Similarities and differences in the tectonics of two passive margins: the Northeast Atlantic Margin and the Australian North West Shelf

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Abstract

The Northeast Atlantic margin (NEA) and the Australian North West Shelf (NWS) are both well-known passive margins, and have much in common in terms of size, orientation, water depth and economic importance. Comparison of their tectonic histories highlights issues that may have general significance for passive margins. In global kinematic terms the NEA and NWS were linked by the fragmentation of Pangea and the closure of Tethys. The NWS occupied an exterior position in Pangea and underwent a succession of extensional episodes, each one leading to break-up of a portion of the extended terrane. In contrast, the NEA occupied an interior position and break-up occurred after several failed rift episodes, the evidence for which is preserved on both sides of the young ocean. Despite these factors and a ca. 80 million year difference in plate tectonic maturity, there are remarkable evolutionary similarities between the margins. These include segmentation of the margin by diffuse NW-SE transfer zones, transition of some segments from shear margin to passive margin during early spreading, and pre-break-up volcanism. The detachment of microcontinental strips is also characteristic of both areas, and may be a paradigm for stretched passive margins during plate reorganisation.

Both margins are dominated by a NE-SW extensional "super-basin", with a sedimentary fill dominated by Permo-Triassic on the NWS and Cretaceous on the NEA. Both strongly overprint older basement and basin fabrics. Reactivation of faults occurs in both areas and there is a common assumed connection between basin development and basement substructure. However, direct evidence for this link is surprisingly difficult to find and requires systematic work to be properly substantiated. On both margins, depth-dependent extension models have been invoked to explain disparities between upper crustal extension and thermal subsidence during rifting. This phenomenon appears to be typical of passive margins at time of break-up, and is being documented in an increasing number of passive margins worldwide.

Volcanism associated with the Iceland mantle plume was a major feature of Paleocene-Eocene break-up in the NEA, perhaps the world's best-known volcanic margin. The Oxfordian-Valanginian volcanism on the Argo, Cuvier and Gascoyne margins was of a somewhat lesser scale and was not associated with the widespread permanent uplift typical of NW Europe. Rapid finite rate extension, and/or depth-dependent extension may explain excessive melt production on the NWS. However, both the wide range of common phenomena and the plate tectonic setting suggest that plume models should still be strongly considered. Characterising the heat input associated with break-up rifting and volcanism is a key issue for maturation modellers on these and other passive margins.

The thick rift-sag successions on both margins underwent compressive reactivation during the Cenozoic, but both cause and effect were different. Inversion on the NWS was caused by oblique continental collision and distributed transtension and transpression along the length of the margin. On the NEA it was caused by forces orthogonal to the margin, probably attributable to ridge push. The implication of different types of inversion for hydrocarbons preservation is a particularly fertile field for comparative study.

The NWS and NEA both host multiple source rocks. The most important are syn-rift Jurassic mudrocks, a global supersource related to an important phase of Pangean break-up. On the whole, source rocks are more gas-prone on the NWS. In both areas, oil systems are more prevalent in inboard rift basins while gas dominates in the deeper water areas. On the NWS, this transition is due to absence or immaturity of the Jurassic in outboard areas allowing the system to be dominated by older, gas-prone source rocks. On the NEA it is due to Cretaceous

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Acknowledgements: We thank the following scientists who provided vital advice during preparation of the manuscript: Grant Ellis, John Gorter, Myra Keep, Ian Longley, Dietmar Müller, Michèle O'Callaghan, Sverre Planke, Steve Moss, Phil Symonds and Bob White. Special thanks to Myra, without whose persistence the manuscript would still be just a good intention. Graphics by John Kipps and Mike McCambridge. Published by permission of Statoil.

subsidence and deep burial of the Jurassic. Continued exploration of the deep water NEA will probably favour the discovery of gas, bringing the oil-gas balance more in line with that of the NWS.

Introduction

Our viewpoint on geological issues – for example, what constitutes a passive margin and what characteristics it should have – tends to be formed by the area on which we are working. This is particularly true where the area is of global importance, has a long history of study and where a worker could conceivably spend a lifetime of research. This paper draws comparisons between two such areas, the North West Shelf of Australia (NWS) and the Northeast Atlantic Margin (NEA), both of which are considered "type" areas for passive margins and both of which are important hydrocarbon provinces. By examining similarities and differences between these provinces, we attempt to draw out generic issues of importance to passive margins. This in turn may provide a platform for cross-fertilisation of ideas, ideally leading to new insights and perhaps challenging a few cherished notions.

For the purposes of this paper, we define the NWS as the chain of basins comprising (from SW to NE) the South Carnarvon, North Carnarvon, Roebuck, (offshore Canning), Browse and Bonaparte basins (Fig. 1). The onshore Canning Basin is not treated as part of the NWS, although its relationship to the offshore structure is clear. The NEA is defined herein (likewise from SW to NE) as consisting of the Porcupine Basin, Rockall Trough, the Faroe-Shetland Basin (and adjacent West Shetland Basin), the Møre Basin, the Vøring Basin (and adjacent Halten Terrace) and the Western Barents Sea (Fig. 2). The North Sea basins are not treated as part of the NEA although, again, their relevance to the area is well understood.

Geographically and geometrically there are significant similarities between the two margins. They have similar NE-SW orientation. The NEA extends for a distance of 3000 km from the Barents Sea to the Porcupine Basin and has an area of approximately 1.2 million km^2, while the NWS extends from the Timor Trough in the north to the southwestern end of the South Carnarvon Basin, a distance of 3100 km, and covers an area of 1.1 million km^2. Both margins attain a maximum width of approximately 600 km. The Continent Ocean Boundary (COB) occurs at around 3000 m water depth in both margins. The maximum sedimentary thickness (depth to crystalline basement) is comparable in the two areas: approximately 17 km in the Møre Basin of the NEA and in the Petrel Sub-basin of the NWS. The NEA spans four national sectors (Ireland, UK, Faroes, Norway), while the

