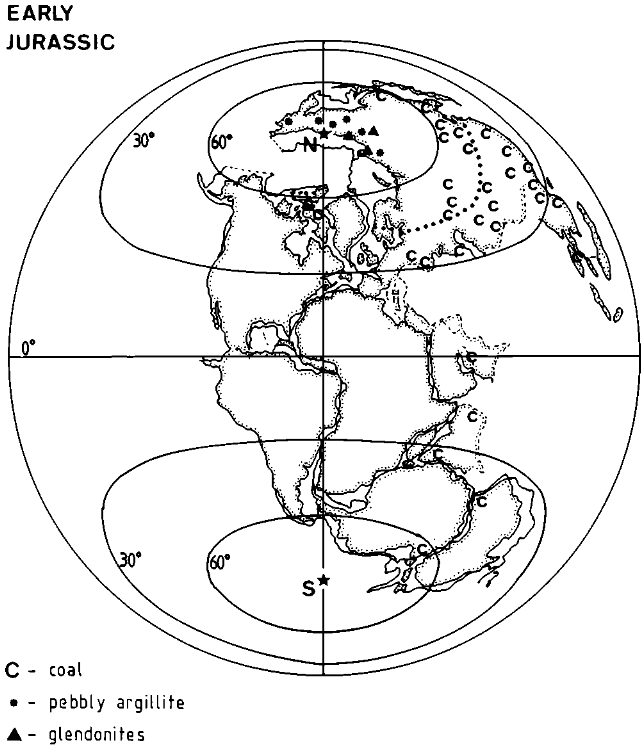

Fig. 4. Global paleogeography in the early Jurassic (Pliensbachian). Continental positions after SMITH et al. (1977). Data on distribution of coals based on BALKWILL et al. (1977), BROWN et al. (1968), MEYERHOFF (1970), NALIVKIN (1973), SATO (1975), VINOGRADOV (1968), and PARRISH et al. (1982). Distribution of Jurassic pebbly argillites, which are assumed to be of glacial-marine origin, according to EPSHTEYN (1978). Stippled line = southern boundary of vegetation of extratropical type during the Lower Jurassic (after VAKHRAMEYEV 1982). Distribution of Jurassic glendonites according to KAPLAN (1978).

matic conditions in high latitudes only for certain intervals in the Jurassic, but they do not represent evidence of a warm and equable climate throughout Jurassic time.

Distribution of coals

Fig. 5 shows the latitudinal distribution of coal deposits in the Northern Hemisphere for several periods and stages of the Mesozoic and Cainozoic and, for comparison, the distribution of recent peat deposits. In the Northern Hemisphere, the maximum volume of modern peat formed along a relatively well-defined belt between 45° and 70° N. The rather insignificant amount of peat in tropical and subtropical regions is thought to result from increased destruction of plant material in low latitudes by oxidation and bacterial activity (FRAKES 1979). Whereas the northward distribution of peat is limited by temperature and sunlight, its southward distribution is limited by precipitation and evaporation.

Although coal formation depends not only on temperature and precipitation, but also on other factors (for instance drainage and subsidence), it can be noted that the principal pattern of coal distribution did not change significantly throughout the Jurassic and Cretaceous. Thus, the bulk of coals of Lower Jurassic age in Northern Asia formed in the humid, cool temperate zone north of the arid, subtropical belt.

Further, it is interesting to note that the northern limit of Jurassic coal deposits corresponds rather well with the northern boundary of modern peat formation, thus indicating similar climatic conditions in these latitudes.

Glacial-marine sediments in Northern Siberia?

Deposits of the Jurassic period in Northern Asia generally consist of gray terrigenous sediments (conglomerate, sand, silt, and clay). The extremely insignificant volume of carbonates, widespread coal deposits, and the absence of evaporites (NALIVKIN 1973) indicate a temperate and humid climate. In several parts of Siberia detrital deposits with *Amaltheus margaritatus* rest transgressively on older formations, thus indicating a significant transgression in the Lower Jurassic (NALIVKIN 1973).

