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Mesozoic Tectonic Events in the North Atlantic and Arctic: Stratigraphic Response in an Adjacent Rift-Flank Basin (Sverdrup Basin, Arctic Canada)

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

Summary: The Sverdrup Basin (Arctic Canada) lies outside the North Atlantic and Arctic rift systems, but on the flanks of both. During Mesozoic time, rivers draining these rift flanks entered the basin at several points around the basin margin. Consequently, the changing pattern of Mesozoic sedimentation in the basin provides a sensitive, independent record of tectonic events in the adjacent rifts. The constraints provided on three Triassic-Jurassic events in the northern North Atlantic rift system are considered.

Evidence exists for an important Early Triassic rifting event in several parts of the northern North Atlantic rift system, but lack of data and poor biostratigraphic control means that the exact timing and regional significance are unclear. The advance and subsequent retreat of Early Triassic deltas into marine shelf environments along the eastern and southwestern margins of the Sverdrup Basin is compatible with regionally important tectonism that rejuvenated river systems draining the rift flanks. Marine faunas provide good biostratigraphic control: tectonism probably began around the Permo-Triassic boundary, peaked during Early Triassic (Nammalian) time and waned by the onset of Mid-Triassic time.

A poorly constrained tectonic event affected the northern North Atlantic rift system around the Triassic-Jurassic boundary. During the same interval, a vast deltaic system built out into the eastern Sverdrup Basin, again implying that regionally significant tectonism controlled the rejuvenation of river systems.

Regional uplift centres developed in the northern North Atlantic region during ?Pliensbachian to Aalenian time, prior to the onset of rifting in Mid-Jurassic time. A reduction of sediment supply to the eastern Sverdrup Basin during this interval is interpreted to reflect modification to drainage patterns caused by uplift in the adjacent North Greenland region. A coeval increase in sediment input to the East Greenland margin of the northern North Atlantic rift system may reflect capture of the drainage network formerly entering the eastern Sverdrup Basin.

INTRODUCTION

As part of a major on-going regional synthesis project, a detailed tectonostratigraphic comparison of all the Mesozoic depocentres in the northern North Atlantic and circum-Arctic regions is being undertaken. For any single depocentre, preserved stratigraphy is rarely sufficient to provide a complete picture of Mesozoic evolution. However, when all the evidence from depocentres is combined, a pattern of regional tectonic events emerges, which can be used to predict the evolution of areas where data are incomplete. These comparative studies demonstrate a broad synchroneity of tectonic events throughout the region, suggesting that a connected system of rifts existed in the northern North Atlantic and proto-Arctic Ocean during this time (Fig. 1).

Against the background of this broadly consistent tectonic template, there are, however, many uncertainties in constraining regional variations in the magnitude, duration and palaeogeographic significance of individual tectonic events, particularly when using the successions that accumulated within a rift setting. These problems arise because: (1) in most parts of the rift system, preserved Mesozoic successions are in offshore locations, many of which are little explored, if at all; (2) the scarcity of data in the Arctic is compounded by uncertainty about rift geometry; (3) great thicknesses of Mesozoic and Cenozoic strata have accumulated in some areas during repeated syn-rift and post-rift subsidence episodes, so that the lower part of the succession is commonly now at or beyond the limits of seismic resolution; (4) in areas that have suffered multiple rift events, earlier events are obscured by later events; (5) stratigraphic relationships within the syn-rift successions are commonly complex, and the nature of some parts of the succession within the rift systems is not conducive to precise dating (e.g. Triassic continental clastics). As a consequence of these limitations, we have looked at depocentres outside the main rift systems in an attempt to provide additional constraints.

SEDIMENT INPUT TO THE SVERDRUP BASIN

The northern North Atlantic and Arctic rift systems developed by a series of discrete rift phases during Late Palaeozoic and, particularly, Mesozoic time. Each rift pulse was separated by a thermal subsidence phase. The Sverdrup Basin (Fig. 1) also developed as a major depocentre during Late Palaeozoic rifting; however, by Mesozoic time rifting had largely ceased and the basin underwent a prolonged period of thermal subsidence, during which most of the succession accumulated (STEPHENSON et al. 1987). This post-rift fill was introduced into the basin mainly from the southwest and east, with a smaller source area to the north.

Although the Sverdrup Basin lay outside the main Atlantic and Arctic rift systems during Mesozoic time, the timing of Mesozoic siliciclastic pulses into the basin and the location of the principal sediment input points has led us to conclude that rivers systems draining the adjacent rift flanks must have been the major sediment source. We have assumed that the sediment input to the eastern side of the basin reflects a major river system, or systems, principally draining the flanks of the

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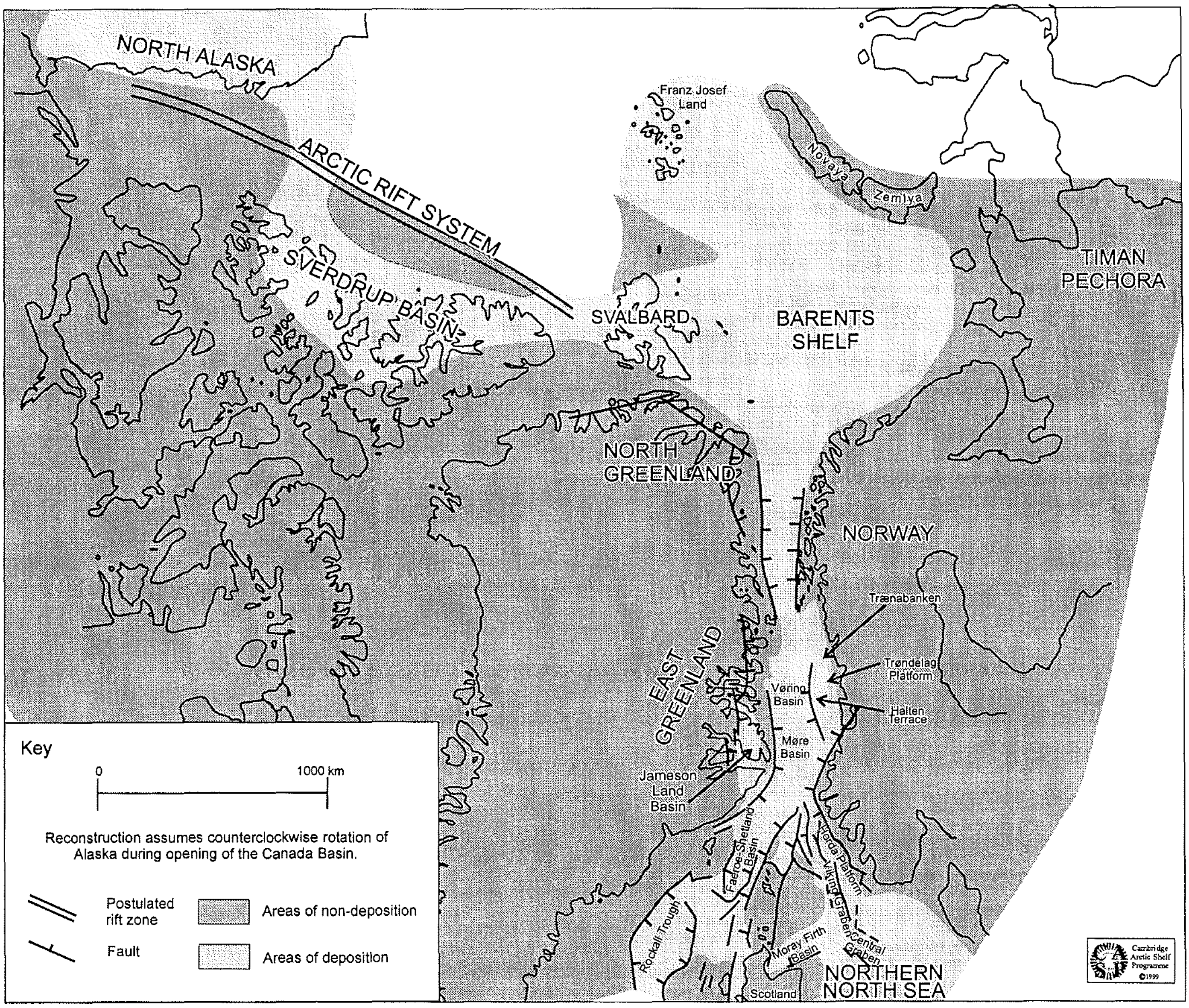