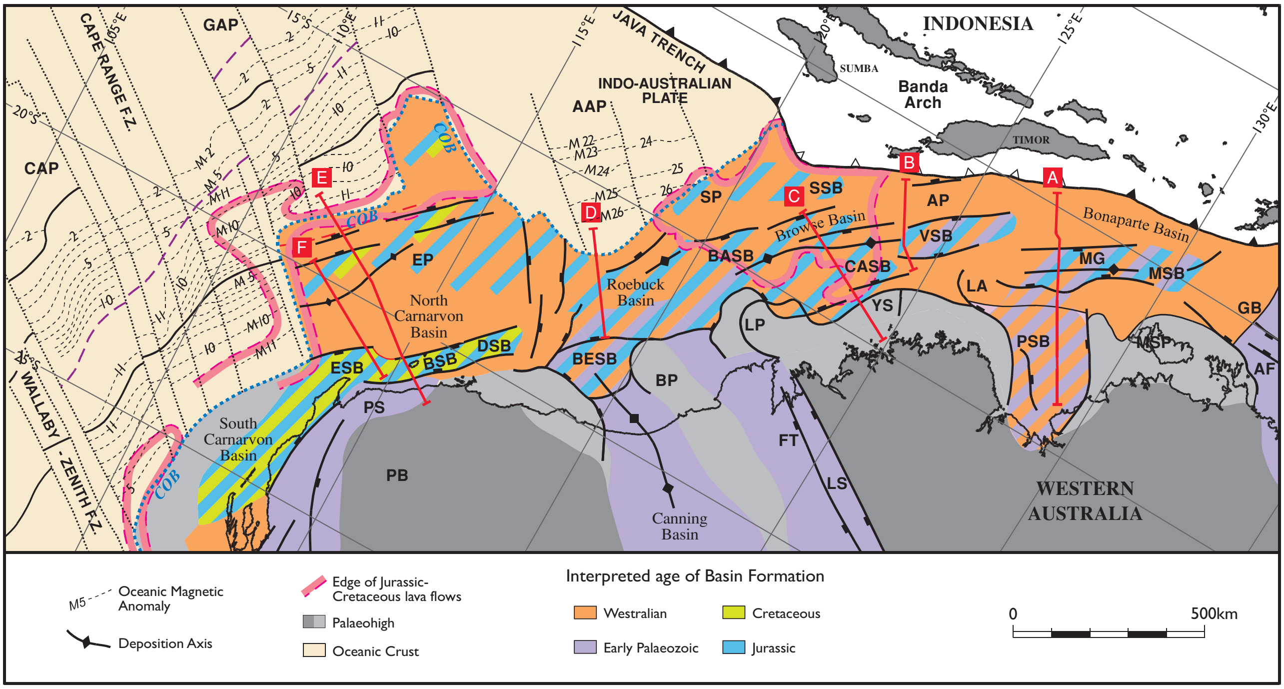

Figure 1: Tectonic elements map of the Australian North West Shelf and adjacent oceanic crust. Basins are coloured according to the principal extensional episodes responsible for their formation. Extent of Late Jurassic-Early Cretaceous lava flows is also indicated. AAP- Argo Abyssal Plain, AF- Arafura Basin, AP- Ashmore Platform, BASB- Barcoo Sub-Basin, BESB- Bedout Sub-Basin, BP- Broome Platform, BSB- Barrow Sub-Basin, CAP- Cuvier Abyssal Plain, CASB- Caswell Sub-Basin, DSB- Dampier Sub-Basin, EP- Exmouth Plateau, ESB- Exmouth Sub-Basin, FT- Fitzroy Trough, GAP- Gascoyne Abyssal Plain, GB- Goulburn Graben, LA- Lacrosse Terrace, LP- Leveque Platform, LS- Lennard Shelf, MG- Malita Graben, MSB- Money Shoals Basin, PB- Pilbara Block, PS- Pilbara Shelf, PSB- Petrel Sub-Basin, SP- Scott Plateau, SSB- Seringapatam Sub-Basin, VSB- Vulcan Sub-Basin, YS- Yampi Shelf. Sections are shown in Figure 8.

NWS is mainly within Australian waters except for the northern part of the Bonaparte Basin which falls under the joint administration of Australia and East Timor.

Commercial hydrocarbons were first discovered in locations bordering the two areas at about the same time - in the Barrow Island Field in the North Carnarvon Basin in 1964 and in the Cod Field of the northern North Sea in 1967. In both areas exploration then proceeded outwards into the deeper water of the ocean margin. In neither area was this a smooth process, exploration proceeding in fits and starts due to removal of restrictions, timing of licensing rounds, changes of offshore legislation, improvements in technology and changing exploration concepts. Both areas have undergone a recent renewal in activity sparked by the discovery on the NEA of the Foinaven and Schiehallion oil fields offshore U.K (1990 and 1993 respectively) and Ormen Lange Gas Field offshore Norway (1998), and on the NWS the Brecknock South and Gorgonichthys-Titanichthys-Brewster gas field clusters in the Browse Basin (1997 to present) and the Geryon, Io and Jansz gas fields in the Carnarvon Basin (1999 to present). Total discovered hydrocarbon resources are approximately 11 billion BOE (barrels of oil equivalent) on the NEA (updated from Fjaeran et al., 1997) and 31.5 billion BOE on the NWS (Longley et al., 2002).

The large and expanding database in both areas has allowed detailed tectonic histories to be proposed for each area: on the NWS by, for example, Bradshaw et al. (1988), Veevers (1988), AGSO (1994), Baillie et al. (1994), Symonds et al. (1998), Mihut & Müller (1998) and Müller et al. (1998), and on the NEA by, among others, Ziegler (1988), Knott et al. (1993), Lundin and Doré (1997), Doré et al. (1999), Roberts et al. (1999) and Spencer et al. (1999). The two areas have also been testing grounds for new models of rift development: for example the Burke & Dewey (1973) model for triple junction formation, the McKenzie (1978) model for extensional basin formation, the detachment model for extensional basins and passive margins (e.g. Lister et al.,1986; Etheridge et al., 1988) and, recently, depth-dependent extension models (e.g. Roberts et al., 1997; Karner & Driscoll, 1999). While the two areas have frequently been cross-referenced in the above studies, to our knowledge there has been no systematic comparison of the tectonics of the two margins.

Both areas have geological histories that can be reconstructed with some confidence back to Proterozoic times, but in the interests of manageability we choose to limit this account to Pangean assembly and subsequent break-up, i.e. beginning in the Permo-Carboniferous. We have also taken the view that it is most instructive to analyse the areas in terms of generic issues, rather than reworking the geological history of each area in detail. The topics we consider are 1) plate tectonic evolution, 2) volcanism, 3) rift models and extensional history, 4) inversion and 5) hydrocarbon systems. In order to make comparisons, we apply the synthesis techniques used in Doré et al.'s (1999) paper on the NEA to both margins. Finally, we