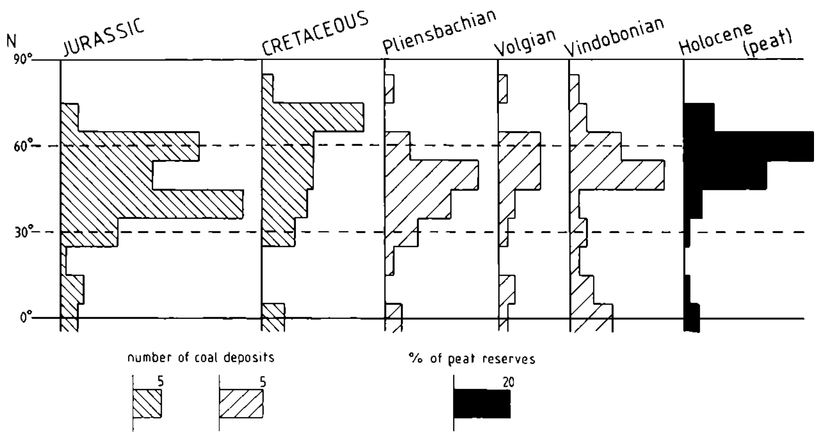

Fig. 5. Histograms of the latitudinal distribution of coals and peat in the Northern Hemisphere. Histograms of the Jurassic and Cretaceous periods are based on data of MEYERHOFF (1970) and DREWRY et al. (1974). Histograms of the Pliensbachian, Volgian, and Vindobonian according to PARRISH et al. (1982).

EPSHTEYN (1978) described from the Nera-Kolyma interfluve pebbly argilites of Bajocian-Callovian age with unusual grain size and material composition, which he interpreted as being of glacial-marine origin. The pebbly argillites are grey in color, and contain randomly distributed, sandy (up to 30 %) and coarsely clastic (up to 7 %) material, among which cobbles (up to 30 cm) and fine pebbles predominate. The pebbly argillites are intercalated into silt-clay and sandy deposits or they form independent units (up to 70–90 m) in company with seams of normal clays. The pebbly argillites have conformable, even, and distinct bedding plains, and have been traced over a distance of about 200 km.

According to EPSHTEYN (1978), the coarse-grained detrital fraction has been transported into the basin by shore-ice flows and icebergs. Further, EPSHTEYN (1978) noted that pebbly argillites of Mesozoic and Cainozoic age have also been described by other Russian authors from different regions in Northern Siberia. Fig. 4 shows locations with Jurassic pebbly argillites assumed to be of glacial-marine origin. It is remarkable that these sediments are all located near the paleopole for the early Jurassic.

Distribution of glendonites

In recent years significant evidence of paleoclimates in polar regions has been obtained by studies of the temporal and spatial distribution of glendonites (KAPLAN 1978, KEMPER et al. 1981, KEMPER 1983). Glendonites are pseudomorphs of predominantly calcite after ikaite. These crystal aggregates are restricted to marine shales and were probably formed in polar oceans at temperatures around 0° C (KEMPER et al. 1981). Modern precursors of glendonites are known only from the Arctic and Antarctic oceans and adjacent seas (SUESS et al. 1982). In the Southern Hemisphere, fossil glendonites occur in the Permian area of glaciation in Australia. In high latitudes of the Northern Hemisphere, glendonites have been traced in sediments of Pliensbachian, Middle Jurassic, and Lower Cretaceous age in Northern Siberia (KAPLAN 1978), as well as in deposits of Valanginian and late Aptian – early Albian age in the Sverdrup Basin and the West Spitsbergen Basin (KEMPER et al. 1981). According to KAPLAN (1978), who studied the distribution of glendonites in Northern Siberia, the pseudomorphs are usually associated with marine clay- and siltstones and can be traced over distances of up to 2000 km.

The close correspondence between the temporal and spatial distribution of glendonites and pebbly argillites in Siberia (Fig. 5 and 6) strongly supports the hypothesis that during parts of Lower and Middle Jurassic time large glaciers existed in Northern Siberia.

