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# Correlation and Non-Correlation of High Order Circum-Arctic Mesozoic Sequences

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Theme 5: The Barents Shelf and the East Greenland Margin: A Comparison

**Summary:** Eighty-two higher-order (1st, 2nd and 3rd order) sequence boundaries have been recognised from detailed studies of the Mesozoic succession of the Barents Shelf (including Svalbard), East Siberia and the Sverdrup Basin. Most of the Triassic sequence boundaries are synchronous throughout the study area, while, half of the Jurassic boundaries are synchronous, and only two sequence boundaries from the Cretaceous appear to be synchronous throughout the Arctic. The duration of third order sequences varies from 1 to 11 Ma in the Triassic, 2 to 16 Ma in the Jurassic and 2 to 21 Ma in the Cretaceous, while the duration of second order sequences varies between 3 and 14 Ma in the Triassic, 10 and 36 Ma in the Jurassic and 7 and 52 Ma in the Cretaceous. This sequence pattern deviates from the conceptual definitions of the Exxon School, where time is used as a criterion for assigning sequences to different orders. The synchronieity of most of the sequence boundaries in the Triassic supports ?eustatic control as a major factor in the formation of these sequences. The decreasing synchronieity of these sequence boundaries through the Jurassic and Cretaceous suggests an increasing degree of tectonic control on deposition, culminating in the break-up of the Pangea supercontinent.

## INTRODUCTION

Lithostratigraphy and biostratigraphy of the Mesozoic succession in the individual Arctic areas (Fig. 1) are presented in a number of papers. However, few papers presently consider the successions within a well-dated and correlated sequence stratigraphic framework.

Published inter-regional sequence correlation at systems tract level (sequences delineated with sequence boundaries and maximum flooding surfaces) of the Arctic is presently restricted to the Triassic. EMBRY (1988) has defined Triassic cycles for the Sverdrup Basin of Arctic Canada. Similar cycles were compared between Svalbard and the Sverdrup Basin by MØRK et al. (1989), and were subsequently correlated to Eastern Siberia (MØRK 1994, EGOROV & MØRK 2000). The hierarchic sequence system used in the present contribution (EMBRY 1993, 1995), was applied for Triassic successions throughout the Arctic and further to other areas by EMBRY (1997), while details on the base Olenekian and base Anisian sequence boundaries were reported by MØRK et al. (1994). A hierarchic sequences pattern was also applied for the Lower and Middle Triassic by VAN VEEN et al. (1993), and VIGRAN et al. (1998) by extending sequences as defined on Svalbard into the central western Barents Sea. The Upper Triassic and Lower Jurassic shallow marine to continental succession were correlated between the Barents Shelf, including Svalbard and the Sverdrup Basin by JOHANNESSEN & EMBRY (1989).

In the Jurassic, sequences of the Sverdrup Basin were reported by EMBRY (1993), and sequence boundaries extending from the Barents Shelf to Svalbard were assigned by SMELFOR (1994). Sequence correlation of the Upper Triassic to Lower Jurassic succession of the Canadian and Norwegian Arctic has been published by JOHANNESSEN & EMBRY (1989). From the Nordkapp Basin of the Barents Sea well dated transgressive-regressive sequences can be interpreted from non-continuous core material (BUGGE et al. in press). Condensed marl sequences in the Lower Cretaceous give several well documented sequence boundaries in platform areas of the Barents Shelf (ÅRHUS 1991, SMELFOR et al. 1998), and transgressive - regressive Cretaceous sequences may also be extrapolated from the paleontologically based paper of KELLY (1988) and from the seismic stratigraphic based contribution by SUND et al. (1986) and GABRIELSEN et al. (1990).

Study and comparison of second and third order transgressive - regressive sequences of the Arctic (Fig. 1), focus on the Barents Shelf and Svalbard, but also integrating the Sverdrup Basin and East Siberian successions was carried out by a group of Norwegian, Canadian, Russian and German workers (MØRK et al. 1995). The results of this study (Fig. 2) form the basis for the discussions of the nature of the correlation of these sequences as defined by their sequence boundaries. The sedimentary succession of the Wandel Sea Basin on northeastern Greenland, although not included in our Figure 2, also shows similar sequence development (HÅKANSSON & STEMMERIK 1984).