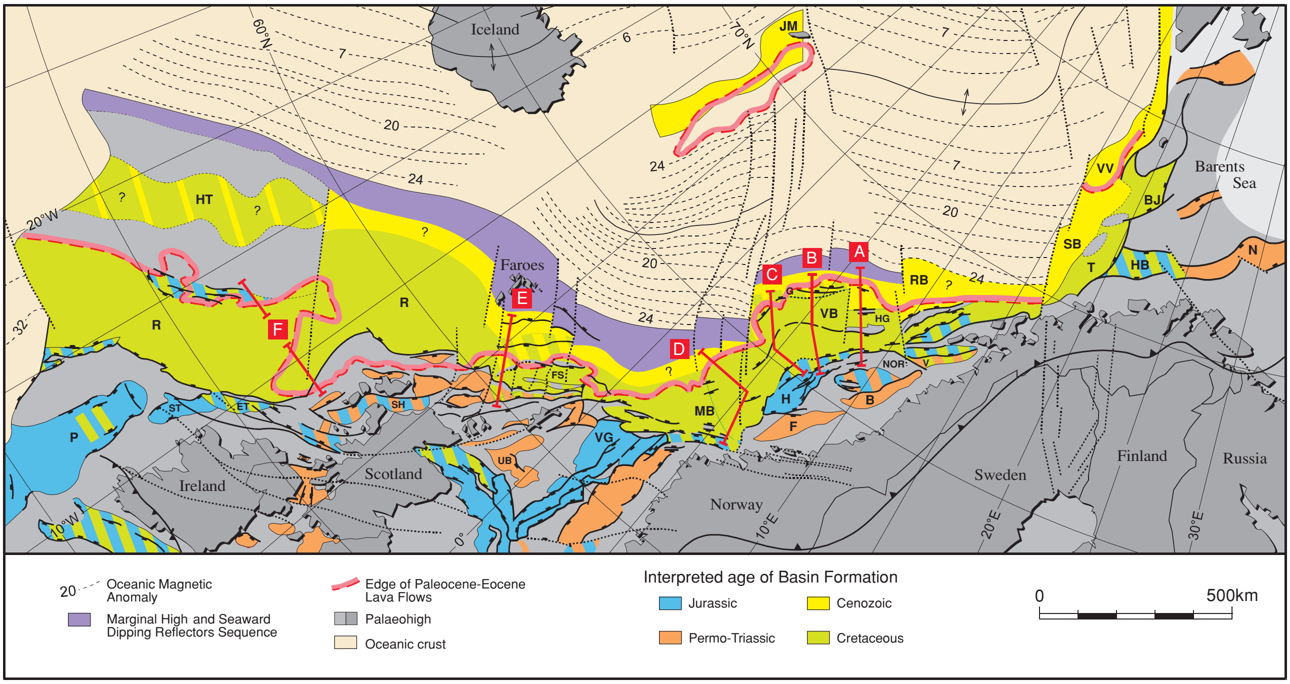

Figure 2: Tectonic elements map of the Northeast Atlantic Margin and adjacent oceanic crust. Basins are coloured according to the principal extensional episodes responsible for their formation. Extent of Paleocene-Eocene lava flows and marginal highs are also indicated. B- Brønnøysund Basin, BJ- Bjørnøya Basin, ET- Erris Trough, F- Froan Basin, FS- Faroe-Shetland Basin, H- Halten Terrace, HB- Hammerfest Basin, HG- Hel Graben, HT- Hatton Trough, JM -Jan Mayen, MB- Møre Basin, N- Nordkapp Basin, NOR- Nordland Ridge, P- Porcupine Basin, R- Rockall Trough, RB- Røst Basin, SB- Sørvestnaget Basin, SH- Sea of the Hebrides, ST- Slyne Trough, T- Tromsø Basin, UB- Unst Basin, V- Vestfjorden Basin, VB- Vøring Basin, VG- Viking Graben, VV- Vestbakken Volcanic Province. Sections are shown in Figure 9.

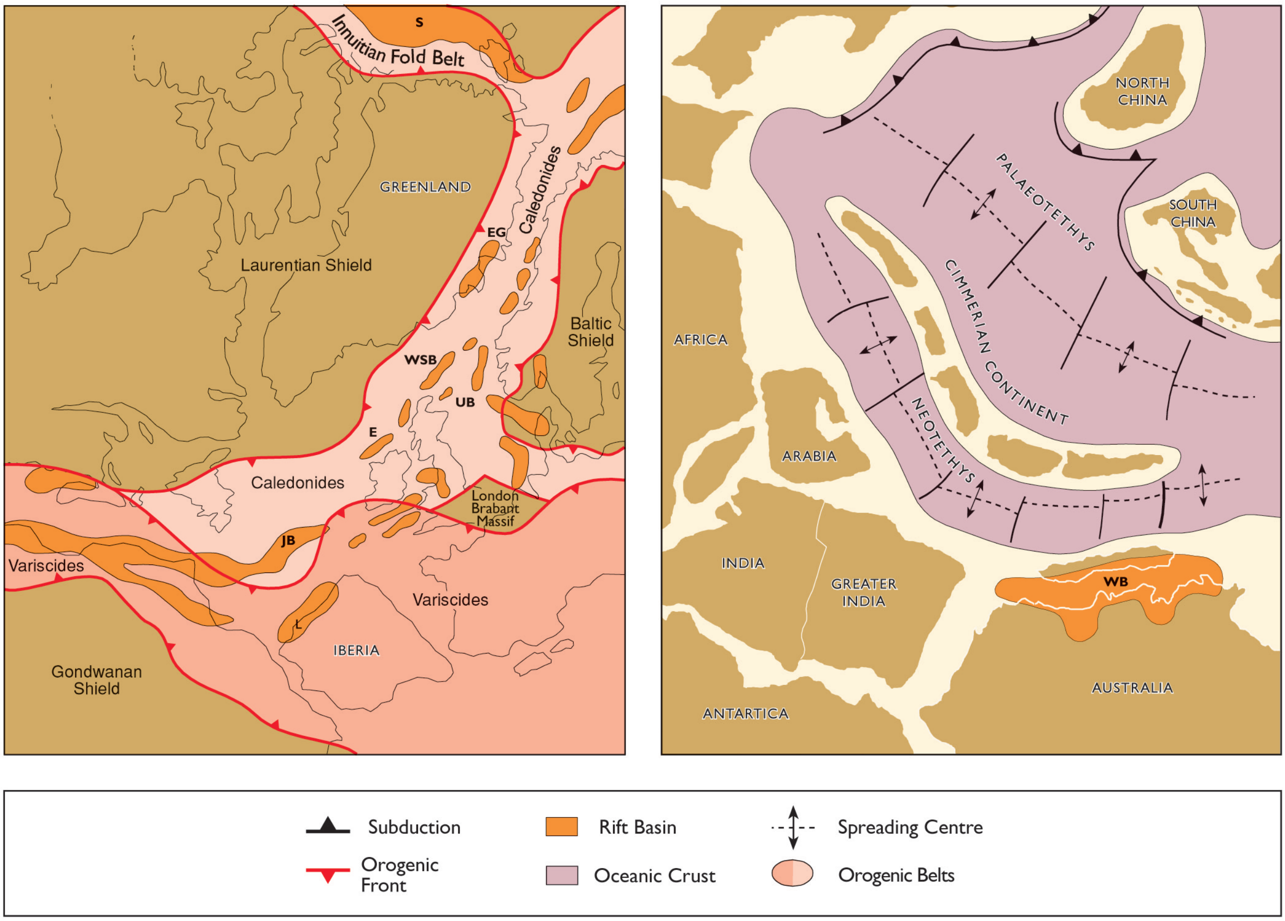

Figure 3: Plate tectonic setting of the Northeast Atlantic Margin and North West Shelf in Permo-Triassic times. E- Erris Trough, EG- East Greenland Rift, JB- Jeanne D'Arc Basin, L- Lusitanian Basin, S- Sverdrup Basin, UB- Unst Basin, WB- Westralian Basin, WSB- West Shetland Basin.

draw these issues together in a summary of the most important similarities and differences, which we trust will provoke discussion and perhaps facilitate new research towards a more detailed comparison of the two margins.