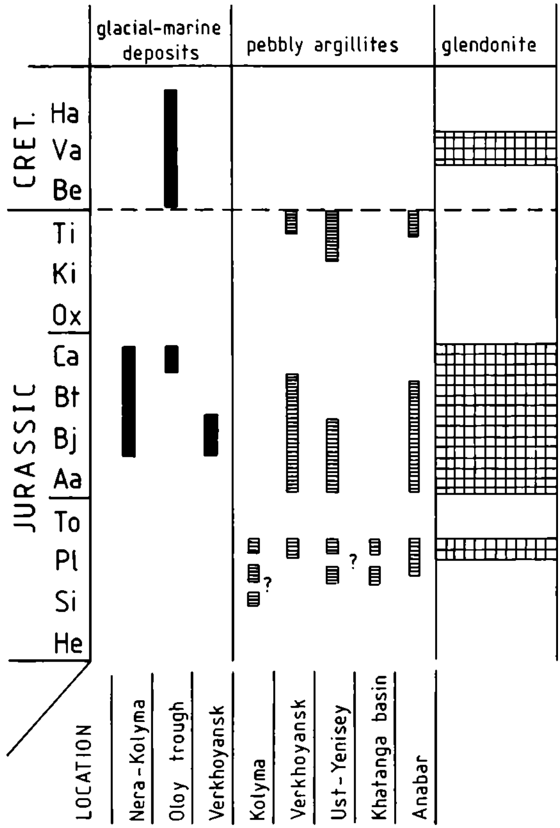

Fig. 6. Distribution of Jurassic and Lower Cretaceous glendonites (after KAPLAN 1978) and pebbly argillites (after EPSHTEYN 1978) in Northern Siberia.

Relationship between climatic and eustatic changes

If an extensive volume of polar continental ice actually existed during part of the Jurassic, changes in climate should have caused significant oscillations in sea level.

VAKHRAMEYEV (1982) determined the contents of *Classopollis* pollen in Jurassic and Cretaceous deposits in Eastern Europe and Northern Asia. *Classopollis* belongs to a group of conifers that became extinct at the beginning of the Tertiary. According to VAKHRAMEYEV (1982), the amount of *Classopollis* pollen in the sediments is related to the type of climate in which it existed. HUGHES (1973) also noted that "the distribution of *Classopollis* indicates a general latitudinal control, which is emphasized by the rarity of these grains in the Arctic".

Fig. 7A shows the content of *Classopollis* pollen in Jurassic and Cretaceous deposits of several regions. Two points seem to be particularly significant:

(1) The contents of *Classopollis* pollen are dependent on the latitudinal distribution of the sample. Thus, pollen content increases successively from N to S.

(2) Good correlation of minima and maxima of the pollen-content curves of the different regions.

This suggests that variations in the content of *Classopollis* pollen were mainly caused by climatic changes.

In the curve recorded in Northern Siberia (Fig. 7A, curve 4) there are only two periods showing significant pollen contents, the Toarcian and the Callovian-Kimmeridgian. According to VAKHRAMEYEV (1982), the two maxima in the

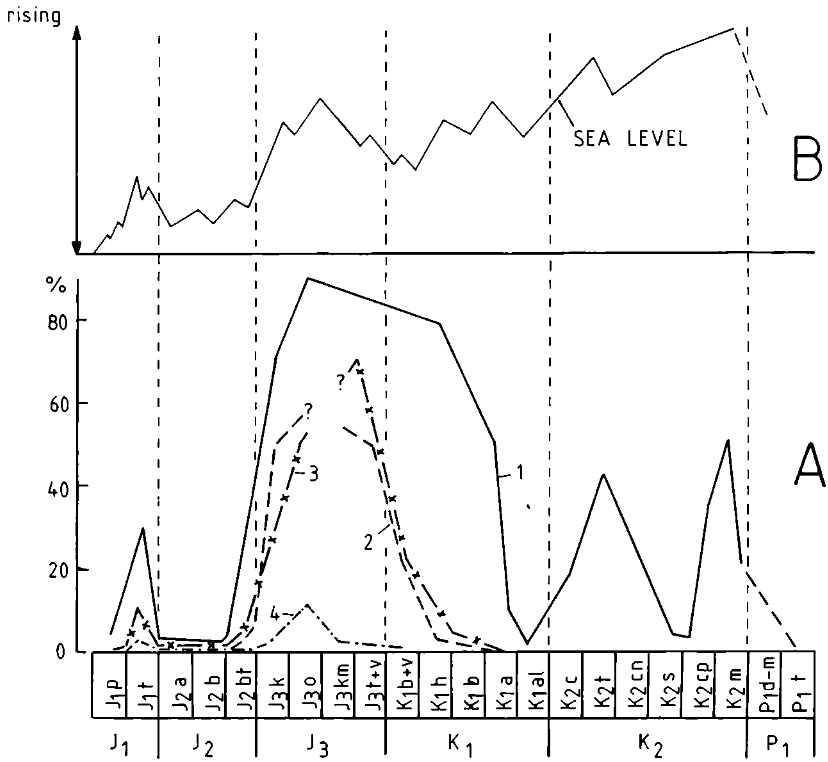

Fig. 7. (A) Curves of *Classopollis*-pollen content in Jurassic and Cretaceous deposits (after VAKHRAMEYEV 1982). 1: southern regions of the USSR; 2: central part of the Russian Platform; 3: Western and Central Siberia; 4: Northern Siberia. (B) Sea-level changes in the Jurassic and Cretaceous. Sea-level curve in the Upper Cretaceous according to HANCOCK et al. (1979).