## CORRELATION PRINCIPLES

In their comparative study of Svalbard - Barents Shelf and the Sverdrup Basin, MØRK et al. (1989) defined simultaneous transgressions as transgressions that occur in various Arctic basins within the same one or two ammonoid zones; i.e. over a time-span of less than two million years, and independent transgressions as well-dated transgressions that have no counterparts in other basins. Most often a sequence boundary is dated by the age of the overlying sediment. In the present study the quality of datings varies. Best control is achieved in those parts of the succession which have good macrofossil control, although, such control is seldom found throughout the Arctic. An example from the Triassic succession is the compilation by DAGYS & WEITSCHAT (1993) where they have correlated approximately 80 ammonoid zones from these three

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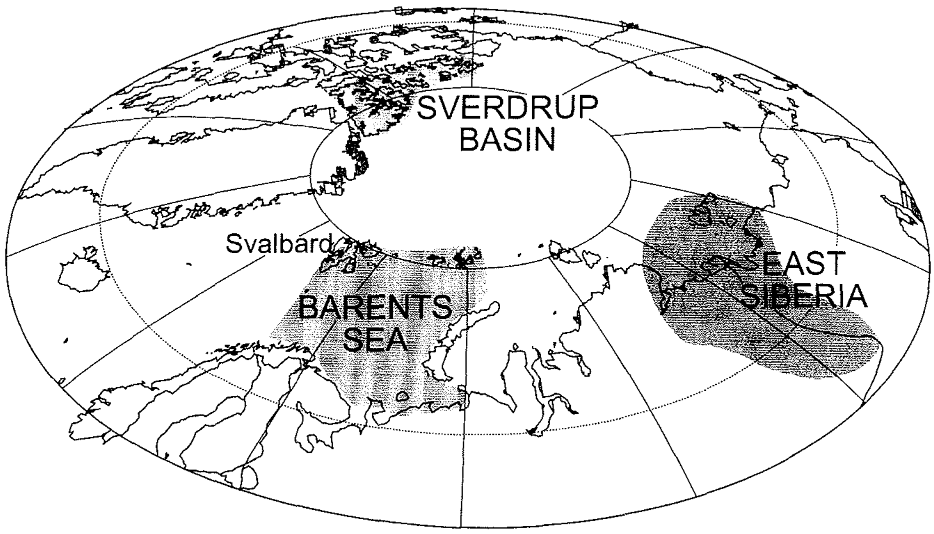


**Fig. 1:** An overview of the Arctic with the three studied areas (shaded).

arctic areas, however, only four of them are defined by the same ammonoid species in all areas. Sedimentation around the time of maximum flooding tends to be slow particularly in basinal settings, with a resulting concentration of pelagic fossils, e.g. ammonoids. Such fossils, however, may be dissolved under conditions of long exposure at the sea-bottom, something which explains many of the undated marine basinal successions. In many sections, there are only a few metres of sediments between the sequence boundary and the maximum flooding surface (i.e. the transgressive systems tract), and consequently the dating based on fauna over this interval may approach the real date of the transgression directly overlying the sequence boundary. This approximation is further improved by the general assumption that transgressions are relatively more rapid geological processes than regressive filling and progradation into sedimentary basins. Often palynomorphs or other microfossils are used for correlation, but they may be most suitable within single regions. The only practical way of correlating many of the episodes (sequence boundaries) is thus based on their relative position within the chronstratigraphical unit (stage), i.e. early Ladinian, early Norian etc.

## HIERARCHY

In the present study, the sequence boundaries are defined and classified according to tectonic influence and change in sedimentary response across the boundary as outlined by EMBRY (1995). In this system a sequence boundary of first order reflects response to major tectonic or orogenic activity. Both second and third order sequence boundaries are assigned after basin-wide studies, and show tectonic disturbance at basin margins while normal sedimentation resulting in deposition of conformal sediment packages took place in the basin. They differ in major change in sedimentary regime across second order boundaries, while the third order boundaries separate similar sedimentary packages. Lower order boundaries (fourth and fifth) mainly have local significance. Note that studying only local parts of a basin may result in the assignment of the boundary to a different, often lower, order than basin-wide studies. The depositional sequences, following the Exxon model, have been organised in a hierarchic system dependant on the duration of the different sequences (cf. MITCHUM & VAN WAGONER 1991, VAIL et al. 1991). No cyclic mechanism for high order sequences are up to now published, making time as a subdivision criterion dubious.

## CORRELATION OF HIGH ORDER SEQUENCE BOUNDARIES

Eighty-two sequence boundaries have been identified throughout the Arctic (Fig. 2), and their correlation is diagrammatically shown in Figure 3. As many as forty-five (55 %) of the boundaries can be followed throughout the Arctic and they delineate fifteen third order and eight second order transgressive – regressive sequences. Only three first order sequence boundaries are present, all in connection with major Cretaceous tectonic activity in the Sverdrup Basin.