Plate Tectonic Evolution

The Pangean supercontinent was formed by the collision of Laurasia, Gondwanaland and other continental masses, beginning in the Carboniferous about 330 Ma and arguably reaching completion with the docking of Siberia with northern Laurasia in the earliest Triassic, about 240 Ma. The NWS and NEA occupied very different positions within the supercontinent (Fig. 3). The NWS, as appears to have been the case throughout much of its history, lay at the boundary between the Australian craton and a major ocean basin, at this time Palaeo-Tethys. The NEA, in contrast, occupied an interior continental position between the Tethyan Ocean to the southeast and the Boreal Ocean (proto-Arctic/Pacific) to the northwest. The area was dominated by mountain belts formed by the Caledonian-Appalachian (400 Ma) and Variscan (280 Ma) orogenies.

These settings, and subsequent post-Pangean evolution, are illustrated by plate tectonic reconstructions for the NWS and NEA in Figures 3 to 7, and summarised below.

North West Shelf

North West Shelf evolution was characterised by the separation of continental strips from the ocean margin, beginning in the Late Permian with the development of a new spreading ridge, the breaking away of the Cimmerian Blocks and the drifting of this elongate microcontinent northwestward to form the Neo-Tethys Ocean (Fig. 3). The blocks accreted to the southern margin of the Eurasian plate in the Late Triassic, c. 175 Ma, an event that just preceded, and was probably generically linked with, the initiation of wide scale Pangean break-up.

The break-up events that gave rise to the present margin occurred in Late Jurassic – Early Cretaceous times (e.g. Baillie et. al., 1994). They began in the Oxfordian (about 155 Ma, Anomaly M26) off the Browse and Bonaparte basins, with the separation and migration northwestward of the Argoland-Burma terrane and the formation of the Argo Abyssal Plain (Fig. 4). A second and highly significant phase of continental

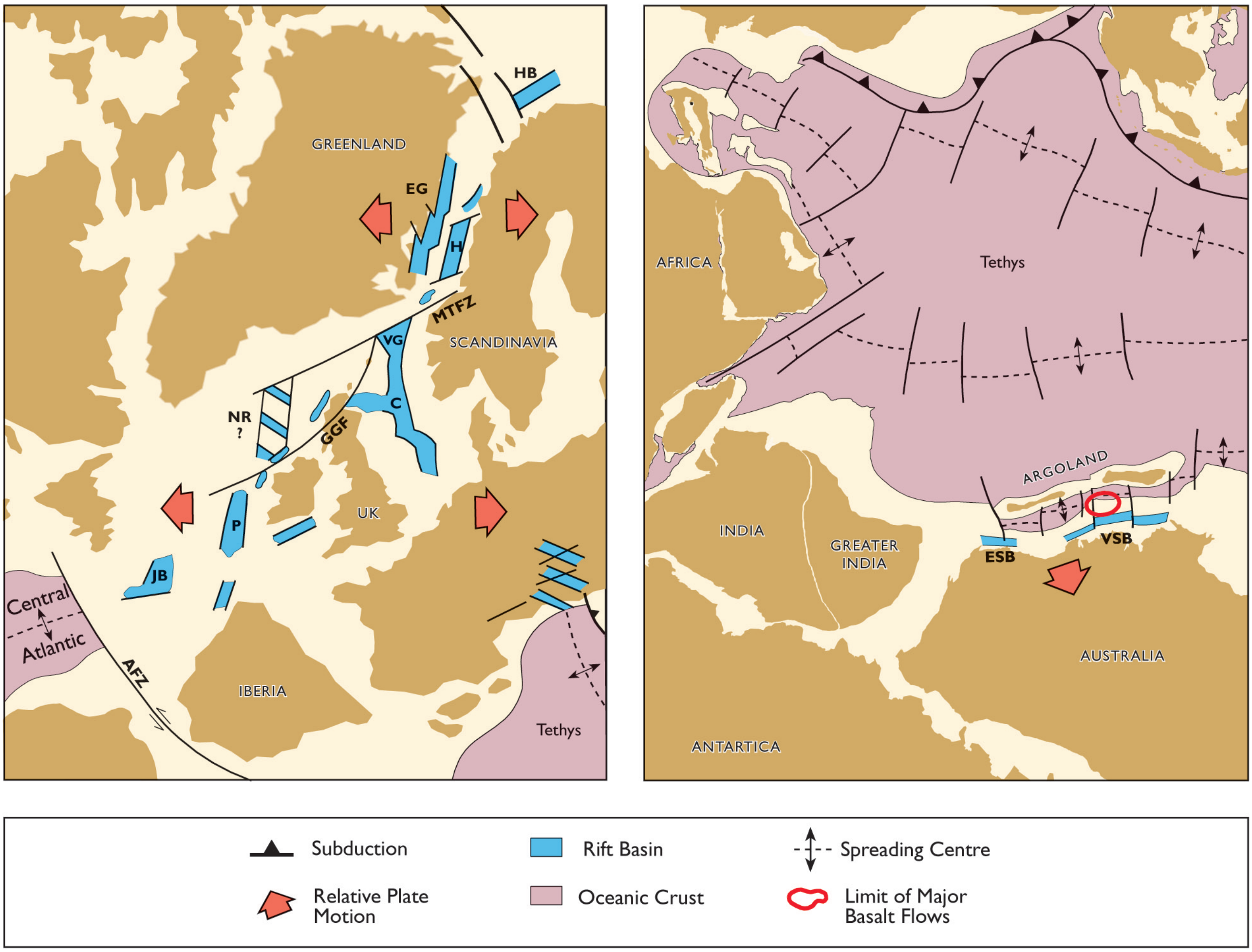

Figure 4: Plate tectonic setting of the Northeast Atlantic Margin and North West Shelf in Middle-Late Jurassic times. AFZ- Azores-Gibraltar Fracture Zone, C- Central Graben, EG- East Greenland Rift, ESB- Exmouth Sub Basin, GGF- Great Glen Fault, H- Halten Terrace, HB- Hammerfest Basin, JB- Jeanne D'Arc Basin, MTFZ- Møre-Trøndelag Fault Zone, NR- Northern Rockall Trough, P- Porcupine Basin, VG- Viking Graben, VSB- Vulcan Sub-Basin.

break-up off the North and South Carnarvon basins and Perth Basin occurred in the Early Valanginian, (136 Ma, Anomaly M14), when Greater India split off to the northwest forming the Gascoyne, Cuvier and Perth abyssal plains (Müller et al., 1998) (Fig. 5). Greater India continued moving in a northwestward direction until an important plate reorganisation took place at about 95 Ma in the Cenomanian. At this time partial subduction of the Neo-Tethys ridge occurred (Müller et al., 1998) and spreading began between southern Australia and Antarctica. The result was a rapid (19.5 cm/yr) northward movement of Greater India towards the Eurasian margin, with orogeny beginning at about 70 Ma (Fig. 6) and cessation of subduction between Greater India and Eurasia at about 42 Ma (Fig. 7). Docking of Greater India and Eurasia caused a further major plate reorganisation and accelerated the northward movement of the Australian plate. This movement brought the Australian continent into contact with the Eurasian plate in the Early Miocene (approximately 25 Ma) resulting in counter-clockwise rotation of the Australian plate, subduction of the plate along the E-W trending Banda Arc, and accretion of the Timor region to the Australian plate at about 2.5 Ma (Richardson & Blundell, 1996) (Fig. 7).