Fig. 1: Location map of basins and other structural elements mentioned in the text, restored to pre-Cretaceous break-up.

Atlantic rift system. Sediment input to the southwestern part of the basin is assumed to reflect rivers originating principally from the flanks of the Arctic rift, representing a conjugate drainage system to that supplying sediment to the Alaskan North Slope. The smaller source area to the northwest is "Crockerland" (EMBRY 1993a), a poorly constrained landmass assumed here to be an uplifted area along the Arctic rift.

We readily acknowledge the limited data on which these assumptions are based. In the absence of preserved Mesozoic sediment outside the immediate confines of the basin, systematic provenance studies combined with apatite fission track thermochronology would provide the best method for constraining sediment source areas and the periods during which they were denuded. Unfortunately, there appear to be no published studies for the Sverdrup Basin and its immediate surroundings that are relevant to the problems addressed here. Without these constraints, many of the relationships we predict remain speculative; however, it is the consistency of timing, and the establishment of plausible regional relationships that lead us to consider this a viable explanation of available data.

Mesozoic sequences in the Sverdrup Basin have been discussed in considerable detail by Embry and co-workers (e.g. EMBRY 1988, 1989, 1991, EMBRY & JOHANNESSEN 1993). The basic genetic unit used by these authors is a transgressive-regressive (T-R) cycle, and nine "second-order" sequences have been identified in the Triassic-Jurassic succession (EMBRY 1988, 1989, 1993b, EMBRY & SUNEBY 1994). Each of these sequences represents a different depositional regime compared with the overlying and underlying sequences, with the change to a different regime interpreted to reflect regional tectonism (EMBRY 1993b). The lithostratigraphy and sequence stratigraphy of the Sverdrup Basin have already been compared with some other circum-Arctic regions for the purposes of regional correlation (e.g. EMBRY 1989, JOHANNESSEN & EMBRY 1989, MØRK et al. 1989. 1994). Here, our interpretation is based on comparisons with equivalent successions in the northern North Atlantic region.

TECTONIC UNCERTAINTIES IN THE NORTH ATLANTIC RIFT SYSTEM

The rocks that record the development of the northern North Atlantic rift system are largely preserved in offshore areas. The only significant exposures of Mesozoic sediments of the northern North Atlantic occur in East Greenland. This area is therefore vital for interpretations of rift system evolution, and provides a key test of inferences made from the Sverdrup Basin succession. However, as with all other areas in the northern North Atlantic, the Triassic to lowermost Jurassic succession of East Greenland is predominantly continental and dating is commonly not well constrained. Furthermore, although the overlying marine strata are comparatively well dated, faunal provinciality, particularly during Middle Jurassic time, affects correlation with the European standard zones (CALLOMON 1994).

We here consider three controversial points regarding the Triassic and Jurassic evolution of the northern North Atlantic: (1) the timing of Triassic rift events; (2) the significance of tectonism around the Triassic-Jurassic boundary, and (3) the duration, cause and evolution of regional uplift centres prior to rifting in the Middle Jurassic. We compare details of the successions from the northern North Atlantic with the changing pattern of sediment input to the eastern Sverdrup Basin to provide independent constraints on these uncertainties. Chronostratigraphic correlation between areas of the northern North Atlantic and the Sverdrup Basin is shown in Figure 2; palaeogeographic relationships between the areas are shown in Figure 3. Information from North Alaska has also been included in the figures and tables because of its apparent link with sediment input into the western Sverdrup Basin, and to emphasise the relationship between the Arctic and North Atlantic rift systems.

TECTONIC EVENTS IN THE NORTHERN NORTH ATLANTIC

Evidence for an Early Triassic rift event

It is apparent that many rift systems became active in Pangea during Early Triassic time (e.g. ZIEGLER 1988). For example, rifting initiated the West Siberian Basin, following the eruption of the Siberian plume volcanics around the Permo-Triassic boundary. The Atlantic rift system was also affected by tectonism at this time, but in the northern North Atlantic region evidence is sparse for the reasons outlined in the introduction. Even in East Greenland, where apparent syn-rift Lower Triassic rocks are exposed, uncertainties remain over the exact timing and significance of tectonism. If this event could be better constrained, and its regional significance confirmed, it would provide a powerful predictive tool for areas with few data. Here we illustrate how the Sverdrup Basin may help provide additional constraints.

In East Greenland, Triassic sediments accumulated in a N-S trending basin inherited from Late Palaeozoic rift events. Sedimentological evidence suggests that Lower Triassic clastics were deposited during active faulting (BIRKENMAJER 1977, CLEMMENSEN 1978, 1980a, 1980b, SURLYK 1990). Fault control on sedimentation is first recognised around the Permo-Triassic boundary, probably peaked during the deposition of the Pingo Dal Formation and had waned by early Mid-Triassic time (Fig. 2). Subsidence curves from East Greenland (PRICE & WHITHAM 1997) confirm a significant rift event during this interval ($\beta = 1.2$), although poor biostratigraphic control adds uncertainty to both timing and magnitude. Despite the uncertainties, this is the clearest available evidence for Early Triassic rifting in the northern North Atlantic region.