In addition to the sequence boundaries that can be correlated throughout the Arctic, ten boundaries can be correlated between two of the studied regions (Figs. 3, 4). Seventeen sequence boundaries are regarded as independent, i.e. these boundaries can either be proven not to correlate with any counterpart, or the dating is too poor to support any correlation.

Looking at the sequence boundaries that can be followed throughout the Arctic, it is striking that most of them (5 second- and 5 third-order) have the same order throughout (Fig. 4), and only five of the boundaries contain mixed order boundaries. This suggests a degree of similarity in the processes that created the boundaries.

Eight independent sequence boundaries occur in the Sverdrup Basin, seven in the Svalbard/Barents Shelf, while only two occur in Eastern Siberia. It should be noted that as many as thirteen of these independent boundaries (77 %) are third order. This may indicate that minor geological processes of local significance were responsible for their formation.

The occurrences of sequence boundaries for the different

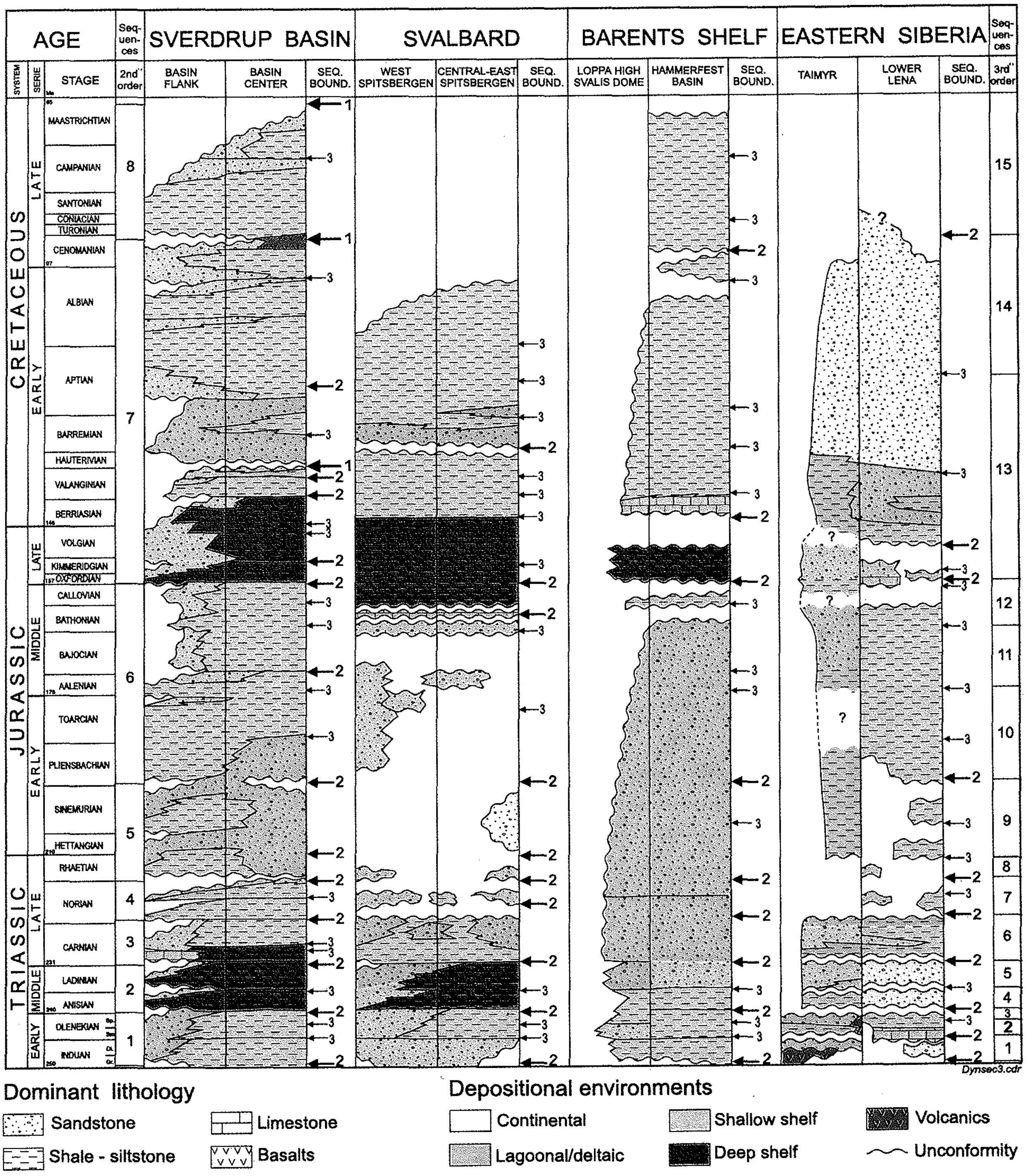


Fig. 2: Summary diagram for the Arctic Mesozoic sequences. The arrows show the localisation of 1st, 2nd and 3rd order sequence boundaries. Main lithologies and depositional environments are also indicated. This diagram forms the basis for the discussions of the present paper.

Mesozoic periods are shown in Figure 5. In the Triassic, more than 90 % of the sequence boundaries can be followed throughout the Arctic leaving only two as independent. The layer cake stratigraphy that occurs in the Triassic is further extended to other areas as the Tethys by the fact that most of the transgressions are initiated at the base of stages (cf. EMBRY 1997). Such a correlation was interpreted by MØRK (1994) to result from the original stages often being defined as transgressive - regressive cycles, or that they were initiated by prominent transgressions following minor breaks in deposition. Half of the Triassic correlative transgressions are of second order and are interpreted as eustatic elements by EMBRY (1988), MØRK et al. (1989) and MØRK (1994). EMBRY (1997) postulates that all the Triassic sequences are synchronous throughout the Arctic. They can also be followed to other areas, giving them a global nature. He attributes this to global tectonics that triggered eustatically controlled sedimentation.

In the Jurassic Period, five of the sequence boundaries correlate throughout the Arctic, four in addition correlate between