Northeast Atlantic Margin

Because of the interior position of the proto-NEA in Pangea (Fig. 3), it represented the last point of separation in the Atlantic Ocean, linking much earlier oceanic crust formation in the Central Atlantic and Arctic. Central Atlantic spreading began at the Early-Middle Jurassic transition, about 175-180 Ma (e.g. Driscoll et al., 1995; Ziegler, 1988), and until mid-Cretaceous times was contained south of a shear margin, the Azores-Gibraltar Fracture Zone (Fig. 4). Starting in the Aptian (about 118 Ma, Anomaly M0) spreading extended northwards, initially between Iberia and Newfoundland and then via a triple junction into the Bay of Biscay (Srivastava et al., 1990), reaching the Charlie Gibbs Fracture Zone by approximately Santonian time (84 Ma) (Fig.

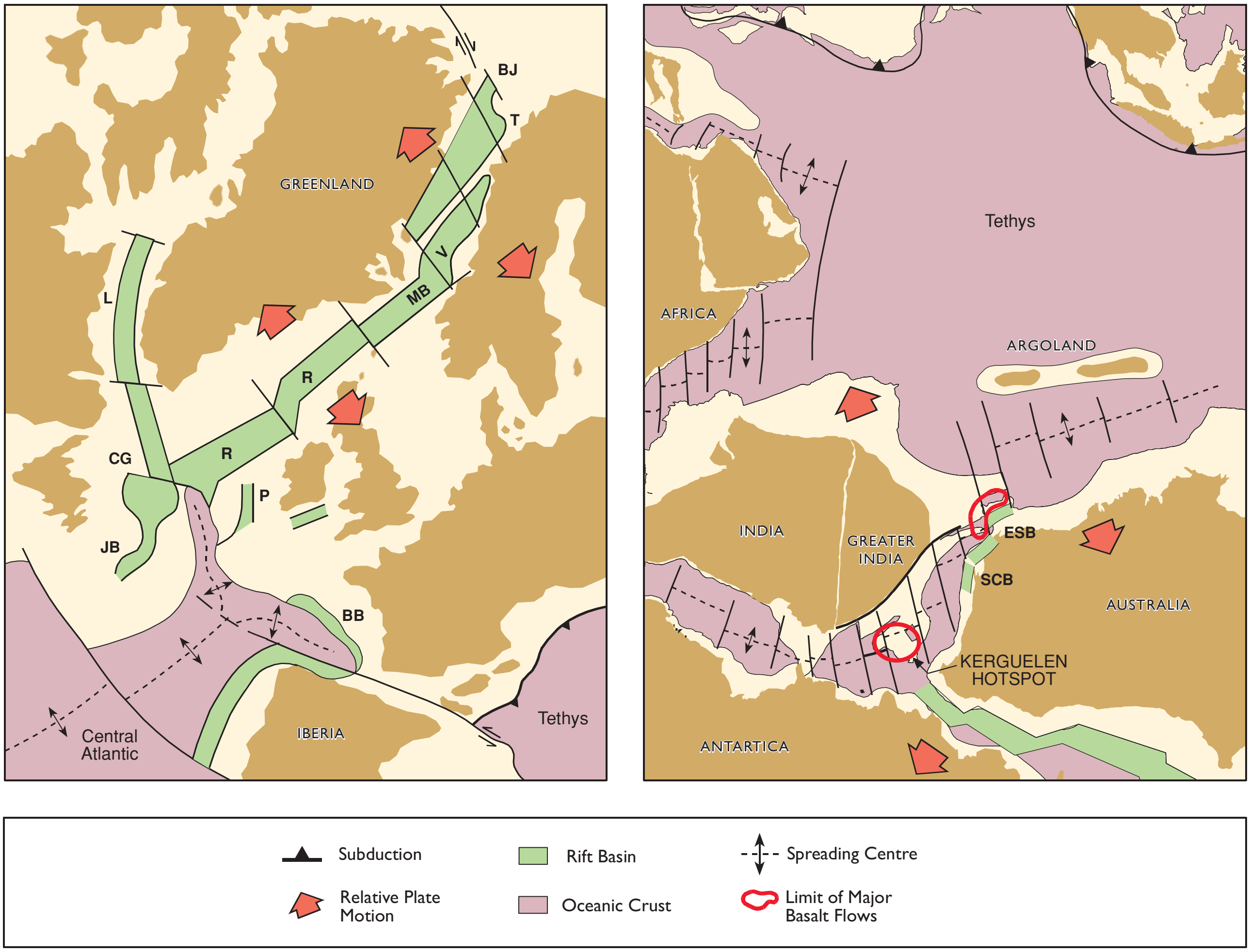

Figure 5: Plate tectonic setting of the Northeast Atlantic Margin and North West Shelf in Early Cretaceous times. BB-Bay of Biscay, BJ-Bjørnøya Basin, CG- Charlie Gibbs Fracture Zone, ESB- Exmouth Sub-Basin, JB- Jeanne D'Arc Basin, L- Labrador Sea, MB- Møre Basin, P- Porcupine Basin, R- Rockall Trough, SCB- South Carnarvon Basin, T- Tromsø Basin, V- Vøring Basin.

5). Farther northwards spreading initially bypassed the NEA, extending instead into the Labrador Sea at Anomaly 27 (Early Paleocene) time (Fig. 6).

In the Arctic area, limited evidence suggests that initial spreading probably took place in the Canada Basin in the Hauterivian-Barremian (starting 130 Ma), succeeded by new ocean floor formation in the Makharov Basin (84 Ma) and Nansen Basin (68 Ma) (Rowley & Lottes, 1988). Unification between the Arctic and Central-Northern Atlantic finally took place with NW-SE spreading in the North-East Atlantic (i.e. between Greenland and NW Europe) at Anomaly 24b time (Early Eocene, 53 Ma) (Fig. 6). Initially, spreading movement was relayed between the Nansen Basin and the North-East Atlantic via a NW-SE shear margin, the Greenland-Senja Fracture Zone. A through-going oceanic connection was only established during a period of plate reorganisation between Anomaly 13-6 times (Oligocene-Miocene, 35-20 Ma) (Fig. 7), when a change from shear to passive drift between Greenland and Europe took place at the Senja margin. The same reorganisation initiated a new spreading ridge and the breaking away of an elongate terrane (the Jan Mayen Microcontinent) from the East Greenland margin (e.g. Kuvaas & Kodaira, 1997; Lundin & Doré, 2002).