In the northern North Sea, much of the geological evidence for the timing of Triassic rifting comes from the Horda Platform on the eastern margin of the depocentre. Here, a series of half-grabens can be identified on seismic reflection profiles (STEEL 1993), but wells do not penetrate the syn-rift wedges. These syn-rift deposits have been interpreted to be of Early Triassic age (e.g. STEEL 1993, ROBERTS et al. 1995; THOMAS & COWARD 1996, LEPERCQ & GAULIER 1996), but there is little evidence to constrain the duration of rifting accurately, and particularly the timing of rift onset. Attempts to estimate the magnitude of stretching from subsidence modelling are also highly dependent on how subsidence is partitioned between the various rift events that affected the succession (ROBERTS et al. 1995). Furthermore, alternative interpretations of Triassic tectonism have been proposed that do not include a discrete Early Triassic rift event (e.g. LERVIK et al. 1989, ZIEGLER 1990).

On the Norwegian margin, Triassic strata have been penetrated by wells on the Trøndelag Platform and in the Halten Terrace area. However, most of these wells have terminated in Upper Triassic strata and none penetrate Lower Triassic rocks (Fig. 2). On the Trøndelag Platform, the Triassic succession is underlain by a pronounced block-faulted topography imaged on seismic reflection profiles, which has been interpreted to be the result of late Early Permian rifting (e.g. BLYSTAD et al. 1995). No mention is made of Early Triassic tectonic activity by BLYSTAD et al. (1995), but they did note evidence for Mid to Late Triassic activity on some Norwegian margin faults.

We must therefore look for additional evidence that could be used in support of a regional tectonic event, and can help to constrain its timing and likely palaeogeographic significance. Along the southwestern, southern and eastern margins of the Sverdrup Basin, large quantities of clastics were introduced by major delta systems during Early Triassic time (Bjorne Formation; Fig. 2). These successions are over 1000 m thick in some areas (EMBRY 1986, 1991). Good biostratigraphic control is provided by marine faunas in the shallow shelf environments into which the deltas advanced. In the eastern Sverdrup Basin, three main progradational cycles are recognised. Overall, progradation began in Griesbachian time and waned by the start of Mid-Triassic time (Figs. 2, 3A, 3B). This is entirely compatible with the timing of events in East Greenland and is consistent with rivers draining the uplifted flanks of the North Atlantic rift (Fig. 3A).

At the same time, the Ivishak Formation built out across the North Slope of Alaska, particularly during Nammalian time (e.g. MOORE et al. 1994, Fig. 2). This implies a linked system

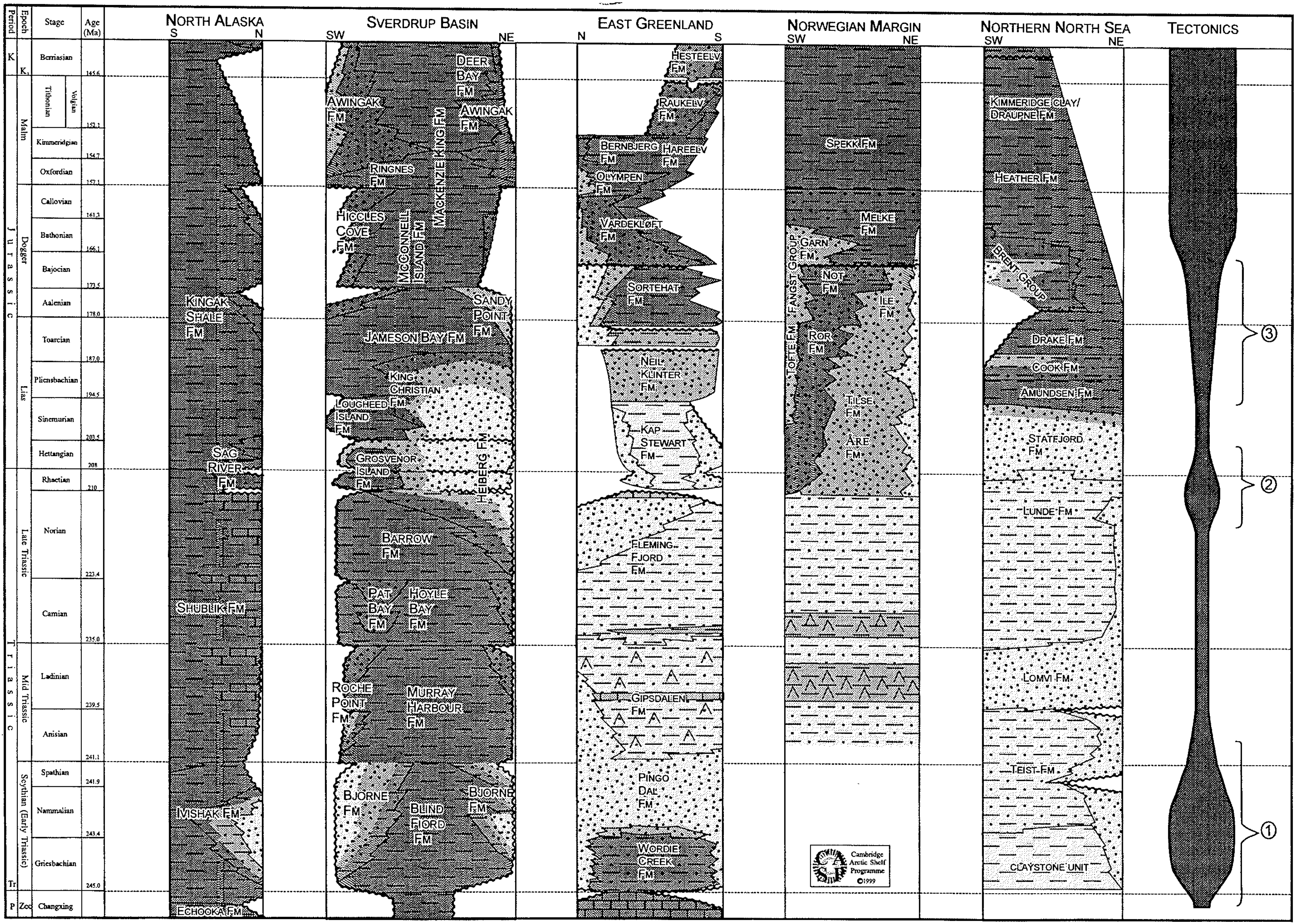


Fig. 2: Comparison of Triassic and Jurassic stratigraphy of Arctic and North Atlantic basins. The approximate magnitude of regional tectonic events is illustrated in the right-hand column, and the three events discussed in this paper are numbered (see Fig. 2 a for key).

of rifts between the northern North Atlantic and Arctic, on which major tectonic events happened synchronously. We interpret significantly increased sediment supply to the south-western Sverdrup Basin during Early Triassic time (EMBRY 1986) to be associated with uplift along the conjugate flank of the Arctic rift zone to that supplying the Ivishak Formation sediment (Fig. 3A).