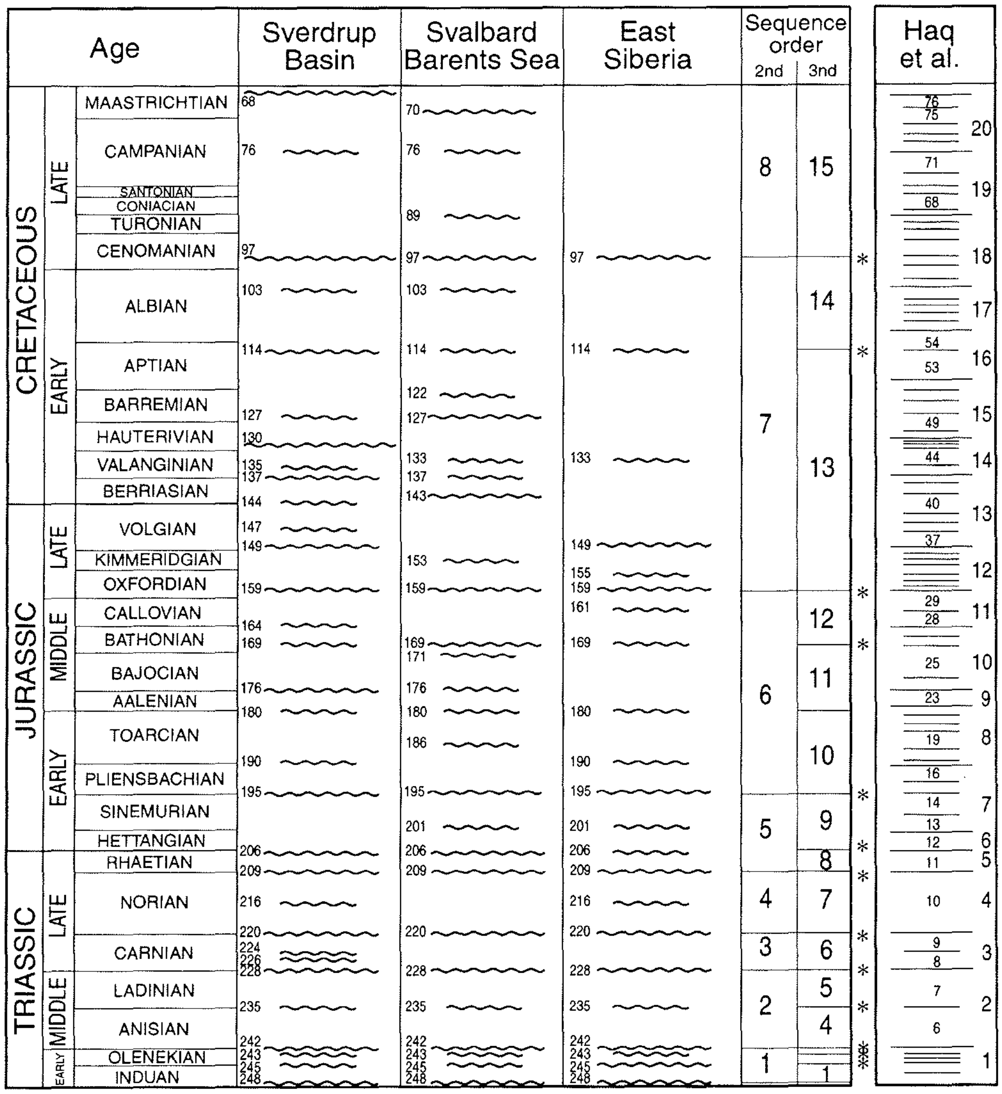

Fig. 3: Correlation diagram showing the observed sequence boundaries. Their given ages (see Fig. 2) are numerically indicated following the timescale of GRADSTEIN & OGG (1996), however, the numbers are only indicated to show the approximate position of the boundaries which by biostratigraphy are tied to the stage definitions rather than the geochronologic numerical values. The resulting 2nd and 3rd order circum Arctic sequences are also indicated. The stars indicate 'global' correlation, i.e. between the Arctic and the HAQ et al. (1988) study.

two of the basins, but as many as seven (23 %) are independent (Fig. 3). Most of the transgressions that correlate circum Arctic are of second order.

In the Cretaceous Period only two of the sequence boundaries can be followed throughout the Arctic (Fig. 3), while four others correlate between two basins. As many