Discussion

On the broadest scale, a significant difference between the NEA and NWS appears to be that the NEA represents a slightly oblique opening along an old NE-SW line of closure (the Caledonian fold belt) in the manner predicted by the "Wilson Cycle" (e.g. Ryan & Dewey, 1997), with the remains of the ancient mountain chain distributed on both sides of the current ocean (Fig. 3). The NWS presents no overt evidence of this kind of reactivation, although it is possible that such evidence may have been lost with the drifting away of successive pieces of the margin. Further south, however, the Perth Basin and the adjacent continental margin appear to have directly exploited a Proterozoic orogen, the Pinjarra Fold Belt (e.g. Li & Powell, 2001).

The overall control exerted by pre-existing structure on both margins is very clear. Coincidentally, the principal trends

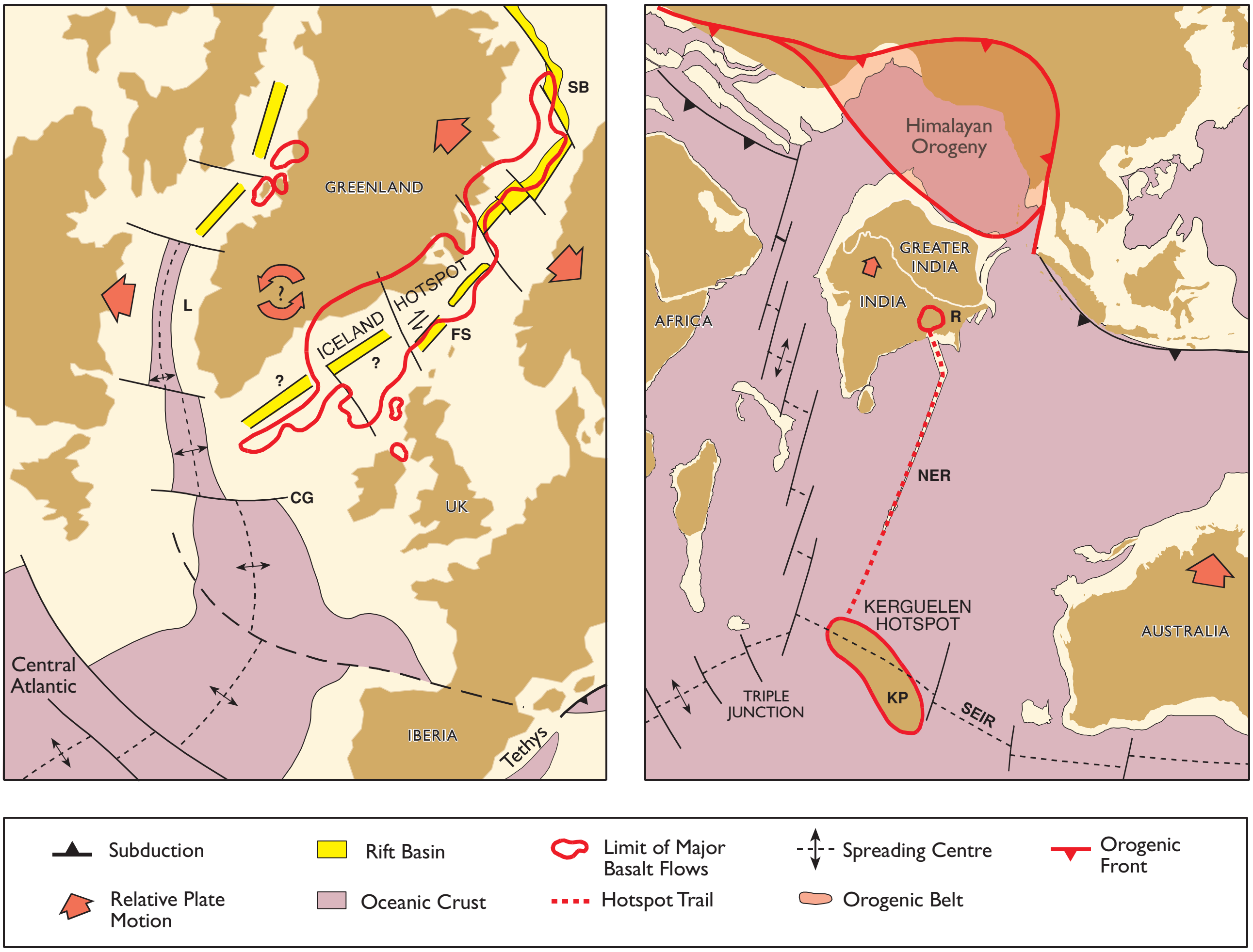

Figure 6: Plate tectonic setting of the Northeast Atlantic Margin and North West Shelf in Paleocene times. CG- Charlie Gibbs Fracture Zone, FS- Faroe-Shetland Basin, L- Labrador Sea, NER- Ninetyeast Ridge, R- Rajmahal Igneous Province, SB- Sørvestnaget Basin, KP- Kerguelen Plateau, SEIR- Southeast Indian Ridge.

are the same. Both margins are dominated by extensional fault systems that mostly predate, and are sub-parallel to, the continental margin and the linear magnetic anomalies in the ocean basin (Figs 1 and 2). In a gross sense, the extensional vector that gave rise to the faults eventually became the drift vector of plate separation. Both margins are segmented by transfer zones, the largest of which appear to be controlled by basement inhomogeneity. These lead into fracture zones in the adjacent ocean, and have played a significant role in continental break-up. In the NEA the most important of these are the Senja Fracture Zone (which separates the Barents Sea basins from the northern Vøring Basin) and the Jan Mayen Lineament (which separates the Vøring and Møre basins and formed the northern limit of the Jan Mayen microcontinent, described above) (Doré et al., 1997a, 1999).

On the NWS a generic link seems very probable between the NW-trending lineaments defining the onshore Canning Basin, of Palaeozoic age, and the segmentation of the shelf into the Browse, Roebuck and North Carnarvon basins. In particular, the structural break on the southwestern margin of the Canning Basin appears to have influenced the northern margin of the Exmouth Plateau and, oceanward, to divide the region of Oxfordian plate separation (off the Browse and Bonaparte basins) from the Valanginian spreading region off the North and South Carnarvon basins (Fig. 1). On both the NEA and NWS the NW-SE segmenting lineaments became shear margins during early plate separation. On the NEA an important shear margin between Greenland and Eurasia formed along the Senja Fracture Zone (Fig. 7), while on the NWS, shear margins developed along pre-existing transfer zones between the Greater India block and the Perth – South Carnarvon basins (Song et al., 2001) and, according to a recent reinterpretation by Mihut & Müller (1998), along the continental margin of the northern Exmouth Plateau (Figs 1 and 7).