Toarcian and Callovian-Kimmeridgian indicate ameliorations of climate. This interpretation is supported by the fact that no glendonites have been found in deposits of Toarcian, Oxfordian, and Kimmeridgian age (KAPLAN 1978). Both periods also mark peaks of major worldwide transgressions (HALLAM 1978, 1981; VAIL et al. 1984).

Climatic amelioration and high sea level coincide with the widespread occurrence of bituminous shales in the Toarcian (Europe, South America, Japan). This agrees well with the conditions during a "polytaxic" or "greenhouse" state (FISCHER et al. 1977), which is characterized by high sea level, high marine temperatures, reduced oceanic circulation, and anoxic bottom waters. Thus, the invasion of the boreal faunal realm in Northern Europe by Tethyan ammonites (HALLAM 1981b) may have been caused by climatic amelioration in the Toarcian.

Shallowing and regression at the end of the Toarcian (Germany, France, Southern Sweden, England) coincides with a sharp decrease in *Classopollis* pollen content and occurrences of glendonites in Northern Siberia.

During Callovian and Oxfordian time a global transgression took place, coinciding in time with climatic amelioration (VAKHRAMEYEV 1982) and increasing aridization. In Europe, a warmer climate is indicated by the northward advance of sponge and coralline reefs and growing biogenic carbonate production (EINSELE 1985, RICKEN 1985). The decreasing influx of terrigenous sediments into the South German Basin may have been caused by increasing aridization in the Upper Jurassic.

Conclusions

The overall rise of sea level in the Jurassic and Cretaceous (Fig. 7B) corresponds broadly to the contemporaneous disintegration of Pangea and the growth of new spreading ridges. Thus it can be inferred that the overall Mesozoic sea-level rise was partly caused by a significant increase in the volume of the oceanic ridge system. However, opening of the Atlantic did not start until late Mid-Jurassic time, therefore the early Jurassic sea-level rises are unaccounted for by the Pangea disintegration (HALLAM 1984).

Deepening-up/fining-up cycles in the Sinemurian-Pliensbachian sequence of the South German Basin indicate that during transgressive periods the rate of sea-level rise was higher than the rate of deposition. Thus, in the *obtusum* Zone and the upper *margaritatus* Zone (Fig. 3) the rate of sea-level rise and subsidence combined should have been significantly higher than the rate of sediment accumulation (4–12 cm/1000 y.). Vice versa, deep erosion of the regressive sediments during periods of falling sea level implies that the rate of sea-level fall was higher than subsidence.

It can be concluded that the short-period eustatic cycles described cannot have been caused by relatively slow geologic processes, such as volume changes of the oceanic ridge system, as the maximum rate of sea-level change due to this process was estimated at about 1 cm/1000 y. only (PITMAN 1978).

Thus, variations in the volume of polar continental ice seem to be the most likely control. A glacioeustatic interpretation is supported by paleogeographic and paleoclimatic data. Annual growth rings in fossil woods, extensive coal deposits, the absence of evaporites, and the insignificant volume of carbonates in Lower Jurassic deposits indicate a cool temperate and humid climate in the southern regions of Siberia. If the pebbly argillites in Northern Siberia, described by EPSHTEYN (1978) are actually glacial-marine in origin, the existence of an extensive continental ice sheet in Northern Siberia during considerable parts of the Lower and Middle Jurassic can be inferred. This assumption is also supported by occurrences of glendonites in Siberian deposits of Lower and Middle Jurassic age (Fig. 6). Further, the remarkable correspondence between climatic and eustatic variations (Fig. 7) suggests that the importance of glacioeustacy during the Mesozoic may have been largely underestimated.

Thus it is proposed that waxing and waning of polar continental ice was the principal cause of the short-period eustatic cycles (of 3rd and 4th order) in the Jurassic. Due to the incompleteness of the sedimentary record in slowly subsiding epicontinental basins, it can be assumed that only part of the original sea-level oscillations have been preserved. Therefore, the average duration of the eustatic cycles in the Lower Jurassic may have been significantly shorter than 1 m.y. Also, biostratigraphic resolution of the Lower Jurassic period is not good enough to allow correlation with Milankovitch cycles (i.e. variations in insolation caused by perturbations of the Earth's orbit).

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Anschrift des Verfassers:

Dipl.-Geol. KLAUS BRANDT, Geologisch-Paläontologisches Institut der Universität, Sigwartstr. 10, 7400 Tübingen 1.