It is clear therefore that the Sverdrup Basin succession is recording sediment flux from both the North Atlantic and Arctic rifts, that this increased flux is happening essentially simultaneously, and thus implying a major tectonic event with regional consequences for drainage networks. Within the northern North Atlantic rift itself, there is some evidence for this event, but at best it is inadequately constrained (East Greenland), in other parts circumstantial (northern North Sea) and in some areas unavailable (Norwegian margin). We believe that the evidence from East Greenland, corroborated by the succession in the Sverdrup Basin, is a reasonable indication that an important Early Triassic rift event probably affected both the northern North Sea and Norwegian margin, and in the absence of unequivocal constraints from the successions in these areas, gives the best estimate of their likely duration and significance.

The significance of tectonism around the Triassic-Jurassic boundary

In the northern North Atlantic region, there is some evidence of latest Triassic to earliest Jurassic tectonism, but attempts to constrain the exact duration, magnitude and kinematics have remained inconclusive. In the northern North Sea, for example, several authors have suggested an increase of tectonic activity around the Triassic-Jurassic boundary (e.g. VOLLSET & DORÉ 1984, STEEL 1993, KNOTT et al. 1993, LEE & HWANG 1993, MORTON 1993), largely on the basis of increased clastic input; however, evidence of fault activity and block rotation is ambiguous. A climatic change to a more humid regime may also be implicated in the increased clastic supply (FROSTICK et al. 1992).

Much the same picture can be obtained from the Upper Triassic to Lower Jurassic succession of East Greenland (Fig. 2): increased clastic sediment supply in Late Triassic time indicates renewed tectonism (CLEMMENSEN 1980a, SURLYK et al. 1981), but may at least in part be explained by an increasingly humid climate (CLEMMENSEN 1980b). Again on the Norwegian margin there is some evidence of Late Triassic tectonism (e.g. BLYSTAD et al. 1995), but the same evidence for climatic change is also recorded (JACOBSEN & VAN VEEN 1984).

However, the regional context provides additional evidence that can be used to support a significant tectonic event in the northern North Atlantic region in Late Triassic to earliest Jurassic time. For example, a significant thermal doming, magmatic and rifting event occurred in the Central Atlantic region at this time (ZIEGLER 1990), which clearly affected Atlantic basins west of the British Isles (e.g. KNOTT et al. 1993). Some contemporaneous tectonic activity along the Arctic rift is also implied by increased clastic input in North Alaska (the Sag River Formation) during mid-Norian to earliest Jurassic time (e.g. MOORE et al. 1994; Fig. 2). It seems improbable that such a regional tectonic event would not affect the intervening northern North Atlantic region in a significant way.

When we look at the Sverdrup Basin (Fig. 2), there is evidence for a major change in the depositional regime during Norian time, with the onset of delta progradation (Heiberg Formation) from the eastern margin (EMBRY 1982, 1991, EMBRY & SUNEBY 1994). In Rhaetian time, a massive increase in clastic supply, possibly combined with basin margin uplift events, resulted in most of eastern and central areas of the basin being infilled, with the development of widespread unconformities as accommodation space disappeared. The synchroneity of the increase and subsequent decrease of clastic supply with known tectonic events in the Atlantic-Arctic rift system clearly indicates a causal relationship. As with the Early Triassic tectonic event, the only conclusion that we can draw is that the increase of clastic supply reflects rejuvenation of river systems draining the flanks of the Atlantic rift system (Fig. 3C). An element of climatic control cannot be excluded, but this in itself could be linked to increased precipitation generated by tectonically induced topography.

Compared with the Early Triassic rift event, the amount of stretching associated with the Late Triassic to earliest Jurassic event was relatively minor in the North Atlantic rift system (KNOTT et al. 1993). This contrasts with the size of deltaic systems entering the eastern Sverdrup Basin. One potential explanation is that the enhanced clastic supply represents erosion of a broad regional dome in the northern North Atlantic region, which developed during a relatively minor rift event. A more convincing explanation is that the rivers were draining more active areas of the North Atlantic rift system

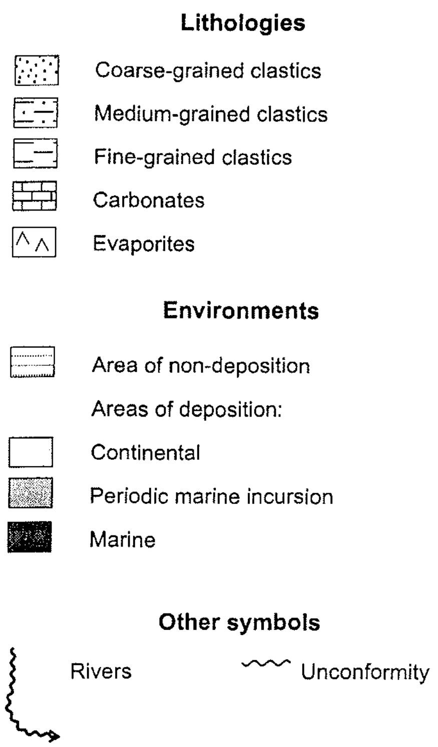


Fig. 2a: Key for Figures 2 and 3.

further south (as depicted in EMBRY 1982). This would imply a much larger drainage system, which is consistent with the volume of sediment supplied.

Regional uplift prior to Middle Jurassic rifting

There is direct and circumstantial evidence for significant regional doming in Arctic and North Atlantic regions prior to the onset of a major rift phase during Mid-Jurassic time. This period of uplift can be regarded as a transitional event between Early Jurassic thermal subsidence and the rifting. The duration of this transitional phase is difficult to define precisely, but was an extremely important episode during Jurassic tectonostratigraphic evolution.

In the northern North Sea, there is a well-documented Toarcian to Late Bajocian interval of transition from a period of relative tectonic quiescence to the onset of major extensional fault activity. This interval was associated with the growth of a dome centred at the intersection of the Viking Graben, Central Graben and Witch Ground/Moray Firth Graben, which had far-reaching consequences for palaeogeography and sediment dispersal patterns (UNDERHILL & PARTINGTON 1993, 1994). The dome grew during Toarcian time and became emergent during Aalenian time (Fig. 3D, 3E), with the maximum areal extent of the related unconformity occurring during mid-Aalenian time. Although the maximum elevation of the dome is suggested to have been less than 500 m (UNDERHILL & PARTINGTON 1993), it produced a broad elliptical area of uplift and low-angle erosion, which was responsible for supplying the uppermost Aalenian to lower Bathonian Brent Group clastics to the northern North Sea area. Overall, the growth of the North Sea dome influenced sedimentation across an area with a diameter greater than 1250 km, comprising a large part of northwest Europe. UNDERHILL & PARTINGTON (1993) argued that the dome developed above a transient plume head prior to rifting, an interpretation consistent with the evolutionary history that they documented.