as eight (33 %) of the sequence boundaries are independent. Epeirogenic activity took place in all areas; in the Sverdrup Basin represented by three first order sequence boundaries (STEPENSON et al. 1987, EMBRY 1991). Svalbard was uplifted in the late Early Cretaceous as an early response to the collision of Greenland and Svalbard during the initial opening phase of the Norwegian Sea (STEEL & WORSLEY 1984, DALLMANN et al. 1993). In Eastern Siberia the Verkhoyanian folding was initiated in the late Jurassic, but major activity took place during the Creta-

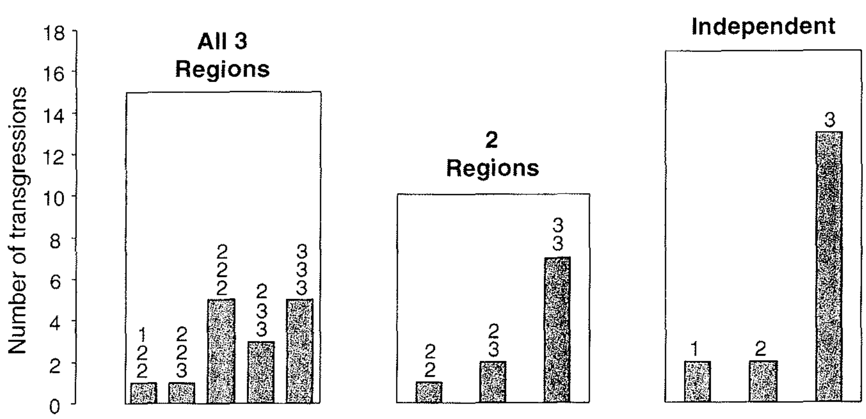


Fig. 4: The three thick bars show the co-occurrences of sequence boundaries between all three regions, between two and two regions while the column to the right show the independent sequence boundaries. The inset bars show the distribution on different orders of sequence boundaries that are correlated.

