# $^{40}Ar/^{39}Ar$ geochronology and structural analysis: Basin evolution and detrital feedback mechanisms, Hold with Hope region, East Greenland

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Detrital white-mica, single-grain laser $^{40}Ar/^{39}Ar$ ages from five Permian to Cretaceous sedimentary packages in the Hold with Hope region, East Greenland, are compared to $^{40}Ar/^{39}Ar$ cooling ages from nearby granitic domains. The data show that the variations in cooling ages between different basement units, separated by a detachment fault, are traceable into the overlying, proximal detritus and can be used to refine aspects of the basin-forming history in East Greenland. The two granitic samples, one above and one below the detachment, yield ages of 414 ± 2 Ma and 413-390 Ma, respectively, and imply younging structurally downwards. Younging downwards complies with models for gradual exhumation of high-grade rocks in East Greenland from Silurian through Early Carboniferous time. The detrital white micas from the Late Permian through Late Cretaceous sedimentary units show direct age relationships to these two granitic basement regions, with added detrital contributions to the Lower Triassic and Lower Cretaceous sands from other source areas. Specifically, the Lower Triassic sands may also include recycled Permian clasts, and sediments from a deeper (younger) basement unit that was not exposed or eroded in Permian time. The wide range of detrital mica ages in the Lower Cretaceous sands corresponds well to the major Late Jurassic-Early Cretaceous rift event documented in the Greenland-Norway corridor, and indicates extensive exposure and erosion of new provenance domains and basin cannibalization at this time. By the Late Cretaceous, sediment source areas appear to have become restricted again, coinciding with global eustatic sea-level rise and limited exposure of basement source regions. The study indicates that detrital, white-mica $^{40}Ar/^{39}Ar$ geochronology is an effective way of differentiating contributions from different source regions and, in some cases, different tectonic events, as recorded in the basin detritus. When coupled with structural studies of controlling faults and constraints on the unroofing histories of basement domains, controls on sediment source regions, transport pathways and sedimentary recycling may also be provided.

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## Introduction

Isotopic provenance studies focus upon dating detritus and comparing these results to available data from potential source regions (e.g. Morton & Grant 1998). Such studies are obviously helpful when a characteristic detritus signature suggests or excludes specific source regions. Links to a specific provenance region are more difficult to make with far-traveled and/or recycled deposits.

This study presents a local approach that compares proximal basins to provenance domains with differentiable, radiogenic age signatures. The goal is to elaborate upon basin models in a well-studied area of East Greenland by combining and comparing the effects of faulting versus eustacy, with a particular focus on basement-to-basin ties.

The Hold with Hope region (Figs. 1 & 2) was chosen as the study site for several reasons. Firstly, the area displays impressive sections through major basins, reflecting a >300 m.y. depositional history and variable, proximal source regions. Secondly, major, unsolved problems related to the basin history still exist: More than half a century of stratigraphic and sedimentologic studies has led to well-established models for deposition within the basins in the region (e.g. Koch 1931, Nielsen 1935; Vischer 1943; Maync 1949; Donovan 1957; Birkelund & Perch-Nielsen 1976; Surlyk 1978a; Stemmerik et al. 1992; Kelly et al. 1998; Larsen et al. 2001), but the geometry of basin-controlling faults and the exhumation of tectonic domains have been less emphasized. A related problem is that the tie between provenance areas and basins has not been extensively investigated.

Based on previous results (e.g. Hartz et al. 2001), we anticipated that provenance domains in East Greenland

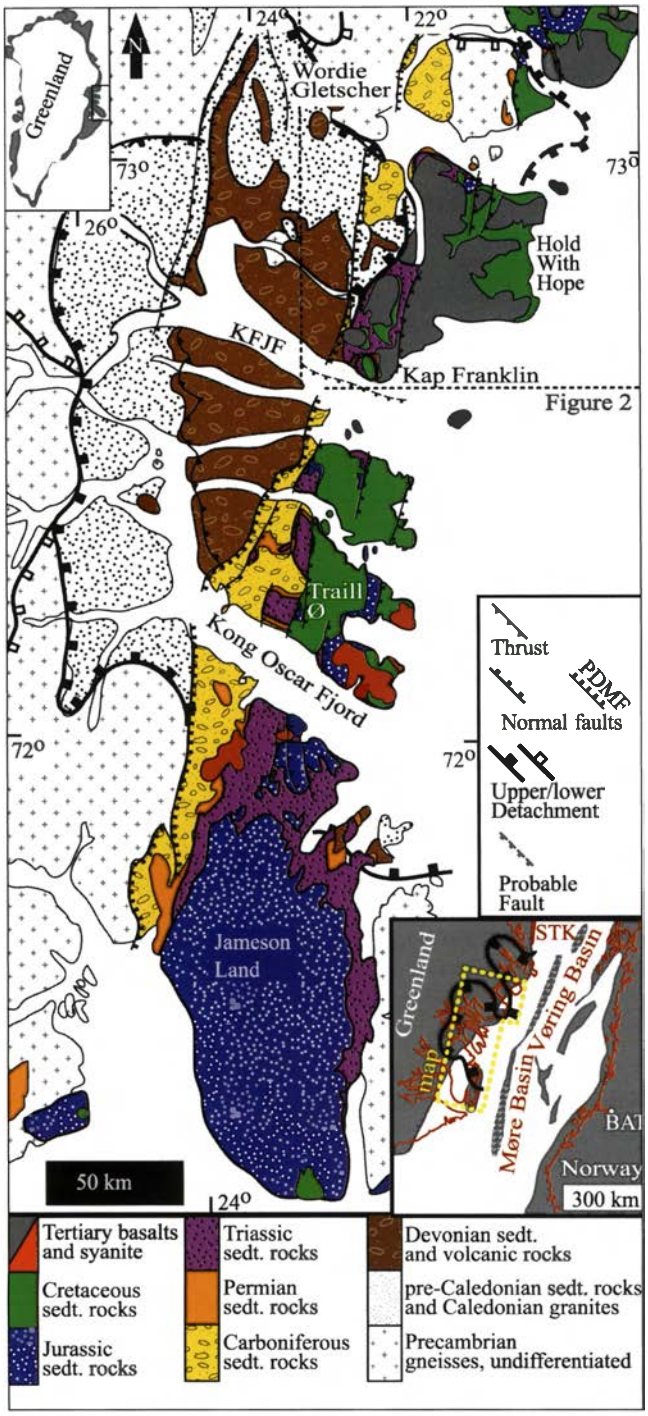



*Fig. 1. Map of the geology of East Greenland, simplified from Koch & Haller (1971). The insert shows the approximate Jurassic position of East Greenland in relation to the Norwegian continental margin, and the trace of the Caledonian detachment. PDMF = Post Devonian Main Fault; KFJF = Kejser Franz Joseph Fjord.*

could be differentiated and separated into at least three groups based on white-mica $^{40}Ar/^{39}Ar$ cooling ages: a supra-detachment domain with white mica typically older than ca. 410 Ma; an upper, sub-detachment domain with white-mica ages typically between ca. 410 and 390 Ma; and one or more domains of deeper sub-detachment domains with white-mica ages younger than 390 Ma. We presumed further that these different groups could be traced and differentiated in the detritus within the Late Paleozoic through Mesozoic basins. The study was thus designed to address timing of exhumation and erosion, sediment pathways, and basin cannibalization. Better constraints on these features should yield more information to examine geological 'events' for Late Paleozoic-Mesozoic periods otherwise lacking a preserved sedimentary record. Most of the samples dated for this study were collected within a rift-type setting compatible to that on the outer Mid Norwegian continental shelf (Whitham et al. 1999; Larsen et al. 2001; Brekke 2001) (Fig. 3). The study thus facilitated evaluating the $^{40}Ar/^{39}Ar$ method's application to offshore regions, where ties between basement and basins can be more complicated.

Isotope provenance studies usually incorporate either Sm/Nd (e.g. Dalland et al. 1995), U-Pb zircon (e.g. Morton & Grant 1996; Knudsen 2001) or Ar-Ar (e.g. Renne et al. 1990) techniques, each with its inherent strengths and weaknesses. The Ar-Ar method was chosen for this study since each detrital white mica carries an $^{40}Ar/^{39}Ar$ cooling age that not only can identify primary basement source regions but can also yield details about the source region's exhumation history (e.g. Renne et al. 1990). Most post-Caledonian detritus in the North Atlantic region is derived from the Caledonides, and micas thus predominantly reflect cooling related to different episodes of Early Paleozoic nappe emplacement and to exhumation/deformation during and after Siluro-Devonian continental collision. Because 'Caledonian' cooling ages in the North Atlantic region can potentially incorporate events ranging from Cambrian to Devonian in age, a thorough network of different basement cooling ages and an understanding of their potential tectonic causes is prerequisite to any detrital mica study. We review briefly the structural setting and primary sedimentary basin features for the Devonian through Paleogene in East Greenland as a background for our $^{40}Ar/^{39}Ar$ white-mica data and their interpretations.

## Structural framework and basin evolution

The Hold with Hope region exposes a complete section of the East Greenland Caledonides (Fig. 2). To the west, deep- and middle-crustal, Caledonized Precambrian gneisses and low-grade, pre-Caledonian sediments are intruded by Caledonian granites and are covered by Devonian terrestrial sedimentary and volcanic rocks (Fig. 4). Towards south and east, these rocks are covered by deposits of Carboniferous to Paleogene ages, representing sections through extensional basins covered by Paleogene basalts (Koch & Haller 1971).