The Pliensbachian-Bajocian successions of many other North Atlantic-Arctic areas also record a progressive change of tectonic regime, suggesting the possibility of similar plume-related processes operating elsewhere. Unfortunately, defining the geometry of any uplifted area, its palaeogeographic evolution and the involvement or otherwise of a plume requires well-preserved stratigraphy, a fortuitous relationship between the growth of a dome and contemporary sea-level, and abundant data, a luxury that is simply not available in other North Atlantic-Arctic areas. Considering the location of the North Sea dome (centred on a triple junction), the most likely focal points of uplift, assuming the same causal mechanism, would seem to be at similar zones of rift bifurcation. More elongate uplift areas may also have been present along rift flanks. Unlike the North Sea, significant parts of these areas were probably already land areas before uplift began. In this case, much of the sedimentary response to uplift and erosion would reflect the progressive modification of existing drainage patterns, rather than the development of a new, essentially radial, network.

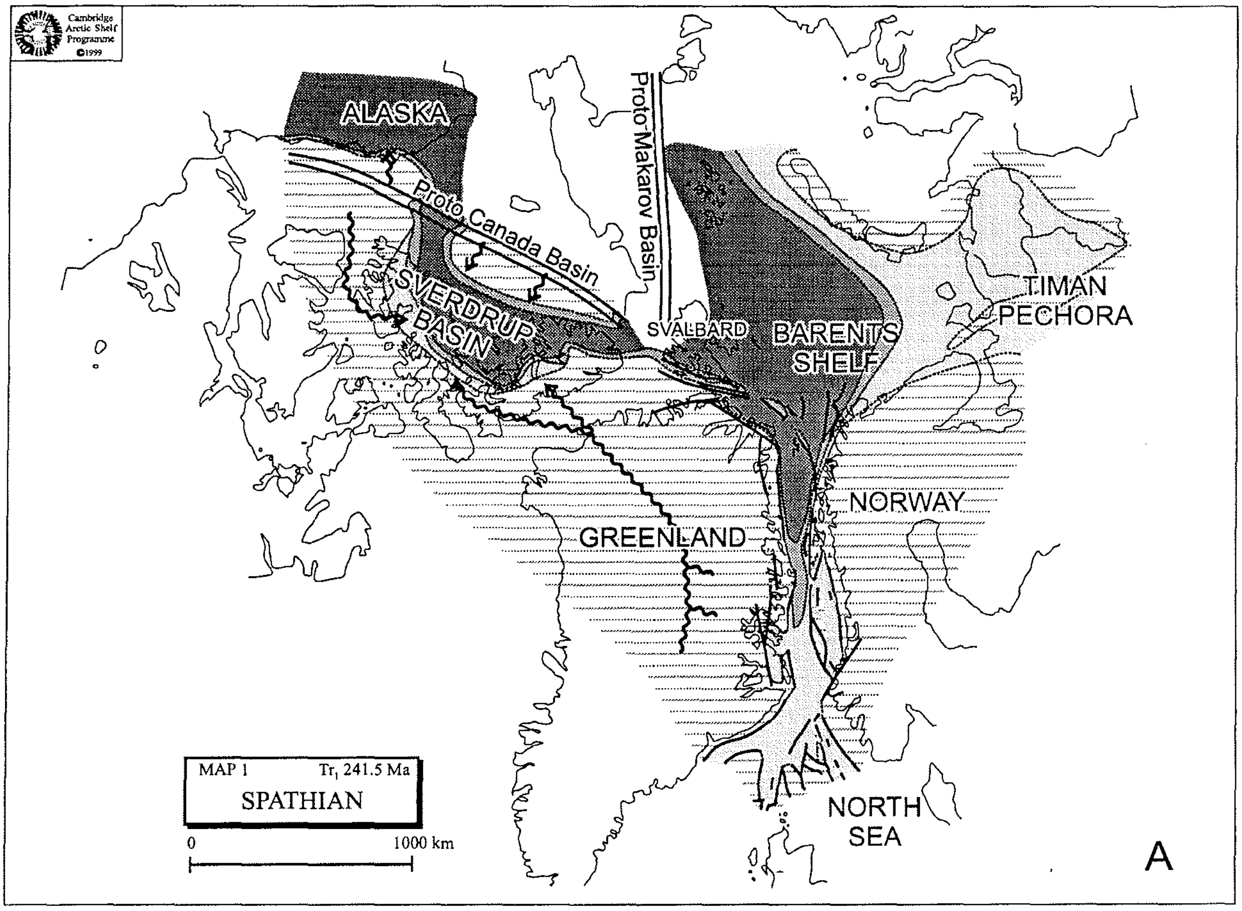
The relationship between uplift of the North Sea dome and deposition of the Brent Group is well established. In East Greenland there are penecontemporaneous successions (the Vardekløft Formation) that are so similar to the Brent Group that there is an unavoidable logic in appealing to a similar causative mechanism. This line of reasoning has been argued by ENGKILDE & SURLYK (1993) and SURLYK et al. (1993), and is the interpretation favoured here. The Vardekløft Formation was deposited in N-S trending depocentres, with sediment entering from the northern end (Fig. 3D, 3E, 3F). This indicates an area of uplift which must have been distinct from the North Sea dome and was presumably located in the North Greenland area.

The Jurassic succession on the Norwegian margin has similarities with the northern North Sea and East Greenland: on most of the Halten Terrace and Trænbanken area, the upper Toarcian to Bathonian Fangst Group (Brent Group equivalent) is overlain by the Bajocian to Berriasian Viking Group. Evidence of coarse clastic input from the north and west has been identified in the Fangst Group on Halten Terrace (DORÉ 1992). In our sequence of palaeogeographic maps (Fig. 3D to 3F), we indicate sediment derivation directly from the Greenland margin, driven by uplift in North Greenland, although alternative interpretations have been made (e.g. DORÉ 1992, BREKKE et al. 1999). The case against these arguments is made in SCOTT (2000). The successions of the Western Barents Shelf (e.g. OLAUSSEN et al. 1984) and Svalbard (e.g. BÄCKSTRÖM & NAGY 1985) can also be used to support the hypothesis of uplift in the North Greenland region during the same interval.