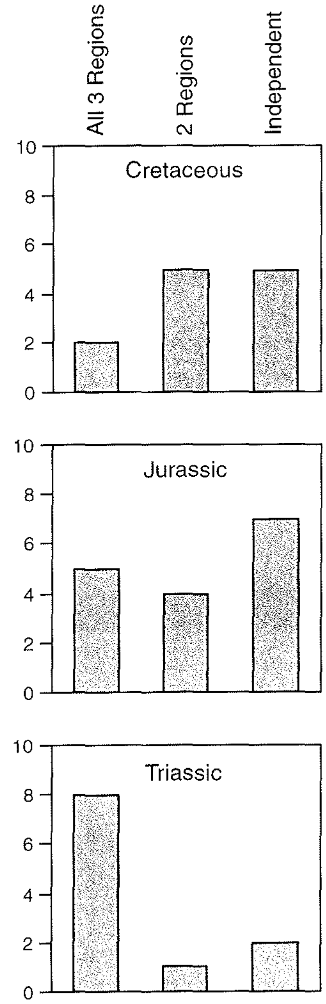


**Fig. 5:** Numbers of synchronous and independent sequence boundaries between the three studied areas through time.

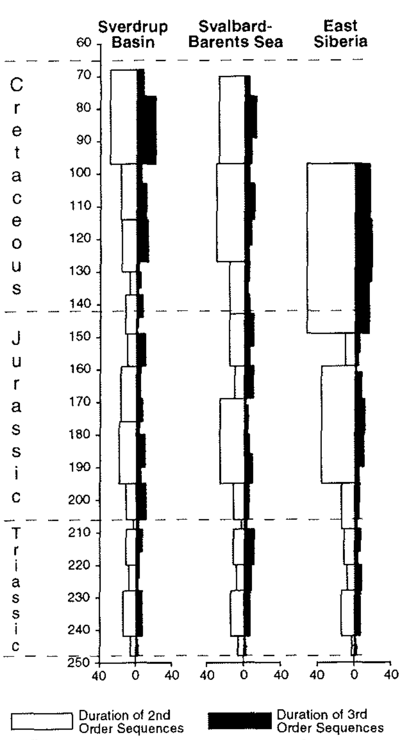


**Fig. 6:** Duration of second and third order sequences. Note the increase in duration of sequences and their decreasing correlation with time.

ceous (PARFENOV 1984) and resulted in continental sedimentation that only continued into the earliest Late Cretaceous (KOPORULIN & EGOROV 1994).

## SEQUENCE DURATION

There is a clear trend of an increase in the duration of both the second and third order sequences with geological time in the individual areas (Fig. 6). There is also a greater variability, however unsystematic, in the duration of sequences from the Triassic to the Cretaceous, especially for the second order sequences. Approximately half the number of second order sequences has duration of 8-16 Ma, while the spread in duration is from 3-52 Ma (Fig. 7). Most of the third order sequences have a duration between 2-16 Ma, with a maximum between 4 and 8 Ma. There is thus a clear overlap (Fig. 7) in the duration of 2nd and 3rd order sequences with the majority of both between 2 and 16 Ma. This pattern clearly differs from that of the Exxon School (MITCHUM & VAN WAGONER 1991, VAIL et al. 1991) where time alone is used as a criterion to delineate sequences of different hierarchic order.

## DISCUSSION

The correspondence of sequence boundaries between two and two areas is illustrated in Figure 8, and it is striking that all areas show very good correspondence in the Triassic. This correspondence diminishes through the Jurassic to being relatively poor in the Cretaceous. In the Triassic the continents were fused into the Pangea supercontinent and all the studied areas were located at its northern palaeo-margin. The great similarity in development reflects a possible eustatic effect on sedimentation, however, these areas are all facing or linked to the same palaeo-ocean, and may have been affected by simultaneous tectonic influence on one and the same lithosphere plate. The apparent sequence correlation also to the classical mid European areas in the Triassic (MØRK 1994) and globally (EMBRY 1997) shows that larger areas than the Arctic were affected by these processes.

During the Jurassic local tectonic control became progressively more important. The apparent combination of tectonic and eustatic influence on the generation of second and third order sequence boundaries may thus reflect significant plate-tectonic reorganisation that affected the intraplate stress regime of the oceanic (eustatic) and continental (tectonic) portion of each lithospheric plate (CLOETINGH 1988, EMBRY 1993, 1997). In the Cretaceous Period the tectonic processes seem to totally control deposition, and the apparent correlations may even be co-incidental.

The number of sequences is fewer than those recognised by HAQ et al. (1988) in their "global" study. In total, 15 third order sequences are recognised, while HAQ et al. (1988) define 76, and in the Arctic, 8 second order sequences are recognised compared to their 20 (Fig. 3). Most of the second order sequence boundaries and some of the third order boundaries correlate with the sequence boundaries of HAQ et al., however, several are assigned to different order. The four boundaries recognised throughout the Arctic in the Bathonian to the Cenomanian succession also have counterparts on the Russian