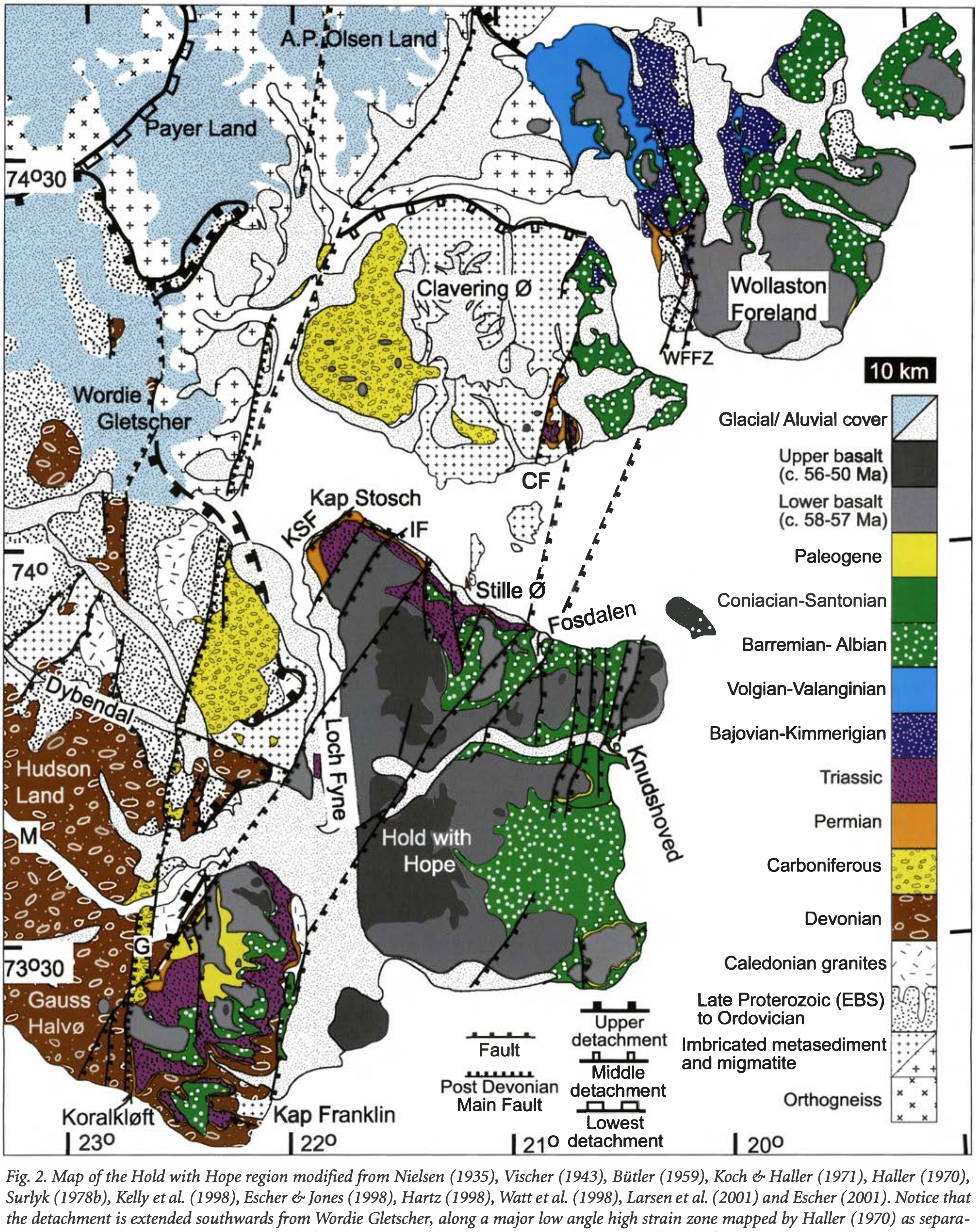



*Fig. 2. Map of the Hold with Hope region modified from Nielsen (1935), Vischer (1943), Bütler (1959), Koch & Haller (1971), Haller (1970), Surlyk (1978b), Kelly et al. (1998), Escher & Jones (1998), Hartz (1998), Watt et al. (1998), Larsen et al. (2001) and Escher (2001). Notice that the detachment is extended southwards from Wordie Gletscher, along a major low angle high strain zone mapped by Haller (1970) as separating granites and pre-Caledonian sediments from gneisses and migmatites. This link needs verification, but reconnaissance mapping confirms the presence of a synmagmatic extensional detachment and white mica in its footwall display typical sub detachment cooling ages (Hartz 1998). The migmatites at southeastern Kap Franklin are undated but appear similar to the Caledonian gneisses father north, and are thus highly marked tentatively as such. G = Gastisdal, M = Moskusoksefjord, KSF = Kap Stosch Fault, IF = Immacradal Fault, CF = Clavering Ø Fault, WFFZ = Wollaston Foreland Fault Zone (a series of widely distributed faults, not differentiated in this study, see Surlyk 1978a for details).*

### *Detachments, faults and supra-detachment basins*

Three major types of structures control the current map pattern: a low-angle extensional detachment, the Fjord Region Detachment (FRD) (Hartz et al. 2001; Hartz & Andresen 1995; Andresen et al. 1998), E-W-trending Devonian to Carboniferous extensional faults (Hartz 2000) with minor cross-faults of Mesozoic age (Surlyk 1978b), and a system of N-S- to NE-SW- trending normal faults (Vischer 1943; Surlyk 1990; Stemmerik et al. 1992). These latter faults generally displace post-Devonian rocks down to the east (Fig. 2) (Koch & Haller 1971; Upton et al. 1980).

The FRD is a set of middle-crustal extensional detachments that were active in Devonian through Early Carboniferous time in East Greenland. Activity on these mid-crustal ductile to semi-brittle, gently-dipping detachments was simultaneous with genesis of major, N-S-trending folds and steep E-W-trending, upper-crustal brittle faults (Hartz 2000; Hartz et al. 2001). The overall detachment map pattern is one of domes and depressions, where the low-angle structures to some degree follow topography along a wavy set of doubly-plunging anti- and synforms (Fig. 1, insert map). Devonian to Early Carboniferous supra-detachment deposits occur only in the depressions. In contrast, the Hold with Hope Late Paleozoic through Mesozoic basins cover both domes and depressions within the FRD trace (Figs. 1 & 2).

Generally, the upper splay of the FRD is easy to recognize as a low-angle, extensional, high-strain fault zone that separates an upper section of relatively low-grade, pre-Caledonian sediments intruded by ca. 425 Ma granites (Figs. 5a,b) from a lower section of highly Caledonized (metamorphic and partly molten) rocks (Fig. 5c). The upper splay of the detachment has paramount significance for interpreting detrital white-mica cooling ages since white micas above the splay generally range in age from 425 to 410 Ma, while those below the splay are up to 50 m.y. younger (Dallmeyer et al. 1994, Hartz et al. 2000) (Fig. 4). Based on isotopic data, displacement along the detachment is argued to have continued into the Carboniferous in the inner fjord (Hartz et al. 2000).

The detachment appears to have governed deposition of Devonian to Early Carboniferous deposits (Hartz 2000). These Devonian-Carboniferous basins formed in N-S-trending synforms, cut by major E-W-trending normal faults (Bütler 1959). Studies of paleocurrents (Olsen & Larsen 1993) show that drainage was typically away from the detachment zone at this time. Outliers of Devonian sediments (Koch & Haller 1971) and thermal modeling of basement $^{40}Ar/^{39}Ar$ K-feldspar data (Hartz et al. submitted) suggest that the detachment hangingwall was buried by thick basins possibly through the end of the Carboniferous.

The Carboniferous to Cretaceous basins are generally suggested to have formed along N-S- to NE-SW-trending half-grabens (e.g. Vischer 1943; Haller 1971; Surlyk 1990; Stemmerik et al. 1992). In the Hold with Hope region, the Post Devonian Main Fault (PDMF), the Clavering Fault and the Wollaston Foreland Fault Zone are typically emphasized in these half-graben models (Vischer 1943; Surlyk 1990) (Fig. 2). The PDMF, for example, is traditionally placed along the westernmost post-Devonian outcrop (Figs. 1 & 2), and is generally suggested to have controlled deposition of Carboniferous to Cretaceous sediments, often marking the western limit of these basins (Vischer 1943; Surlyk 1978b; 1990; Stemmerik et al. 1992). The PDMF is typically identified as the most probable candidate for a major, down-to-the-east controlling fault for the half-graben basin models, placed directly west of Permian and Triassic deposits in Koralkløft (Fig. 2). However, the trace of a major fault scarp in the area is not easily identified from available outcrop (Fig. 5d) and we do not presently emphasize the PDMF (sensu Surlyk 1990 or Stemmerik et al. 1992) as a primary controlling fault for Late Paleozoic-Mesozoic sedimentary deposition in the area (Figs. 2 & 5a).

### *Late Carboniferous through Cenozoic deposits*

*Carboniferous:* - At Clavering Ø and west of Loch Fyne, Late Carboniferous deposits (Vischer 1943; Stemmerik et al. 1992) rest on sub-detachment gneisses and indicate that the uppermost detachment footwall was exhumed by this time. These deposits rest on basement rocks flanked by pre-Caledonian sediments towards the west (Hudson Land) and (more distantly) towards the northeast (Wollaston Foreland) (Fig. 2).

Father south in Gastisdalen, the Carboniferous deposits occur in a narrow N-S-trending graben (Koch and Haller 1971) (Fig. 2). Faulting along the graben appears to be post-depositional and pre-Late Permian since the deposits do not appear to be offset along the faults (Bütler 1959). Carboniferous outliers outside the graben show that the basin may have extended much more widely than the area delimited by the present graben structure (Fig. 2). In the Gauss Halvø-Hudson Land Region, the Carboniferous basins were controlled by ESE-WSW-striking normal faults, with basins deformed into N-S-trending folds that were later cut by post-Carboniferous faults (Bütler 1959).