In the central and eastern parts of the Sverdrup Basin, the Rhaetian to Pliensbachian part of the Heiberg Formation comprises fluvial-dominated deltaic sediments that built out from the southeastern margin of the basin in response to Atlantic tectonism (see above). During Pliensbachian time this drainage system began to wane, and by Toarcian time there was a very low sedimentation rate across the basin (Fig. 2, Fig. 3D). Since this change was coeval with the proposed uplift of North Greenland, we believe that the area of uplift was large enough to deflect the river system feeding the Heiberg delta away from the southeast Sverdrup Basin.

It could be argued that the decay of the drainage system during Pliensbachian-Toarcian time simply reflected the waning influence of the Late Triassic to earliest Jurassic tectonic event. However, during the subsequent, much more intense rifting event which started in Mid-Jurassic time, the river system was not rejuvenated again (Fig. 3F). This would suggest a more significant change to the drainage network had occurred. There is insuffcient information to establish exactly how the drainage pattern was changed, but it is possible that the river system may have been deflected east around the southern margin of the uplifted area and was captured by drainage systems flowing into the Atlantic rift along the East

Fig. 3: Paleogeographic reconstructions for Early Triassic to Middle Jurassic time in the Arctic – North Atlantic region. Reconstructions assume counterclockwise rotation of Alaska-Chukotka during Early Cretaceous opening of the Canada Basin (see Fig. 2 a for key).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ALASKA
Proto Makarov Basin
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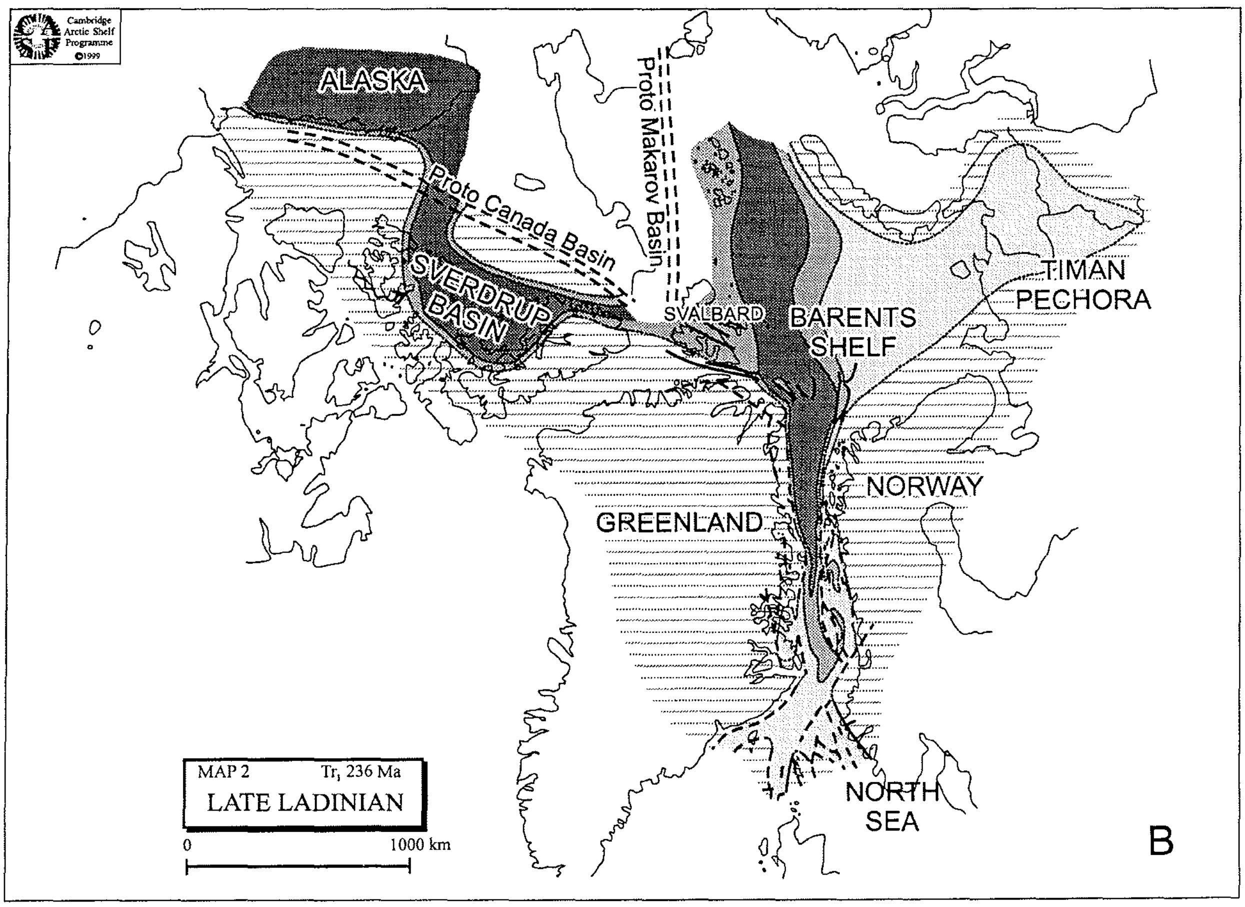
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ALASKA
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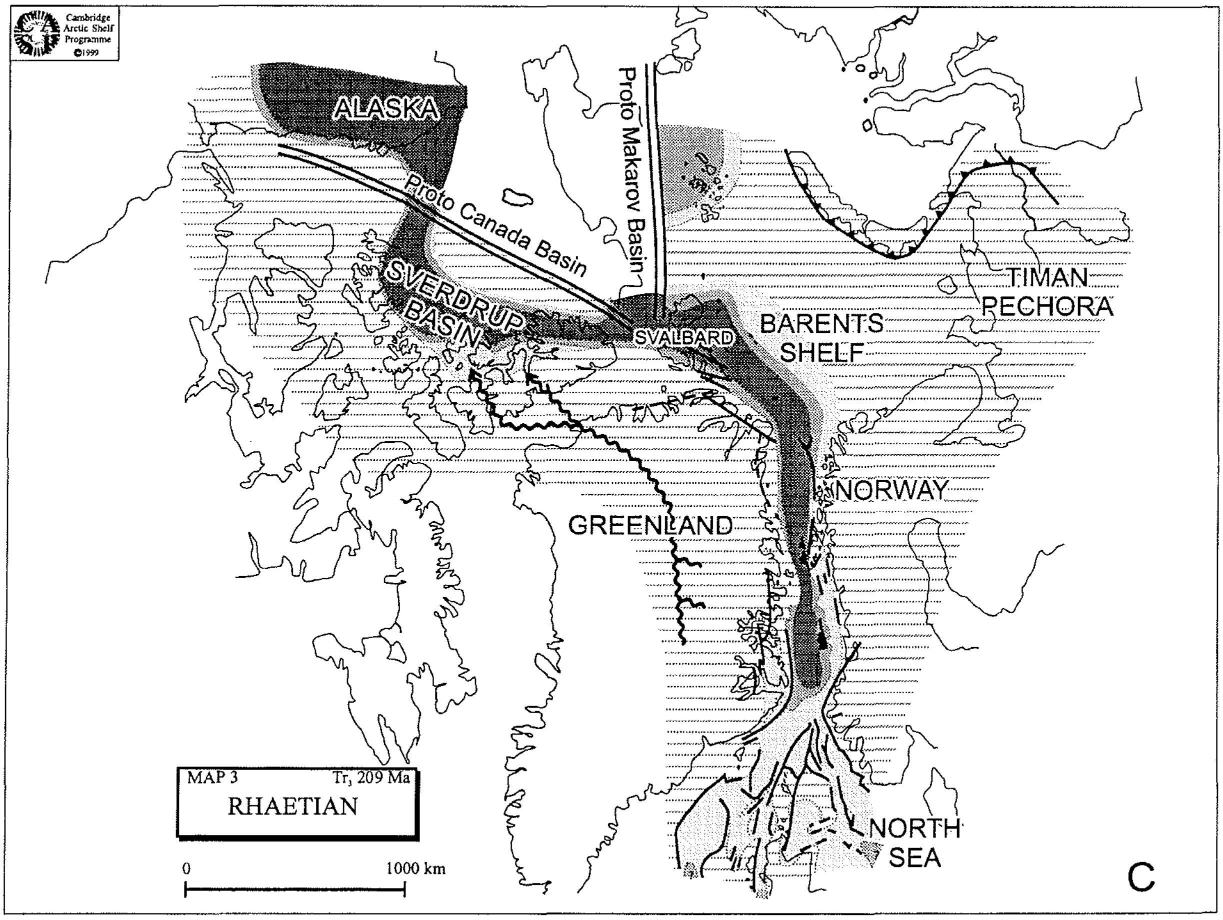
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ALASKA
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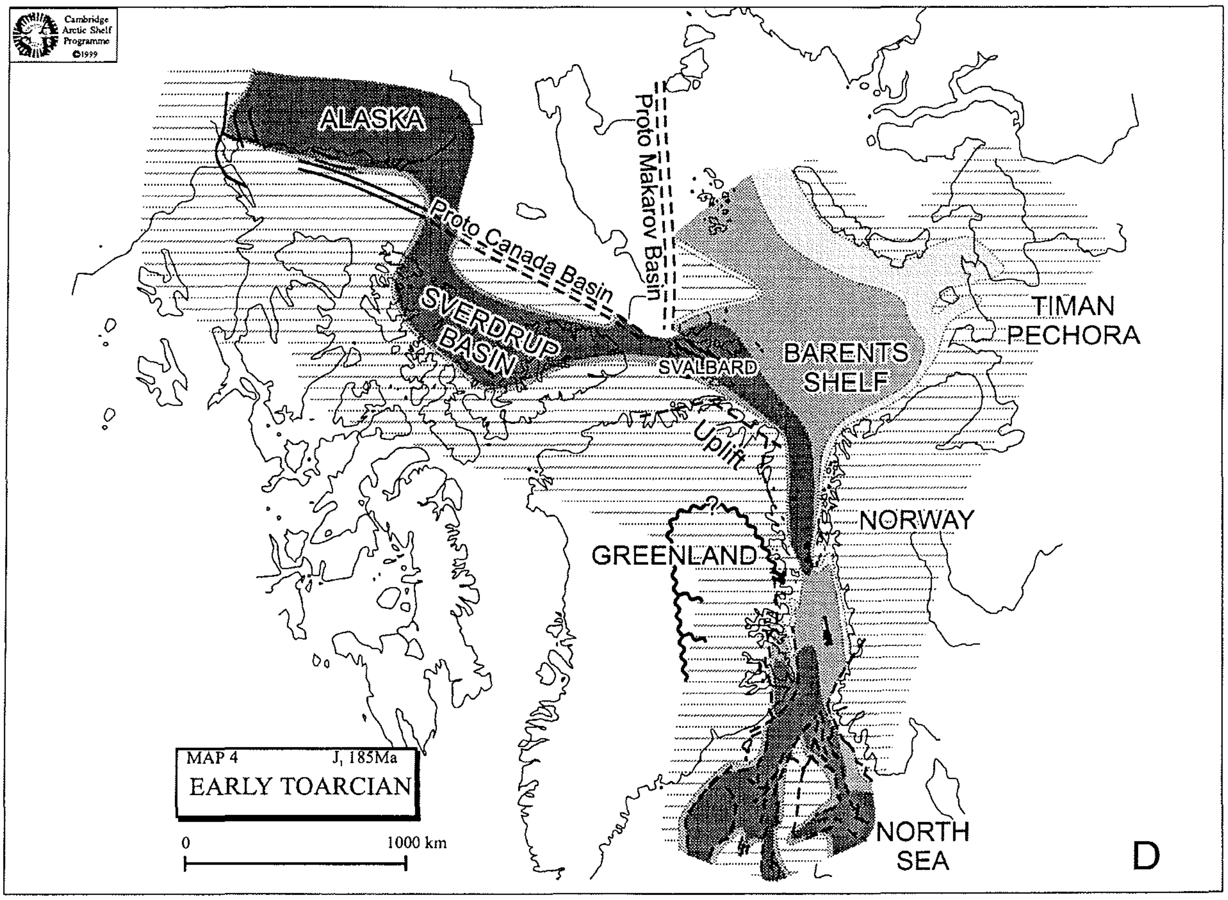
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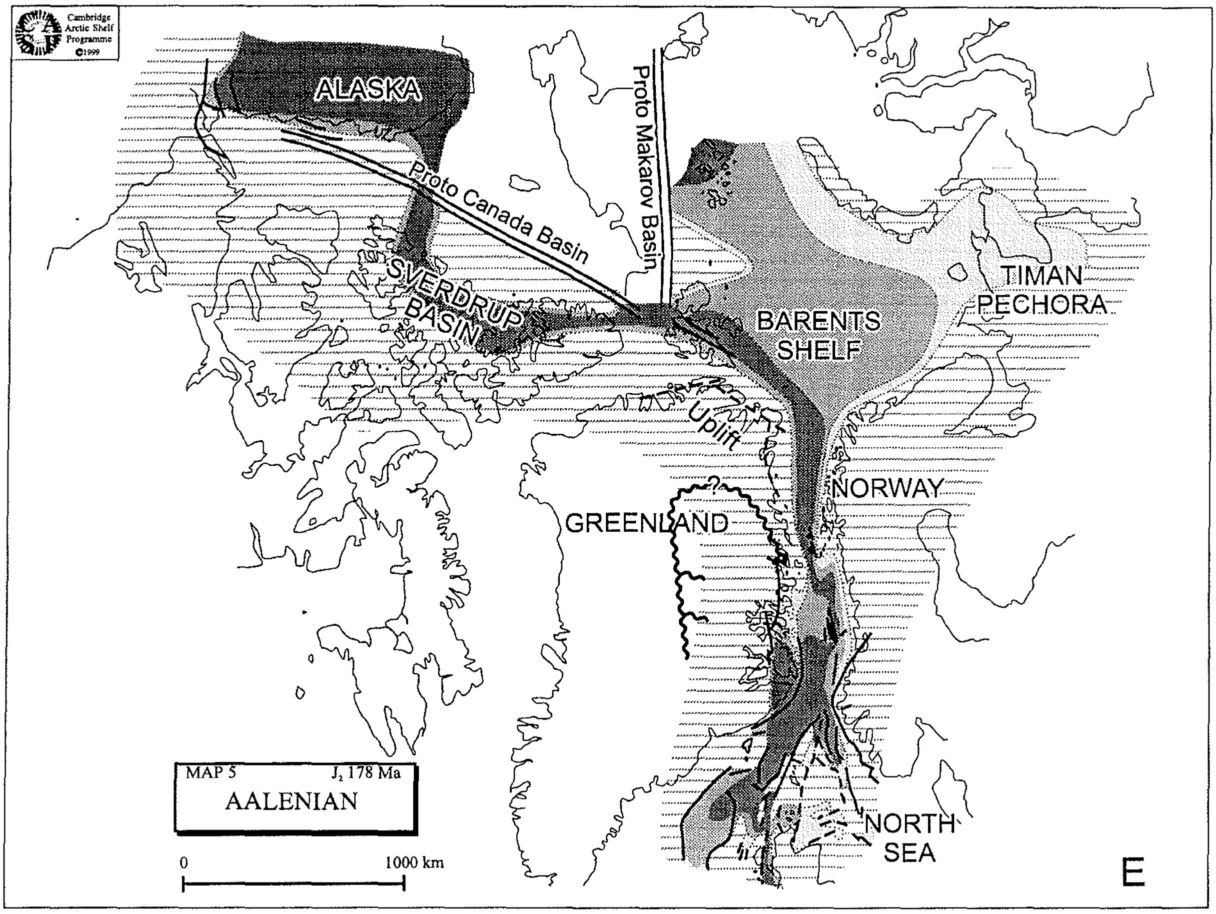