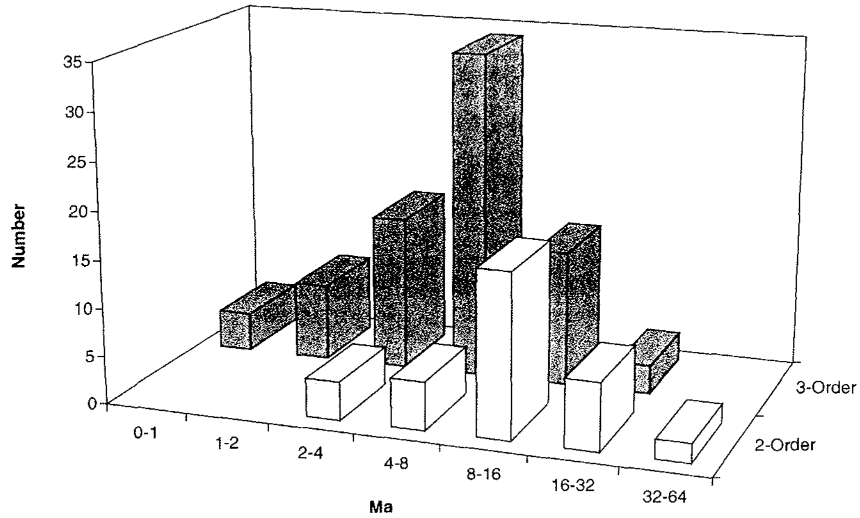


**Fig. 7:** Histograms showing the duration of second and third order Mesozoic sequences of the Arctic. Note the overlap between duration groups of the 2[nd] and 3[rd] order sequences.

Platform (SAHAGIAN et al. 1996). These co-occurrences of many sequence boundaries from the Arctic to other regions indicate that they reflects eustatic origin. One consequence of defining sequence orders according to the duration of the sequences (MITCHUM & VAN WAGONER 1991, VAIL et al. 1991, HAQ et al. 1988) is that a process of fixed duration is presumed to occur in a cyclic pattern. Such a process has not yet been documented, as both glaciation and Milankovich cyclicity will produce lower order sequences. MIALL (1992) points out that with the number of cycles presented in the chart of HAQ et al. (1988) correlation of new stratigraphic sections will almost always be successful. The positive correlation is thus of limited value if the boundaries that are correlated are not given a hierarchical rating by an independent method. The time independent hierarchical subdivision will thus limit the numbers of sequence boundaries and enable the different levels of boundaries to be correlated with statistical significance.

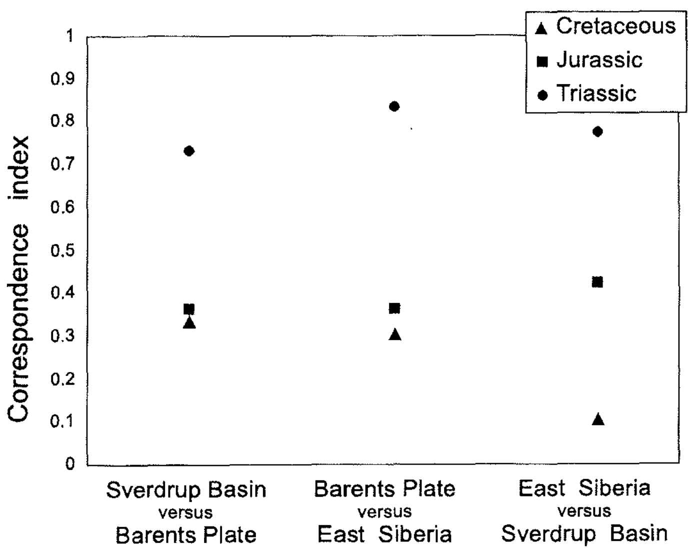


**Fig. 8:** Correspondence index comparing neighbouring areas of the Arctic. An index of one implies that all sequence boundaries of the given period between the two compared areas are synchronous and of the same order, while no synchroniety gives index of zero. Sequence boundaries that are synchronous, but of different order are given a value of 0.5.

Although there is an overlap in duration of second and third order sequences there is a tendency of increasing duration of the sequences during the Mesozoic Era (Fig. 6). The increase in sequence duration and decrease in correlation of sequence boundaries through time (Fig. 8) also indicate that local tectonic processes have increasingly controlled the sedimentation throughout the Mesozoic.

## CONCLUSIONS

The present study shows that sequence boundaries, as dated by their transgressive beds, can to a large extent be correlated throughout the Arctic. Circum Arctic synchronous sequence boundaries were formed in the marginal basins of the Pangea supercontinent during the Triassic, and the control was mainly of eustatic nature. Local control by tectonic processes became gradually more important during the Jurassic, and tectonic control dominated in the Cretaceous, as a result of the splitting of the Pangea supercontinent. Duration of the sequences of a given order varies and is controlled by non-cyclic geological processes. The regular pattern of sequence boundaries as seen in the Triassic succession on Svalbard (Fig. 9), may consequently serve as a predictive tool both for the Arctic as well as for other areas.