*Late Early Permian:* - In the Hold with Hope Region, the latest Carboniferous (Kasimovian; Vigran et al. 1999) to late Early Permian (Kungurian; Stemmerik et al. 1992) represents a regional hiatus (Koch & Haller 1971) that signals a strong shift in East Greenland's post-Caledonian tectonics. Entirely continental basins that formed in the Hold with Hope region were defor-

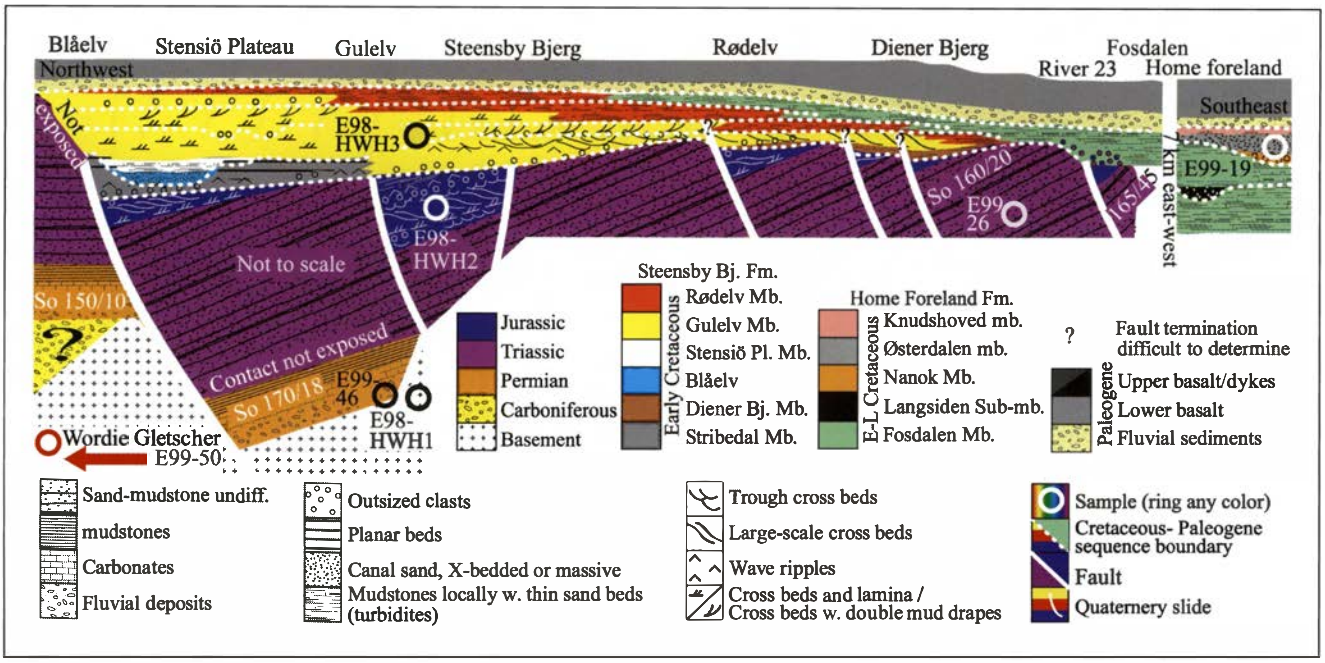



*Fig. 3. Depositional model for the Cretaceous-Paleogene along northeastern Hold with Hope. The Steensby Bjerg section is modified from Larsen et al. (2001) and the Jurassic section is modified from Larsen et al. (1998). The profile is otherwise based on Koch & Haller (1971), Upton et al. (1980; 1995), Kelly et al. (1998), Larsen et al. (2001) and own studies. We tentatively present the Fosdalen and Rødelv member as lateral equivalents, but emphasize that in several areas, in particular in the mudstones at Rødelv and Fosdalen, needs further study to univocally determine the timing of faulting, and stratigraphic relationships.*

med along N-S-trending fold axes and cut by E-W-striking normal (or oblique?) faults prior to the hiatus (Bütler 1957). In contrast, basins younger than late Early Permian were mostly marine, and predominantly cut by N-S-trending normal faults (Vischer 1943), with occasional ESE-WNW-trending cross-faults (Surlyk 1978b) parallel to the fjords (Figs. 2 & 5h). The unconformity indicates considerable erosion in the Hold with Hope area; recent apatite fission-track data from Clavering Ø show cooling related to unroofing at this time (Johnson & Gallagher 2000), consistent with presence of the erosional unconformity.

*Late Permian:* - Regionally extensive fluvial- to shallow-marine conglomerate (Fig. 5f), carbonate reefs and evaporites typically overlie the late Early Permian unconformity. These sedimentary rocks are, in turn, deeply incised and overlain by carbonate reefs and deep-marine shales (Vischer 1943; Stemmerik et al. 1992). The Permian sections in the Hold with Hope region generally resemble those recorded elsewhere in East Greenland (Stemmerik 2001).

*Early Triassic:* - The Triassic fill was deposited in west-tilted half-grabens, arranged with en echelon right step-overs over a 300 km exposure (Fig. 1) (Clemmensen 1980; Surlyk 1990; Stemmerik et al. 1992; Seidler 2000). In the Hold with Hope region, this model largely stems from Vischer (1943) who showed the basin as a set of drowned half-grabens bounded by the Kap Stosch Fault (Figs. 2 & 5e) and Clavering Fault (Fig. 2), with estimated Early Triassic offset of 2.5 and 1.2 km, respectively (Vischer 1943). The minor Immacradal fault (Fig. 6a), also part of this half-graben model, has an estimated Early Triassic offset of a few tens of meters (< 150 m) (Nielsen 1935). The half-graben geometry is supported by the occurrence of major syn-tectonic deltaic clastic fans building southwards into the basin along the faults (Nielsen 1935; Vischer 1943, Stemmerik et al. 1992) (Fig. 5g).

*Early Jurassic:* - No sediments of Late Triassic to Early Jurassic age occur in the Hold with Hope region and the Early Jurassic marks a period of regional subaerial erosion (Vischer 1943; Maync 1949; Surlyk 1990) (Fig. 2). Apatite fission-track data from Carboniferous deposits at Clavering Ø suggest that the rocks were heated through the Triassic, and then experienced major cooling (Johnson & Gallagher 2000) (Fig. 4). This cooling would have corresponded in time to regional excavation of the pre-Mid Jurassic basins.

*Mid Jurassic:* - Mid to Late Jurassic deposits are recognized in major half-grabens on Wollaston Foreland (Visher 1943; Maync 1949; Surlyk 1978a) and were recently discovered in comparable, but deeply eroded, grabens along northeastern Hold with Hope (Stemmerik et al. 1997; Kelly et al. 1998; Larsen et al. 2001) (Figs. 2-4, 6b-c). In this part of Hold with Hope, the Jurassic deposits occur in a section of up to 360 m-thick conglomerates, sandstones and subordinate shales, suggested to have formed in upper shore-face to offshore

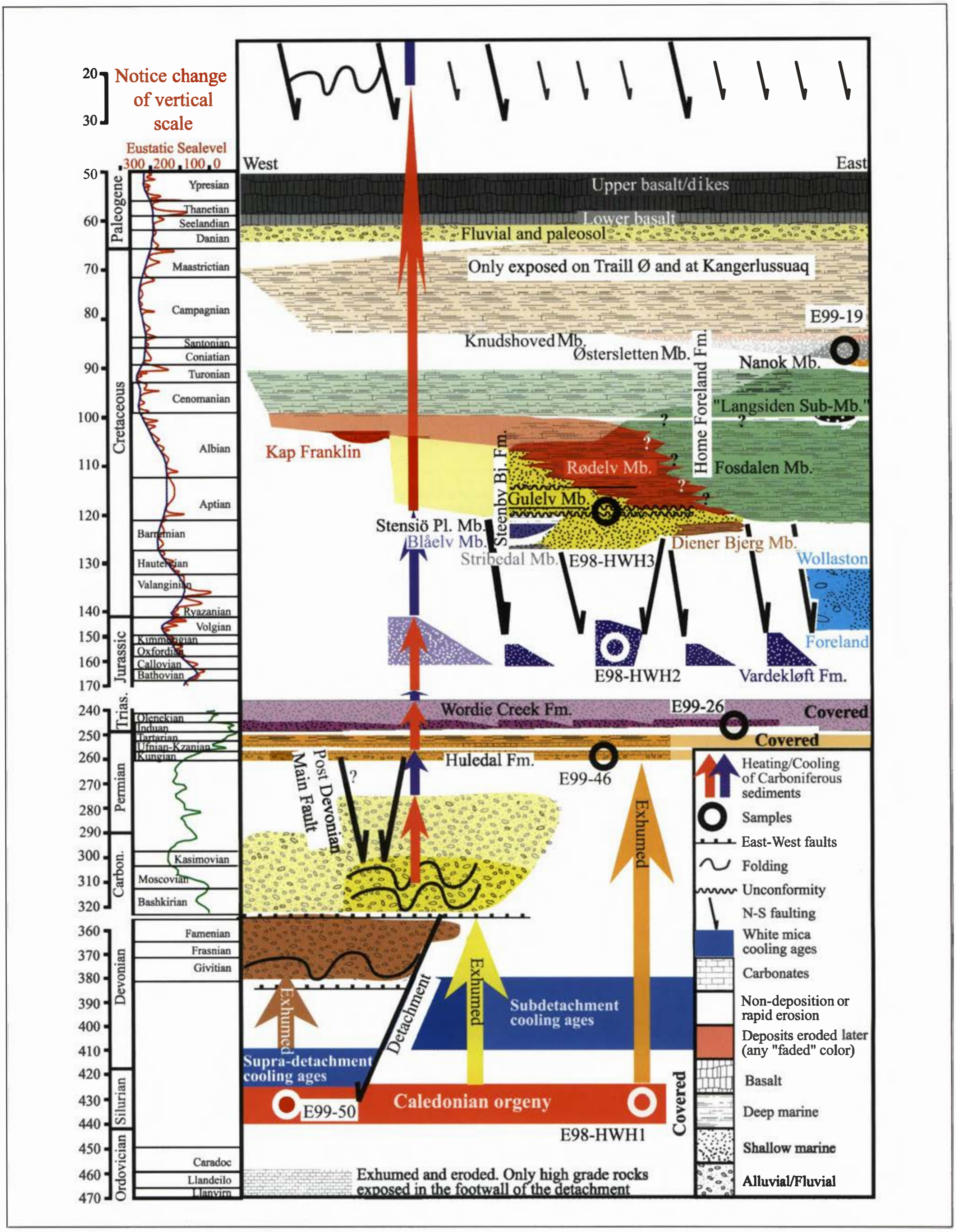



*Fig. 4. Tectonostratigraphic diagram illustrating events along a schematic East-West transect of the Hold with Hope region. The diagram presents the Caledonian and younger deposits, and based on data listed in text, speculate in the origin of erosional hiati. Albian stratigraphy reflect our tentatively interpretation of the geology but needs further study where uncertainties are marked by "?". Heating and cooling (reflecting burial and exhumation) is based on apatite data by Johnson & Gallagher (2000). The eustatic curves of Hardenbol et al. (1998) (Red and Blue lines) and Golonka & Ford (2000) (Green line), utilize the timescale of Gradstein & Ogg (1999), which also is followed here.*

conditions (Larsen et al. 1998). The Jurassic rocks rest on the Early Triassic deposits in both foot- and hanging-walls of Late Jurassic to Early Cretaceous faults (Larsen et al. 2001) (Figs. 3, 4, 6b-c).