The separation and drifting away of elongate microcontinents appears to be a feature of both passive margins. On the NWS these included the Cimmerian Blocks in the Late Permian and Argoland in the Oxfordian, while there is evidence for earlier (pre-Pangean) detachment of

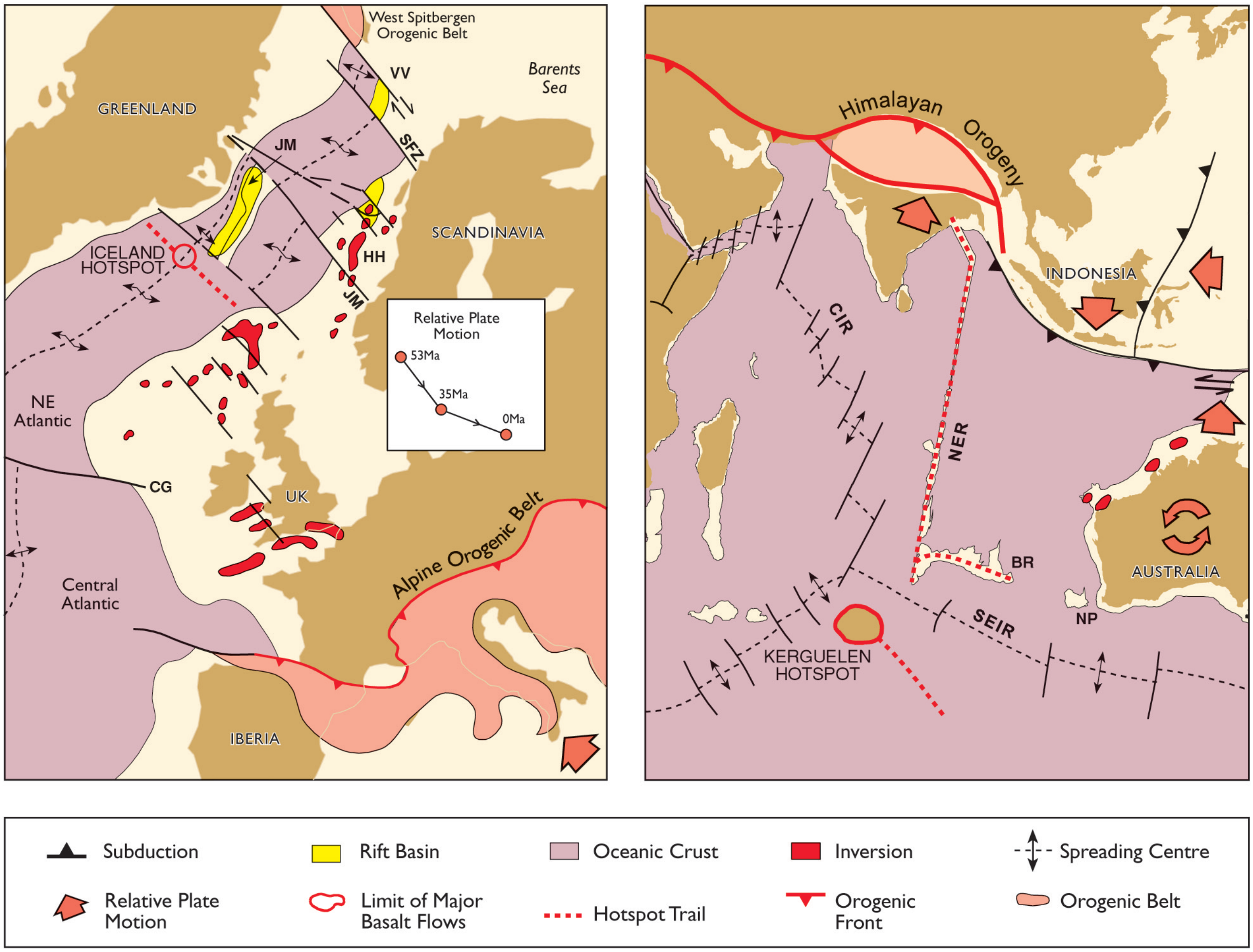

Figure 7: Plate tectonic setting of the Northeast Atlantic Margin and North West Shelf in Oligocene-Miocene times. BR- Broken Ridge, CG- Charlie Gibbs Fracture Zone, CIR- Central Indian Ridge, HH- Helland-Hansen Arch, JM- Jan Mayen Fracture Zone, NP- Naturaliste Plateau, NER- Ninetyeast Ridge, SEIR- Southeast Indian Ridge, SFZ- Senja Fracture Zone, VV- Vestbakken Volcanic Province.

terranes, for example the Tarim Block, from the same margin (Li & Powell, 2001). In the younger NE Atlantic it can be argued that this process is starting with the Oligocene-Miocene separation of the Jan Mayen Microcontinent from Greenland. The events appear to have taken place during periods of significant plate reorganisation. The Oxfordian detachment of Argoland (Fig. 4) was coincident with one of the most significant Pangean break-up events, the separation of the Gondwanan block containing Australia, India, Antarctica, Madagascar and part of South Africa from western Gondwanaland (Baillie et al., 1998). As indicated earlier, the Oligo-Miocene detachment of Jan Mayen (Fig. 7) took place during an important change in relative plate motion between Greenland and NW Europe. Doré et al. (1999) and Lundin & Doré (2002) have shown that this change was manifested as an extensional episode on both sides of the NE Atlantic. It may be a paradigm that passive continental margins, previously thinned by multiple margin-parallel rifting episodes, are preferentially exploited and shed thin continental slivers as an accommodation to plate readjustment. Interestingly the Arctic Ocean, now linked to the NE Atlantic via the Knipovitch spreading ridge, showed similar behaviour through time, for example with the separation of the Lomonosov Ridge (an elongate continental terrane now at abyssal depths beneath the Arctic Ocean) during Nansen Basin spreading at the end of the Cretaceous (Rowley & Lottes, 1988).

Although there are many similarities between the two margins, an obvious difference is that of age. If the main break-up event on the NWS is taken to be the separation from Greater India, then there is an approximately 80 m.y. time difference between the two margins. The difference in maturity is exemplified by the fact that oceanic crust of the Australian Plate is now being consumed by subduction at the northeastern end of the NWS, a fate that has not yet befallen the NE Atlantic, but which will most probably occur within the next 80 million years (Scotese, 2002). This significant time difference and its geological consequences should have a major impact on the hydrocarbon systems of the two areas. However, as we shall see, this difference is modified and overprinted by the effects of hotspot activity, by denudation and availability of basin-filling clastic sediments, and by geologically recent inversion phenomena. In summary it can be stated with some confidence that the NWS and NEA are very similar in terms of break-up exploiting pre-existing structure, segmentation of the margin, interplay of passive and shear margin segments and shedding of microcontinental fragments. A further common aspect of the two areas is their role as volcanic margins, a subject that is considered separately below.