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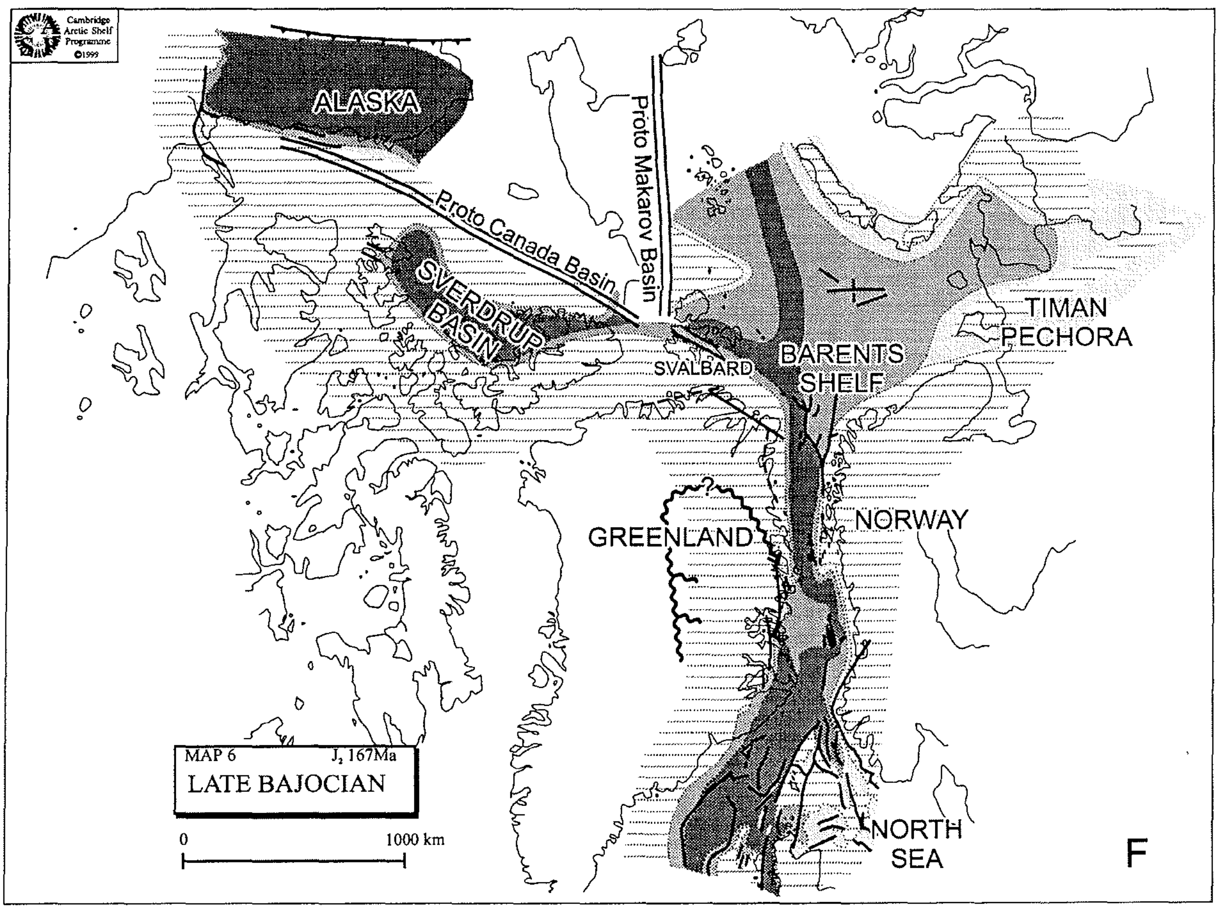
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Greenland margin (Fig. 3D, 3E, 3F). The decay of the Heiberg river system coincides reasonably well with the increase of fluvial input into the northern Jameson Land Basin of East Greenland (Fig. 2). Alternatively, the river system may have been diverted into the Labrador Sea rift area, if this was a topographic entity at the time.

Evidence from East Greenland, the Norwegian margin, Western Barents Shelf, Svalbard and the eastern Sverdrup Basin can therefore be used to support arguments for Pliensbachian-Bathonian uplift centred in the North Greenland region. This uplift generated coarse clastic sediments that became important reservoirs, and induced significant changes to drainage patterns, in exactly the same way as occurred in the northern North Sea. Unlike the northern North Sea, we have few constraints on the evolving palaeogeography, nor can we prove the involvement of a plume; however, the pattern of evolution appears very similar.

ACKNOWLEDGMENTS

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