In the Wollaston Foreland region, the Mid Jurassic basins are described as early syn-rift deposits (Surlyk 1978a). Eustacy appears to be the main guide for this regional transgression, recorded in all of East Greenland (Surlyk 1990). The transgression and marked deepening of the basin recorded at Hold with Hope (Larsen et al. 1998) are synchronous with a 150 m-rise in eustatic sea level (Hardenbol et al. 1998) (Fig. 4).

The Mid Jurassic sequence at Hold with Hope was transgressive towards the north, with basin fill towards the south (Surlyk 1990), similar to the Triassic deposits. The overall physiography thus probably was similar from Triassic to Jurassic times in this area.

*Late Jurassic-Mid Cretaceous:* - The Late Jurassic to Early Cretaceous period marks the most pronounced Mesozoic rifting in the Hold with Hope region (Surlyk 1990). Along the northeastern coast of Hold with Hope, the earliest sediments are associated with the Early Cretaceous (Hautervian) rifting event (Kelly et al. 1998). Mid Jurassic sediments are rotated and cut by faults that do not cut the Early Cretaceous deposits. The Volgian to Hautervian hiatus in the Blåelv to Fosdalen transect also marks a major period of rotational extensional faulting (Whitham et al. 1999; Larsen et al. 2001) (Fig. 3). Mid Volgian to Valanginian time also corresponds to a eustatic drop in sea level (Hardenbol et al. 1998) (Fig. 4). The rifting event was synchronous with development of coarse, syn-rift basins in the Wollaston Foreland area (Figs. 2 & 4) (Surlyk 1978a). The lack of Volgian to Hauterivian syn-rift deposits in the Hold with Hope area suggests that the section west of Fosdalen was in the footwall of the major fault zone, probably the Wollaston Foreland Fault Zone, at this time (Figs. 2 & 3). A pronounced period of cooling is recorded in apatite fission-track data from Carboniferous sediments at western Clavering Ø (Johnson & Gallagher 2000) and Late Jurassic to Early Cretaceous deposits on Wollaston Foreland (Thompson et al. 1999).

The Mid Cretaceous basin along the northeastern shore of Hold with Hope has recently received considerable attention with publication of a refined stratigraphic subdivision (Kelly et al. 1998; Whitham et al. 1999), as well as detailed depositional models (Larsen et al. 2001). The basinal succession is divided into two formations (Fig. 4): 1) the Late Hautervian (or earliest Barremian) to Mid Albian Steensby Bjerg Formation (Figs. 3, 6d,e), and 2) the Mid Albian to Late Santonian Home Forland Formation, which in turn is subdivided into several members (Kelly et al. 1998; Whitham et al. 1999). A depositional model for the Steensby Bjerg Formation defines three internal sequence boundaries within the formation, and illustrates major lateral depositional variation (Larsen et al. 1998). These studies constitute a major breakthrough in the understanding of the Cretaceous on East Greenland, and form a primary basis for the present study. Apatite fission track data (Johnson & Gallagher 2000) from Clavering Ø suggest that slow heating initiated at the same time as deposition of the Steensby Bjerg Formation, and possibly that the Early Cretaceous seas and deposition continued far west of present exposures.

*Mid to Late Cretaceous:* - The Home Foreland Formation, at easternmost Hold with Hope consists of the > 1000 m thick Albian to Santonian Fosdalen Member, the 6 m-thick Late Turonian or Early Coniacian Nanok Member, the 46 m-thick Santonian Østersletten Member, and the > 25 m-thick Santonian Knudshoved Member (Kelly et al. 1998) (Figs. 3 & 4). The Fosdalen Member consists mostly of shales and siltstones (Fig. 6d) with a central, ca. 300 m of cross-bedded sandstone (Kelly et al. 1998). These sands (here informally referred to as the Langsiden sub-member) may reflect channellized low-stand deposits within the muddy Fosdalen Member (Figs. 3 & 4). Major extensional faulting in Mid Albian time has also been recently suggested based on interpretations of unconformities and fault geometries in the area (Whitham et al. 1999; Kelly et al. 1998; Larsen et al. 2001). Alternative interpretations for faulting and related unconformities in the area at this time have tended to downplay the extent of a Mid Albian 'event' (Hartz et al. 2002). The low-stand deposits of the Nanok Member (Kelly et al. 1998), which are preceded and overlain by marine mudstones deposited below wave-base, appear to correlate with a short but distinct drop in eustastic sea level in the Turonian (Hardenbol et al. 1998) (Fig. 4). No Cretaceous sediments younger than Santonian occur in the Hold with Hope profile, but apatite fission track data from Clavering Ø (Johnson & Gallaghar 2000) suggest that the region remained buried through the Late Cretaceous (Fig. 4).

*Cenozoic break-up and volcanism:* - A widespread, pre-basalt erosional hiatus is evident throughout the area. Fluvial sandstones of probable Danian age succeed the hiatus, and are in turn overlain by Seelandian to Ypressian (58 to 50 Ma) basalt flows (Upton et al. 1980, 1995; Hartz 1998) (Fig. 4). The pre-basalt subcrop (Koch & Haller 1971; Escher 2001) illustrates that the underlying rocks had undergone considerable exhumation in the latest Cretaceous to earliest Paleocene. Generally, Cretaceous deposits which were not protected in topographic lows (either channels at Kap Franklin or grabens at Hold with Hope, Clavering Ø and Wollaston Foreland) were removed. The exhumation cannot be quantified, but stratigraphic comparisons suggest that considerable sedimentary successions were eroded.
The basalts are key features for unraveling timing and