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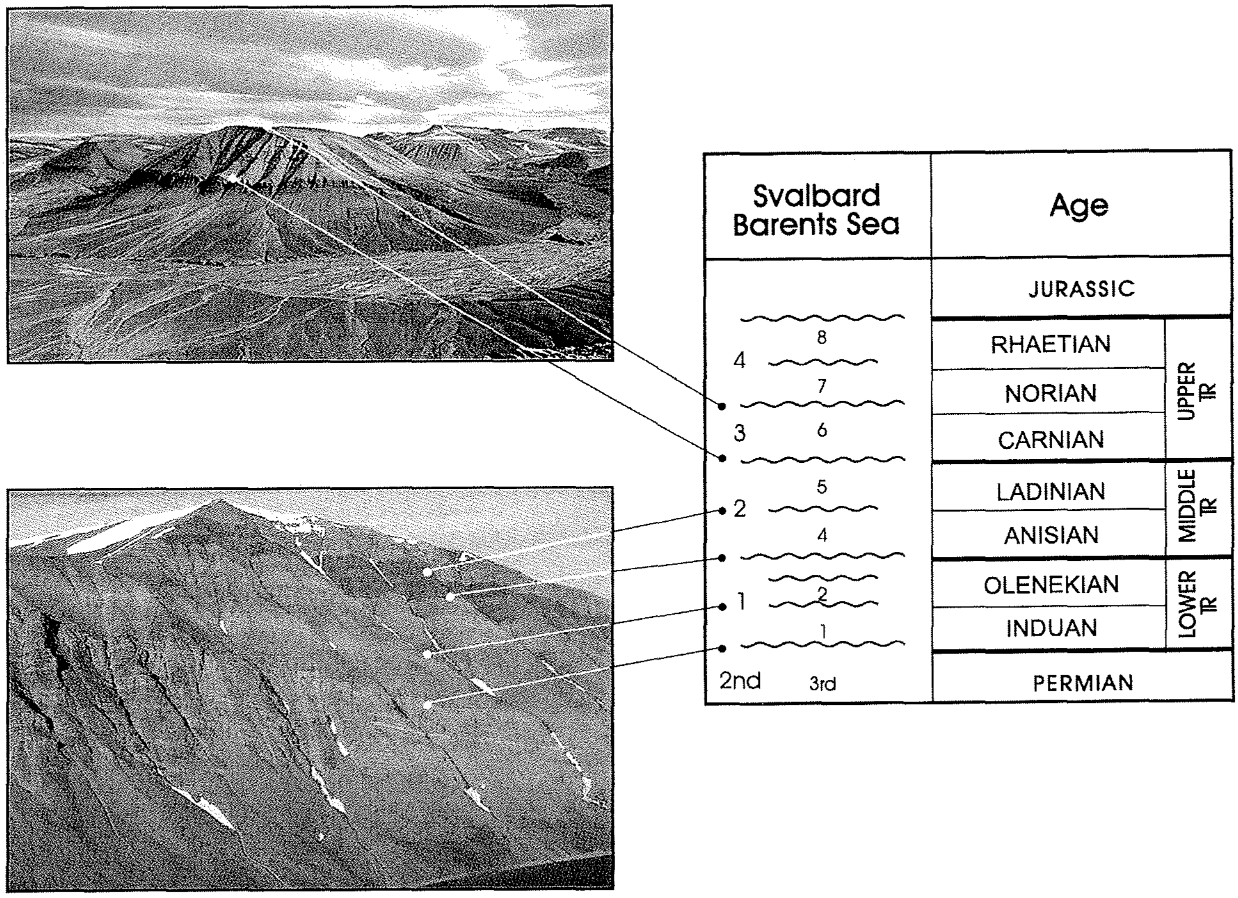


**Fig. 9:** Triassic sequence boundaries as they occur in Bravaisberget at Bellsund on Western Spitsbergen (lower photo) and at Dalsnuten (upper photo) at central Spitsbergen. 2nd order sequence 1 is of Early Triassic age composed by the 3rd order sequence 1 consisting of the Vardebukta Formation and 2 and 3 consisting of the Tvillingodden Formation. 2nd order sequence 2 comprises the Middle Triassic Bravaisberget Formation, in this area consisting of two 3rd order sequences. 2nd order sequence 3 mainly consists of the Tschermakfjellet and De Geerdalen formations, the top of the mountain probably representing the base of the Wilhelmøya Subgroup.

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