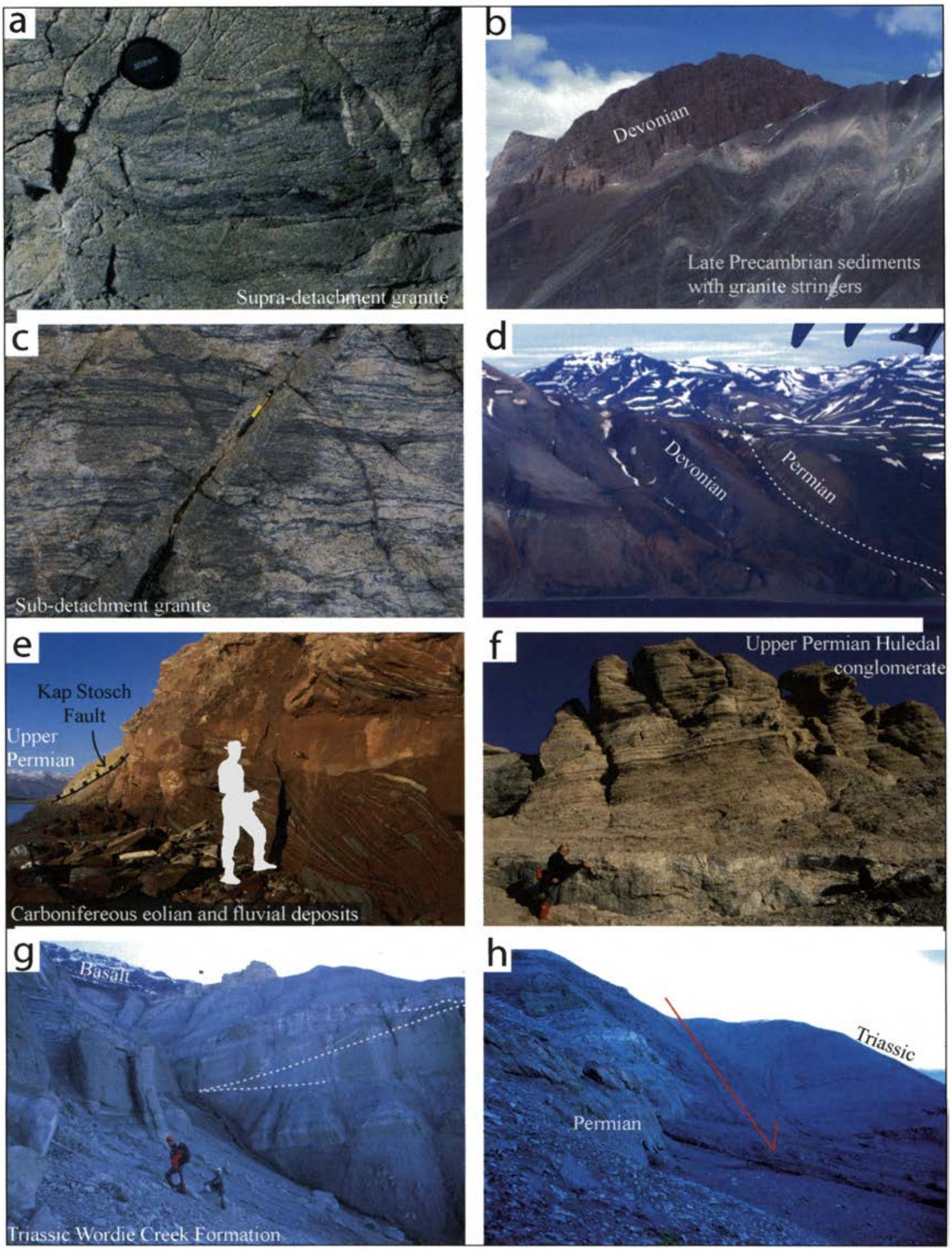



*Fig. 5. Photographs from the Hold with Hope region showing: (a) Granites south of Wordie Bugt (E99-50). (b) Devonian conglomerates overlying Upper Precambrian sediments, cut by a net of granite veins. View to the NW, in Dybendal. (c) Granites (E98-HWH1) at southernmost Stille Ø. (d) Koral Kløft at Gauss Halvø where Devonian conglomerates and sandstones, covered by Permian pebbly conglomerates and evaporates (light) and Triassic siltstones and shales (dark). The picture is taken at the western flank of a synform folding all rocks (including the Tertiary sills to the far right). Notice that no major offset of Devonian occur in the canyon, where Post Devonian Main Fault typically is placed. The sub-Permian peneplane (dotted line) extends westward above the steeply dipping Devonian deposits (view to the NE). (e) Kap Stosch Fault (Vischer 1943) juxtaposing Carboniferous deposits in the foreground against Upper Permian deposits (light rocks) in the background. View to the NE. (f) Upper Permian conglomerates of the Huledal Formation (and interbedded layers of gypsum). The outcrop occur in the direct hanging wall of the Kap Stosch Fault, as seen in figure 5e. View to the SE. (g) Forty meters thick layers of coarse sand and boulder conglomerate form southward dipping clinoforms interpreted as a southward-progating Gilbert type delta. View to the NW, 'River 7' (Nielsen 1935)). (h) Triassic siltstones of the Wordie Creek Formation in fault contact with Upper Permian deposits. The Permian deposits include the Huledal conglomerates at the base, white layers of carbonates and gypsum (10 m thick), and black shales. The slightly left-lateral normal fault (300/75/100, estimated offset > 50 m) is one of the few exposed 'cross-faults' parallel to the fjords. View is to the NW, 'River 7' (Nielsen 1935). One of the cross-faults are exposed on northernmost Hold with Hope as a post-Triassic NNE-dipping normal and slightly left-lateral fault (300/75/100) with an estimated offset of more than 50 m*

displacement on faults and folds in the region. The post-basalt faults generally use pre-existing NNE-SSW-trending faults towards the west and follow NE-SW-trending dikes towards the east. Basalts are rotated 5 to 20° by block faulting and the cumulative displacement in the Hold with Hope region exceeded 5 km at this time (> 10% extension) (Fig. 2) (Upton et al. 1980). These structures thus control the outcrop pattern observed today.

## $^{40}Ar/^{39}Ar$ data and interpretation

White micas from two granitic basement units and from a time-stratigraphic sequence of five sandstone and conglomerate units in the overlying basins at Hold with Hope were extracted for $^{40}Ar/^{39}Ar$ analysis; biotites from one of the basement units were also analyzed. All samples were collected from continuous outcrop in the well-studied profile along the northeast shore of Hold with Hope, thereby maximizing the opportunity to tie radiogenic age and field data together in a sedimentary provenance history for the basins. Basement samples were collected above (leucogranite, E99-50M) and below (two-mica granite E98-HWH1) the upper splay of the FRD. The sedimentary rocks were collected within sections documented in recent studies (Upper Permian conglomerate sample E99-46, and Lower Triassic sandstone sample E99-26: sections described by Nielsen (1935) and Vischer (1943); Mid Jurassic sandstone sample E98-HWH2 from sections described by Larsen et al. (2001); Lower and Upper Cretaceous sandstones E98-HWH3 and E99-19, respectively, described by Kelly et al. (1998) and Larsen et al. (2001)).

Micas were separated from the samples though standard separation techniques and were irradiated at the McMaster nuclear reactor facility, Canada. Samples E99-50M, E99-46, E99-26 and E99-19 were analyzed at the Geological Survey of Norway (NGU); samples E98-HWH1, E98-HWH2 and E98-HWH3 were analyzed at the Massachusetts Institute of Technology (MIT). The samples were dated by fusing single grains with a $CO_2$ laser operating at infrared wavelengths (NGU) and with a defocused laser beam operating at visual wavelengths (MIT). The exception is sample E99-50, which was dated by furnace step-heating. Some of the larger detrital white-mica grains were dated by laser step-heating, but most grains were dated by total fusion. The background levels for the NGU $CO_2$ laser port were between 1.64-2.74 x $10^{-12}$ cc STP for mass 40 and 2.18-5.48 x $10^{-14}$ cc STP for mass 36; background levels on masses 37, 38 and 39 were similar to those in Eide et al. (2002). Analytical methods otherwise followed those described in detail in Hodges (1998) and Hartz et al. (2000) (MIT) and Eide et al. (2002) (NGU). Ages and their errors were calculated in the same way; regardless of the laboratory used. All ages are cited with two-sigma errors, including uncertainty in J-value. Notice that the error weighted-mean ages only have a geological significance when all micas have the same cooling history (i.e. basement rocks). Complete tables with $^{40}Ar/^{39}Ar$ data are available upon request from the first author.

*Granite below the detachment (E98-HWH1)*

The sample is an undeformed vein of fine-grained, two-mica granite that cuts the coarse, red migmatitic layering (Fig. 5c). Migmatites at Stille Ø represent the southernmost exposure of the substrata below the basins of Hold with Hope (Figs. 2, 3 & 4). Stille Ø and all nearby islands geologically compare to Clavering Ø, which comprises primarily migmatitic pelites (Escher 2001; Jones & Escher 2002). The migmatites are deformed by N-S-trending open folds. The crystalline rocks are previously mapped as being unconformably overlain by the Permian sedimentary section (Vischer 1943); although this probably once was the case, the base of the Permian is not exposed at the island, and the actual contact is a west-dipping normal fault (Fig. 3). Twenty white mica grains were dated by single-grain laser fusion, and show a large spread in individual ages, ranging from 413 ± 11 to 390 ± 11 Ma (error weighted mean age = 401 ± 3 Ma). Although the ages collectively show a Gaussian distribution (Fig. 7), the dataset is somewhat surprising in that it shows a wide distribution of individual ages from a single granite sample.

Twenty biotite grains were also analyzed with the laser, and yielded a similarly broad spread of ages from 430 ± 28 to 305 ± 9 Ma, with all but three grains ranging from 414 ± 12 to 387 ± 12 (error weighted mean 390 ± 3 Ma). Excluding the three biotite outlier ages, the white mica and biotite yield statistically similar ages.

*Leucogranite above the detachment (E99-50M)*

A white, two-mica leucogranite, intruding the lower Eleonore Bay Supergroup, (Figs. 2 & 4) is medium-grained, with faint primary layering (Fig. 5a). Preliminary U-Pb zircon analyses from the sample suggest an age of approximately 424 Ma (F. Corfu, pers. comm.). Both the texture and U-Pb age are typical for the Caledonian leucogranites in the area (Hartz et al. 2001).

Furnace step-heating of the sample yielded a set of semi-concordant apparent ages comprising ca. 79% of the radiogenic $^{39}Ar$ gas released in the experiment. A mean age for this segment of the release spectrum is 414 ± 2 Ma with ages on individual steps varying between 416 ± 4 and 410 ± 2 Ma (Fig. 7).

*Upper Permian Huledal Formation (E99-46)*

The Huledal Formation at the base of the Foldvik Creek

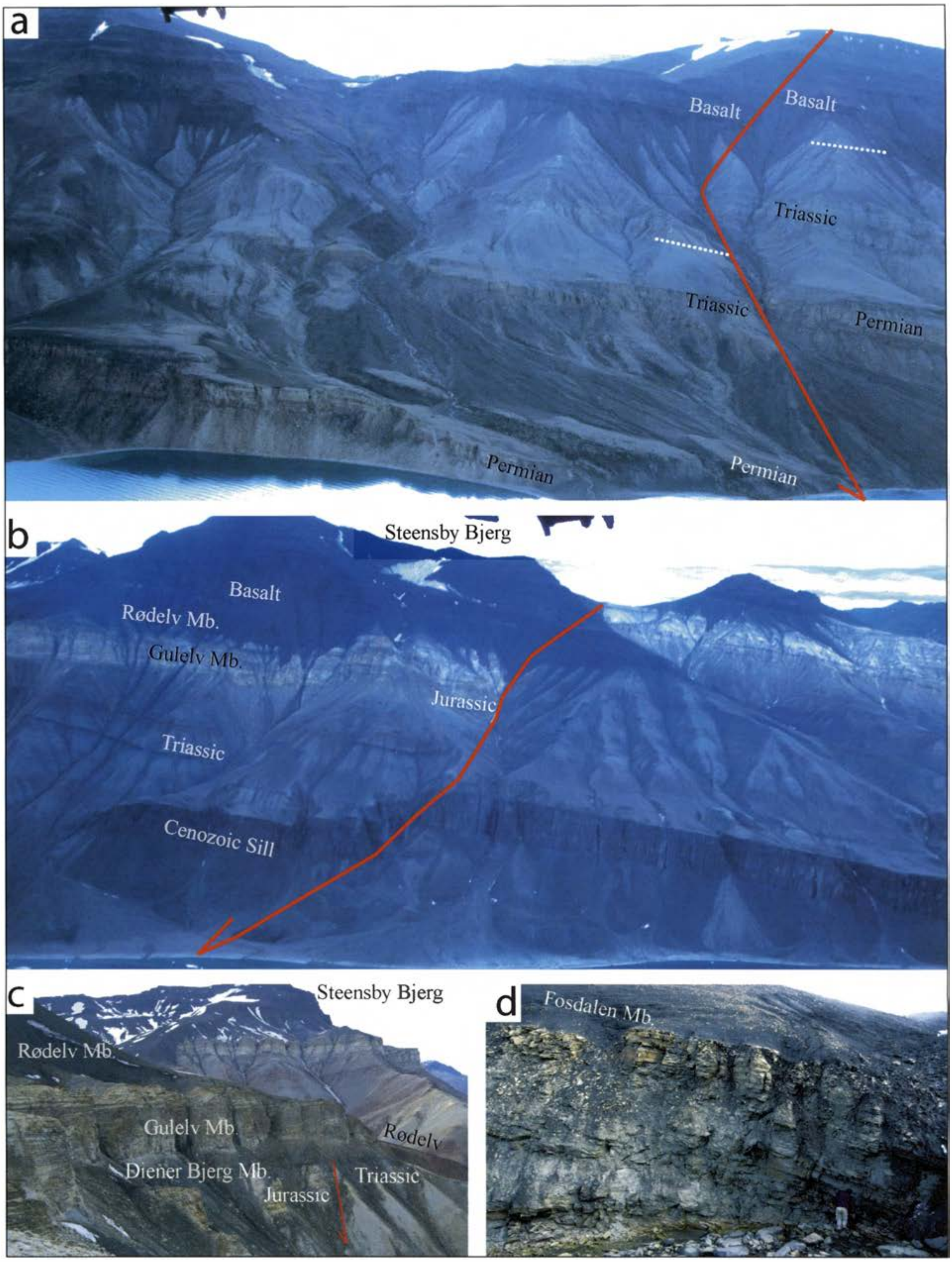



*Fig. 6. Photographs from the Hold with Hope region: (a) Immacradal Fault. The fault offsets the Upper Permian and lowermost Triassic deposits with 285 m. (Nielsen 1935) however some (ca. half) of the displacement also offset the Paleocene basalts (Upton et al. 1980). 'Conglomerate 4' above the dotted line, doubles in thickness across the fault (Nielsen 1935). View towards SW. (b) Steensby Bjerg is cut by an east-dipping normal fault displacing all rock-units. The Jurassic and Cretaceous deposits were sampled in the section to the right. Notice the truncation of Triassic deposits below the Cretaceous units. View towards the SW. (c) The Triassic to Paleocene succession in the Rødelv area. Notice the Late Jurassic to Early Cretaceous faults in the foreground offsetting the Jurassic deposits, but not the Cretaceous. A splay of faults offset the Cretaceous deposits in Rødelv, however the age of the faults is controversial. View towards the NW. (d) The "classic" site of the Fosdalen Mb. onlapping Triassic and Jurassic sediments in 'River 23'. The onlap surface dip to the south. View to the SE.*

Group was sampled at Stille Ø (Figs. 2, 3 & 4). We sampled the lowermost section where fluvial deposits consisting of alternating massive conglomerate and trough-crossbedded pebbly sandstones. These deposits occur below carbonate-cemented coarse conglomerates, which form the bulk of the member.

Eighteen white mica grains were dated by laser step-heating, and the individual steps for each grain were used to calculate a total fusion age. The total fusion ages for each grain were then incorporated in the cumulative probability diagram (Fig. 7). Each grain was dated with up to five steps (total of 56 steps divided amongst the 18 grains); relatively large age variations were detected (up to 18 m.y.) within each grain. The total fusion ages range between 412 ± 1 and 396 ± 1 Ma, with two coarse divisions in the dataset: One set of ages ranges between ca. 412 and 403 Ma while the other set ranges between 400 and 395 Ma. A bimodal distribution with peaks at about 410 and 395 Ma can be suggested from the data (Fig. 7).

*Lower Triassic Wordie Creek Formation (E99-26)*

The Wordie Creek Formation was sampled in the footwall (west) of the fault at "river 23" at 100 m above sea level (Figs. 3 & 4). The sampled red sandstone included highly mica-rich layers, which were separated for analysis. Fourteen grains range in age from 416 ± 1 to 372 ± 3 Ma, and show two broadly distinguishable age populations (Fig. 7). Four grains cluster around 413 Ma (416 ± 1 to 411 ± 1 Ma) and another set of ages range from 385 ± 2 to 372 ± 3 Ma. One grain yielded an age of 402 ± 2 Ma (Fig. 5). Two of the youngest grains were dated by step heating and showed little internal age variation. Despite the small number of analyzed grains, the two main age groups are statistically distinguishable.

*Mid Jurassic Vardekløft Formation (E98-HWH2)*

The Mid Jurassic Vardekløft Formation was sampled in the Gulelv profile, at the eastern side of Gulelv at 460 m altitude (Figs. 3 & 4). The sample was collected from a highly micaceous layer of shallow-marine, white, cross-bedded, coarse sandstone, directly above the red Triassic siltstones. Twenty-nine white-mica grains yielded ages ranging between 424 ± 16 and 394 ± 15 Ma (Fig. 7). The majority (23 grains) cluster between 416 ± 18 and 407 ± 15 Ma. The other six grains yielded ages between 424 ± 16 and 416 ± 18 Ma.

*Lower Cretaceous Hold with Hope Group (E98-HWH3)*

Highly micaceous white sandstones of the Gulelv Member were sampled at the top of the member in profiles directly east of the river Gulelv (Figs. 3 & 4). The rocks were collected from the mega cross-bedded, delta-front deposits in the second sequence (Larsen et al. 2001).

The 29 dated grains show the largest dispersal of age data and included the some of the oldest (423 ± 14 Ma) and youngest (357 ± 12 Ma) cooling ages recorded for this study (Fig. 7). The majority range from 419 ± 16 to 394 ± 13 Ma. Four of the grains are very young with ages between 380 ± 13 and 357 ± 12 Ma.

*Upper Cretaceous Hold with Hope Group (E99-19)*

The Østersletten member of the Home Foreland Formation in the Hold with Hope Group (Figs. 3,4) consists of faintly cross-bedded white sandstones with thick layers of almost pure white mica. The grains have distinct, equigranular and euhedral shapes, suggesting igneous origin. Seventeen grains yield a tight age group ranging from 421 ± 2 to 409 ± 2 Ma (Fig. 7). Two of the grains were dated by laser step heating and showed little internal age variation.

## Discussion

In the following sections we discuss the white-mica data in a tectonostratigraphic context by presenting the post-Caledonian history of the Hold with Hope region in a sequence of eight time slices (Fig. 8); the time slices combine discussions of basin models and provenance-to-basin links. The provenance-to-basin ties assumes the shortest viable route to the deposition area, given the structural constraints of the basin geometries; other sediment routes to the depocenters are also possible.

For the sake of differentiating provenance domains, the white-mica data from the basement regions have been split into four groups: 1) older than 410 Ma, 2) between 390 and 410 Ma; 3) between 375 and 390 Ma; 4) less than 390 Ma. The oldest group broadly corresponds to supra-detachment ages (Hartz et al. 2001), supported by our data from sample E99-50M (414 Ma). The younger ages divide sub-detachment domains into structurally deeper (younger white-mica ages) rocks. These divisions were determined from the dataset presently available from the detachment footwall (Hartz et al. 2000; 2001) (Fig. 4). The sub-detachment age domains may reflect tectonic domains in the Hold with Hope region separated by deep splays of the detachment (Watt et al. 1999; Gilloti & Elvevold 2002) (Fig. 2). However, resolution of these footwall domains requires more $^{40}Ar/^{39}Ar$ data, and the three divisions we make in study should be regarded as general markers only.

*Late Devonian - Early Carboniferous*

The Devonian to earliest Carboniferous basins are suggested to have formed in the detachment hanging-wall, during footwall exhumation (Hartz 2000). This model is supported by data from the granites cutting the Late Precambrian sediments above the detachment which typically yield white-mica cooling ages that are only slightly younger (ca. 419 to 413 Ma) than the U-Pb granite intrusion age (ca. 425 Ma) (Hartz et al. 2001). In contrast, micas in the footwall of the detachment typically cooled later than those in the hanging-wall and have ages ranging from ca. 410 to 375 Ma with a general younging trend structurally downwards. This trend is interpreted to reflect gradual exhumation of the high-grade rocks (Hartz et al. 2000) (Fig. 4).

The sample from the detachment hanging-wall collected at Wordie Gletscher (E99-50M) and dated to ca. 414 Ma was thus among the last rocks above the detachment zone to close to argon loss in white micas. The relatively young age for this sample probably reflects its low structural level within the hanging-wall, relative to structurally higher hanging-wall samples with older cooling ages. White mica from similar granites sampled 1.5 km higher in Dybendal (Fig. 2) are dated to ca. 419 Ma, with the bulk of single grains ranging from 425 to 414 Ma (Hartz et al. 2001); the 414 Ma age thus could be regarded as a minimum age for supra-detachment rocks.

The white mica ages (413 to 390 Ma) from the sub-detachment granite at Stille Ø (E98-HWH1) should be regarded as maximum ages for the detachment footwall. The youngest ages from the laser populations (ca. 401 Ma for white mica and ca. 389 Ma for biotite) represent relatively old ages for the detachment footwall. This is consistent with the regional scenario of footwall exhumation younging towards the west (Hartz et al. 2001), and the fact that the sample was collected from the uppermost sub-detachment domain.

A model illustrating the tectonic setting for this time period is presented in Figure 8a. The supra-detachment granites were exhumed and then covered by Devonian (Fig. 5b) to Early Carboniferous deposits overlying E-W-trending faults, and N-S-trending folds (Bütler 1954, 1957, 1959; Hartz 2000). The sub-detachment rocks were exhumed through the Mid Carboniferous, and were then covered by Late Carboniferous deposits.

*Late Carboniferous*

The structural pattern of E-W-trending faults and N-S-trending folds appears to continue into the Carboniferous, although these structures are far less constrained by outcrop data (Bütler 1959). By the Mid Carboniferous (Bashkirian, Vigran et al. 1999), deposits started to accumulate on the uppermost detachment footwall (Fig. 8b). The PDMF is generally inferred to have major (3 km) stratigraphic offset in the Carboniferous (Vischer 1943), with a possible product of this activity preserved in the Late Carboniferous or Early Permian Gastisdal Graben, in eastern Gauss Halvø (Bütler 1959) (Figs 8c). However, kilometers of post-Devonian down-to-the-east displacement in this area are indicated from our field observations father south along the structure at Gauss Halvø (Fig. 5d) and we suggest that the geometry of the Carboniferous basins requires further study.

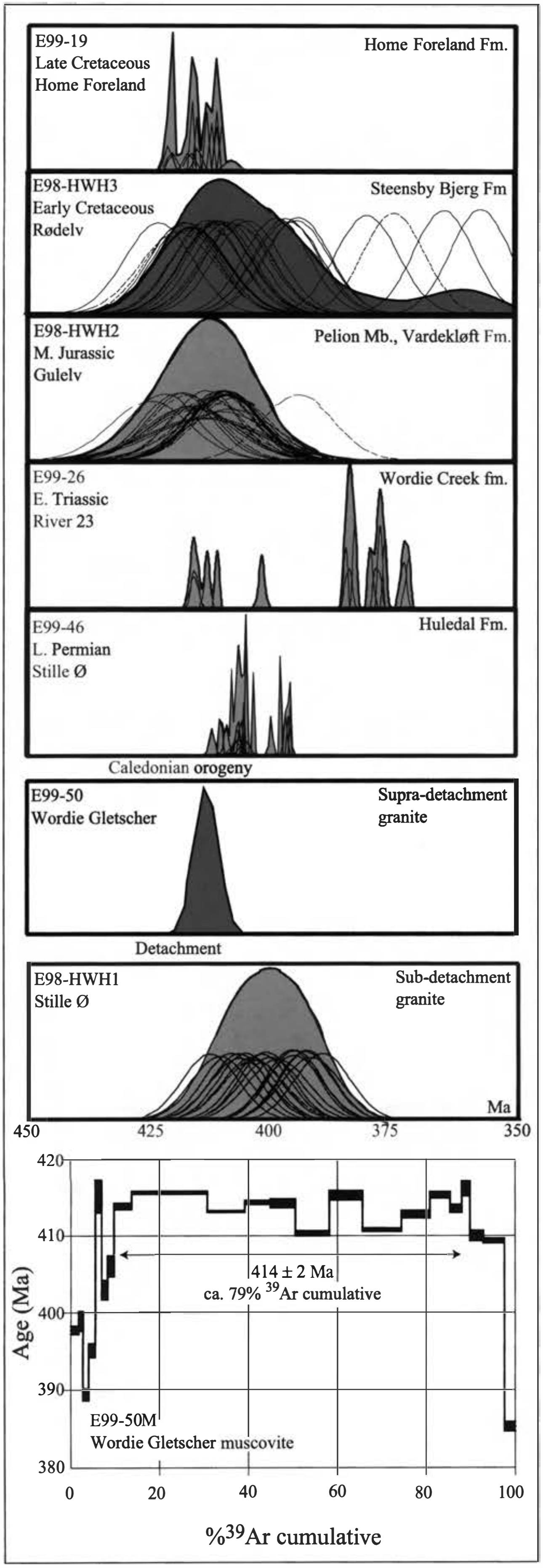
*Late Permian*

The post-unconformity, Upper Permian Huledal Formation includes regionally exposed conglomerates, from which the lowermost detritus (E99-46) was dated for this study. The detrital white micas (ca. 413 to 390 Ma) from these sediments compare directly to cooling ages of micas in the underlying crystalline rocks (E98-HWH1), with a possible minor input of 'young' supra-detachment micas (Figs. 7 & 8c). The sampled outcrop includes clasts of pre-Caledonian quartzites and limestones clearly derived from above the detachment, however the data are consistent with a local, northerly provenance for the detrital white micas.

The regionally extensive, Upper Permian marine transgression is generally considered to reflect faulting along the PDMF combined with post-extensional thermal subsidence (e.g. Surlyk 1990; Stemmerik et al. 1992). We nevertheless follow Vischer (1943), who did not link the transgression to faulting, and thus emphasize thermal subsidence following a prolonged period of post-Caledonian crustal thinning. The marine transgression was synchronous with a worldwide drop in eustatic sea level (Golonka & Ford 2000). Regional subsidence of considerable magnitude would be required to overcome the effects of eustasy.

*Early Triassic*

Detrital white mica (E99-26) from the easternmost deposits of the Wordie Creek Formation (Fig. 3) show that several distinct sources were being eroded at this time (Fig. 7). Basically, the white-mica ages are divisible into old grains (416 to 411 Ma) with a supra-detachment source, one intermediate-age grain (402 Ma) that corresponds in age to grains found in the Permian deposits, and younger grains (385 to 372 Ma). The old grains could either be derived from the Wollaston Foreland area, from regions being exhumed along the Clavering Fault, or the NW section of the Hold with Hope region exhumed along the Kap Stosch Fault or parallel faults (Fig. 8d). The single intermediate-age grain, could either be derived from the upper supra-detachment basement, or as a recycled grain from the Permian




deposits. A recycling scenario is supported by abundant clasts with Permian fossils identified in the Early Triassic deposits at Hold with Hope (Nielsen 1935). The bulk of the detrital white-mica grains show significantly younger cooling ages than those in the Permian deposits, suggesting that deeper crustal rocks were also being eroded into the basin (Fig. 7). The only area where such deep crustal domains are exposed in the vicinity is in the northeastern Hold with Hope region (Watt et al. 1999; Gillotti & Elvevold 2002; Escher 2001) (Fig. 2), which is thus suggested as a possible sediment source region at this time (Fig. 8d). Given that sediments were transported southwards into the basin (Stemmerik et al. 1992), a distal northerly source is likely for the grains.

The Triassic deposits are cut by the syn-depositional Kap Stosch, Immacradal and Clavering Faults (Nielsen 1935; Vischer 1943; Oftedal & Andresen 2002) (Fig. 8d). However, our observations do not corroborate suggested Triassic displacement along the PDMF (e.g. Surlyk 1990; Stemmerik et al. 1992). We suggest that the accommodation space needed for this basin fill may instead result from a combination of factors including synchronous earliest Triassic eustatic sea-level rise (Hardenbol et al. 1998), continued thermal subsidence, isostatic loading and activity on faults other than the PDMF (i.e. Kap Stosch Fault, Immacradal Fault, and Clavering Fault).

### *Mid Jurassic*

The Late Triassic to Early Jurassic is again marked by a regional unconformity. The subsequent Middle Jurassic Pelion Member probably covered most of the region, but today only occurs in downfaulted blocks (Figs. 2, 3). The majority of white mica ages from the Mid Jurassic sandstones (E98-HWH2) vary from 424 to 407 Ma, suggesting a dominant supra-detachment input, similar to that of the oldest grains in the Triassic deposits. The older ages in this population suggest supplemental input derived from the older (upper) supra-detachment domain. These old detrital ages are (in the present literature) only matched by ca. 419 Ma white-mica ages recorded from the uppermost granites that lie directly below the Devonian unconformity in Dybendal, north of the Devonian basin (Hartz et al. 2001) (Fig. 2). These grains thus suggest that erosion had begun to excavate granites that had otherwise been buried since the Devonian. Erosion of the thick Paleozoic basins in this area would have led to unroofing and

*Fig. 7. Cumulative histograms showing the total distribution of $^{40}Ar/^{39}Ar$ white mica analysis, and individual analyses plotted with 1 sigma error-bells. The lowest diagram present the step heating of sample E99-50. The other samples are dated by laser fusion. See text for details.*

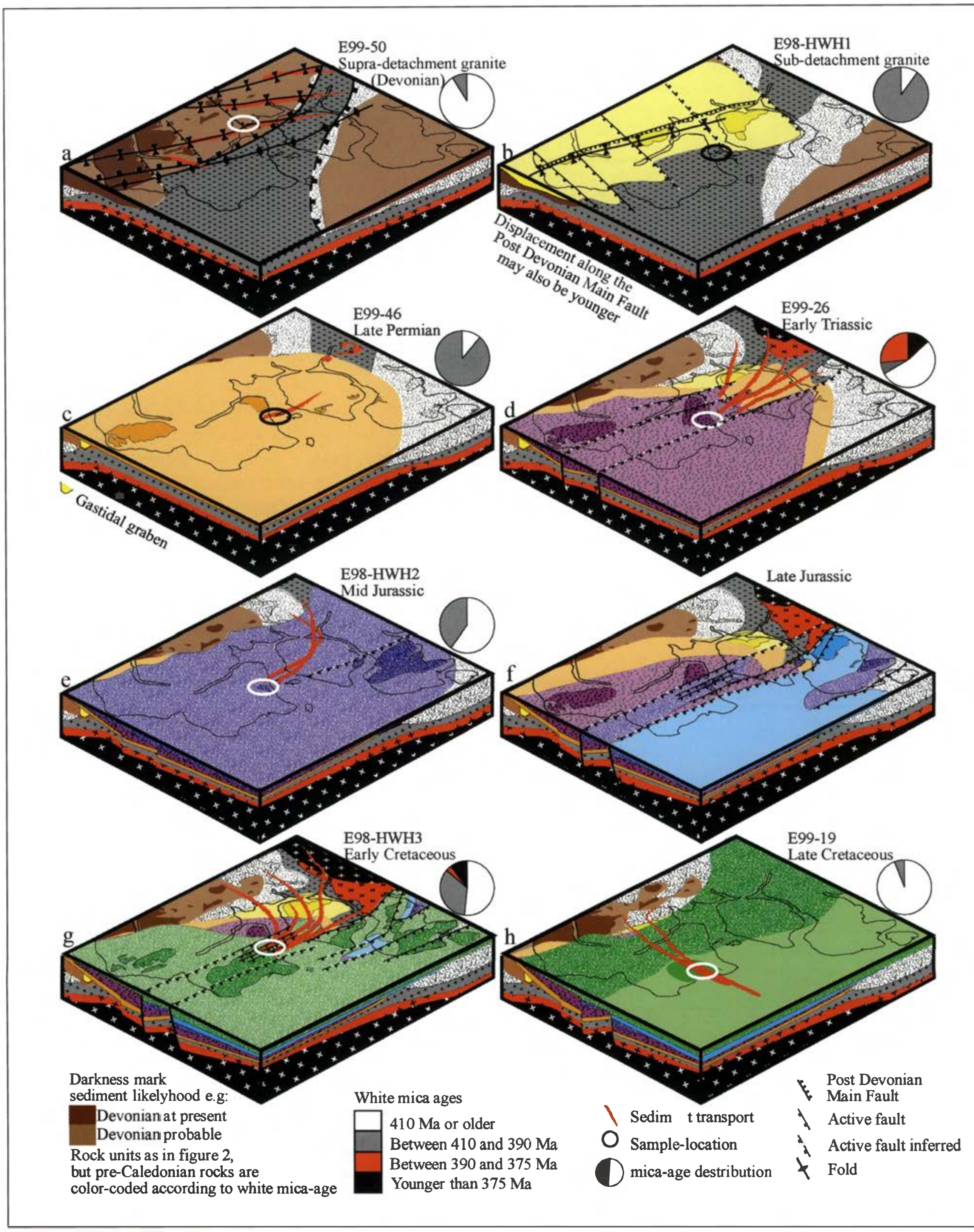



*Fig. 8. Schematic time-slices illustrating proposed outcrop and subcrop in the Hold with Hope region from the Devonian to the Cretaceous. Notice that the fully colored regions mark rocks present today, and the lighter regions mark regions where basins probably (or possibly) was formed, but later was eroded or covered. The present study focus on the link between provenances and basins, and we thus do not mark sedimentary farcies, which have been published previously and cited in the text. We also do not mark terrestrial deposition after the Late Permian. The main transport direction or links between basin and provenance is marked with red lines where it can be established. Notice that three sub-detachment and one supra-detachment domain is differentiated, based on Ar-cooling ages, and that possible minor faults that do not involve crustal scale reorganization are not marked. The eight timeslices represented here does not give full justice to all events occurring in the region, and thus reflect a simplification. The present outcrop pattern is based on studies referenced in figure 2.*

recycling of detrital white micas with gradually older cooling ages (Fig. 7), opposite that expected when *in situ* basement rocks are eroded (Sherlock 2001). As mentioned previously, westernmost Wollaston Foreland is also a viable source for 'old' white micas.

Only one of the dated white micas from the Jurassic sandstones gave a characteristic, young sub-detachment (ca. 394 Ma) age. At first, it may be surprising that young mica is not more common in the Jurassic sediment, especially since the bulk of the underlying Triassic detritus yielded much younger age populations (385 to 372 Ma). The lack of young detrital mica in the Jurassic sediment has two implications: 1) The detrital white micas in the Jurassic deposits were derived from a primary source and not recycled from the Triassic deposits (also strongly suggested by the euhedral shapes and much larger average grain sizes compared to the Triassic mica grains), and 2) Deep crustal domains were covered by Permian to Triassic sediments, water, or both, by the time the Mid Jurassic sediments was deposited. The latter interpretation is supported by the structural pattern with sub-detachment rocks sitting in topographic lows compared to the supra-detachment rocks. However, detrital data from other outcrops of the same age are needed to test if this hypothesis holds regionally (Fig. 8e).

### *Late Jurassic to Early Cretaceous*

Late Jurassic to Early Cretaceous rifting resulted in two distinct tectonic phases in the Hold with Hope region. The early phase involved faulting, but no deposition west of Fosdalen along northeastern Hold with Hope (Fig. 2) (Larsen et al. 2001), and the later phase involved widespread syn-depositional half-graben formation west of Fosdalen. The area thus appears to have been exhumed, probably along the Wollaston Foreland Fault Zone, which projects southwards below Fosdalen (Figs. 2 & 8f).

Detrital white micas from the Gulelv Member (Fig. 3) (E98-HWH3), ranging in age from 423 to 357 Ma, record erosion of several provenance domains (Fig. 7), and confirm that the preceding major rift phase exhumed new basement domains and cannibalized pre-existing basins. About half of the grains record large supra-detachment contributions only matched in age by the Devonian sub-strata (Hartz et al. 2001), suggesting this region was undergoing increasing excavation (Fig. 8g).

The other half of the grains record a range of ages typical for sub-detachment rocks, whereof some are the youngest recorded in this study, and are only matched by cooling ages recorded from below a second, deep splay of the (FRD) detachment in Kejser Franz Joseph Fjord (Hartz et al. 2000) (Fig. 1). The detrital grains at Hold with Hope are probably not derived from such a distant source area, but orthogneisses in a similar, deep-crustal setting were mapped north of Wordie Gletscher. These gneisses lie below a deep-seated detachment (Watt et al. 1999; Gilotti & Elvevold, 2002) and we suggest that these rocks constitute another likely provenance at this time (Fig. 8g).

Collectively isotopic, field and stratigraphic data confirm a model for Barremian to Aptian deposition into a pronounced Volgian to Valanginian (Hautervian) rift topography (Kelly et al. 1998; Whitham et al. 1999; Larsen et al. 2001) where white micas were derived from newly excavated source regions (Fig. 8g). We see less evidence for major Mid Albian extensional faulting along and east of Fosdalen, but note that further study is required to differentiate Mid Cretaceous and Tertiary faulting events and their impacts on basin geometries and sedimentation. The drowning of rift-shoulders that initiated in the Aptian may have continued into the Late Albian, synchronous with pronounced onlap at Wollaston Foreland (Vischer 1943) and Kap Franklin (Donovan 1957) (Fig. 8h). This regional trangression followed a major rise in eustatic sea level (Hardenbol et al. 1998) (Fig. 4), but may also reflect thermal subsidence following Late Jurassic to Early Cretaceous rifting.

### *Late Cretaceous*

The Home Foreland Formation appears to include at least two periods of low-stand deposition. The first low stand is represented by the major sandstone bodies of the Langsiden sub-member, within the Fosdalen Member (Norsk Hydro, in-house data) (Fig. 4). These sandstone bodies probably reflect low-stand channel deposits and major late Cretaceous eastward sediment transport. The second low-stand is marked by the Nanok Member, occurring above the Fosdalen Member (Fig. 4) (Kelly et al. 1998), and may represent major sediment transport eastwards (Whitham et al. 1999)

The older (421 to 409 Ma) white mica grains (E99-19) from the Østersletten Member suggest that the sediments were only derived from a supra-detachment source. An isolated source region corresponds well to the suggestion outlined above that Cretaceous deposits had already covered all low-lying terranes, including the sub-detachment gneisses to the north (Fig. 8h). It is virtually impossible to determine how much father west the Late Cretaceous basin extended. The major Late Cretaceous transgression overlaps with high eustatic sea level (Hardenbol et al. 1998) (Fig. 4), and the increased accommodation space may thus in part reflect thermal subsidence following the pronounced Jurassic to Cretaceous rifting.

## Conclusions

The present study has shown that detrital white-mica $^{40}Ar/^{39}Ar$ geochronology can be applied to solve issues of basin evolution. We note, however, that interpretations of detrital data never become better than the existing provenance reference age database, and that an in-depth understanding of the cooling history of the potential provenance domains is a clear prerequisite to any provenance study. Our study shows that even discrete variations in provenance cooling histories can be differentiated in the detritus from different sedimentary sequences, and that this information not only hints toward the origins of the detrital grains themselves, but also carries a record of the previous tectonic (cooling) histories of the detrital grains. Perhaps the foremost advantage of studies like this is that they provide feedback on tectonic models. Such feedback can spark structural tests for proposed basin models by showing which basement regions were exhumed, and at which times. In the present case, the detrital study, coupled with traditional field techniques and eustatic sea-level data, confirm some of the 'accepted' tectonic events for the Hold with Hope region and suggest need for re-evaluation of others.

Collectively, the white micas from the basement samples confirm that rocks below the detachment cooled later that rocks above it, and that this downwards-younging age trend can be traced into the detritus as the rocks were subsequently exhumed and eroded into the basins. The FRD furthermore appears to have controlled Devonian to Mid Carboniferous deposition, as basins of this age predominantly (entirely?) formed above the hanging-wall of the detachment. Late Carboniferous basins cover the uppermost sub-detachment rocks, which thus must have been exhumed by this time.

We see little compelling structural or detrital evidence that the Post Devonian Main Fault in the Hold with Hope region was the primary control on the Late Permian to Mesozoic basin evolution. In contrast, we suggest that Upper Permian basins formed during major thermal subsidence, following the post-Caledonian extensional events, and that renewed Early Triassic rifting occurred along faults east of the PDMF (i.e. the Kap Stosch Fault, Immacradal Fault and Clavering Fault).

The wide range of detrital ages in the Early Triassic and Early Cretaceous sands corresponds well to the major, Early Triassic and Late Jurassic-Early Cretaceous rift events documented over the Greenland-Norway corridor, and indicates extensive exposure and erosion of new provenance domains and the cannibalization of earlier basins at these times. In contrast, sediment source areas appear to have been restricted in the Late Permian, Mid Jurassic and Late Cretaceous, coinciding with tectonically less-active periods, global eustatic sea-level rise and limited exposure of basement source areas. A major Mid Albian rift event is not required by the field and detrital data. The local sampling of source regions that seems to have been the norm in the Permian, the Mid Jurassic and the Late Cretaceous, has direct implications to offshore areas in terms of provenance markers.

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