Volcanism

Both the NEA and NWS were subject to voluminous magmatism at time of break-up. In this section we compare the two episodes in terms of scale, associated phenomena and relationship to hotspot/mantle plume activity.

North West Shelf

The basaltic volcanic province along the Argo, Gascoyne and Cuvier margins is over 2000 km long and 500 km wide (Fig. 1). Its formation was closely associated with rifting, continental break up and shear margin development (Symonds et al., 1998). Dating of the activity is not precise. It is thought to have taken place on the Argo Margin between the Bathonian and Tithonian, a period of 21 Ma (Crawford & von Rad, 1994; Ramsay & Exon, 1994) (Fig. 4). The volcanics on the Gascoyne and Cuvier margins have been postulated as being Valanginian, leading up to and immediately following break-up (e.g. Symonds et al., 1998) (Fig. 5).

On the Gascoyne and Cuvier margins (i.e. the Exmouth Plateau and the outer parts of the North and South Carnarvon basins) widespread flow basalts were accompanied by mid-upper crustal intrusions, the formation of SDRs (seaward-dipping reflectors identified from drilling as subaerially emplaced flood basalts with minor sedimentary layers), hyaloclastite constructions on the newly-formed ocean floor and the introduction of high seismic velocity layers at the base of the crust, interpreted as underplating (Frey et al., 1998). On the Argo Margin up to 3 km of lava flows have been identified on seismic data off the Scott Plateau, on the fringe of the abyssal plain, while almost 700 m of subaerial volcanics and volcaniclastics (the Ashmore Volcanics) have been drilled in Browse Basin. Intrusives and SDRs have also been reported for the Argo Margin (Symonds et al., 1998).

Northeast Atlantic Margin

The North Atlantic (Thulean) volcanic province extends for essentially the whole length of the margin, more than 3000 km (Fig. 2). Across the margin, it extends landwards some 1300 km to the Bristol Channel, and on the Greenland side of the ocean some 1000 km to the western Greenland coast. On the margin, the province is represented by massive subaerial basalt flows (with lava deltas and hyaloclastite build-ups marking a transition to submarine flows) and central intrusive-extrusive complexes along the axes of the Rockall Trough and Faroe-Shetland Basin. Sills are common in the Vøring, Møre and Faroe-Shetland Basins. The marginal highs on the NW flanks of the Vøring Basin, Møre Basin and Rockall-Hatton Trough (Fig. 2) are believed to consist of highly extended and intruded continental crust, capped by basalt flows and bounded oceanwards by SDR sequences (e.g. Olafsson et al., 1992).

The timing of igneous activity is very well constrained by radiometric dating of lavas, sills and intrusive complexes encountered on land and drilled offshore. The volcanic phase may have begun as early as the Maastrichtian (Hitchen & Ritchie, 1993) but the main episode encompassed the Palaeocene to Early Eocene, 65-53 Ma, (Naylor et al., 1999) (Fig. 6). There is general consensus that the volcanism derived from continental break-up in the presence of the large mantle plume currently beneath Iceland, with migration of plume-generated melts into the thinned axis of incipient continental separation (Skogseid et al., 1992). Underplating associated with this melt generation is recorded from refraction, ocean-bottom seismometer (OBS) and crustal modelling data on the Vøring margin, Møre margin and Hatton Bank (Skogseid et al., 1992; Olafsson et al., 1992; White et al., 1987) while some workers postulate much more widespread underplating, for example beneath the British Isles (e.g. White & Lovell, 1997).

Discussion

A major difference between volcanic continental margins such as the North Atlantic and non-volcanic margins is that at the time of crustal separation the former remain above sea level whereas the latter immediately begin to subside by 2 km or more (White, 1988). The origins of the uplift can be thermal (from injection of heat into the asthenosphere), dynamic (due to the transient upward pressure of a plumehead) or isostatic (due to the presence of underplated material). In this respect the NWS can be described as a typical volcanic margin; the volcanic episode and contemporaneous break-up were associated with uplift of the outer edge of the Scott Plateau, a pre-break-up episode of peneplanation in the Browse Basin, and uplift of the outer Exmouth Plateau (Symonds et al., 1998).

There is, however, a major difference in scale between the NWS and NEA volcanism. The presence of the Iceland plumehead at or near the rift axis of the NEA during the Paleocene caused emergence and subaerial eruptions to take place along virtually all 3000 km of the margin, while the elevated hotspot "trail" (the Greenland-Iceland-Faroes Ridge) remained as land or as a barrier to marine circulation until middle Miocene times (Eldholm & Theide, 1980). Major uplift and emergence of previously submerged areas bordering the NEA, for example the British Isles, also took place along with shallowing of many of the peripheral basins (e.g. Doré et al., 1997b). The permanent nature of this uplift suggests that underplating may be the cause (e.g. Jones et al., 2002). However the absence of igneous activity in some uplifted areas such as Norway and the incomplete seismic evidence for underplating leave this question open. Jones et al. (2002) also point out from regional free-air gravity data that the Iceland plume results in a major deflection of the geoid today, manifested as anomalously elevated ocean floor, spreading ridges and bordering continental areas.

Uplift of provenance areas during the Paleocene caused rapid influx of siliciclastic material into subsiding basins in the northern North Sea and off Mid-Norway (Doré et al., 1997b). During the Neogene northern hemisphere glaciation, nucleation of ice on residual or reactivated highlands caused further rapid erosion and redeposition (e.g. Doré & Jensen, 1996; Japsen & Chalmers, 2000). These phenomena, directly or indirectly attributable to the Iceland Plume, have some parallels and some contrasts with the NWS. The volcanic phases on the NWS were accompanied by basin-wide planation (in the Callovian) and significant rejuvenation of continental hinterlands (with the development of the Barrow Delta in the Neocomian). However, palaeogeographic reconstructions show no indication of the permanent uplift and landmass reshaping that took place on the NEA (Bradshaw et al., 1998; Longley et al., 2002). A further contrast is in the Cenozoic sedimentary history. Compared to the thermally rejuvenated NEA, the NWS was largely starved of terrigenous sediments and dominated by shelf carbonates from Eocene to Recent times (e.g. AGSO, 1994). These significant differences in denudation and redeposition were reflected strongly in the hydrocarbon system, as will be shown later in this account.

The difference in scale between the NWS and NEA volcanism also affects the ability to explore the two areas for hydrocarbons. On the NWS these phenomena have so far had such a minor effect on the progress of exploration that many basin histories published for the area do not mention, or barely mention, the volcanics. Large areas of the NWS show no volcanic activity, with the result that structural features can often be well imaged on seismic data. In contrast, the pervasive sills and basalt flows on the NEA seismically obscure the prospective pre-Late Paleocene section in some basins, for example the Faroe-Shetland and Møre basins. Much effort and expense has been spent on sub-basalt imaging techniques such as OBS, pre-stack depth migration and wide-angle seismic in these areas (e.g. White et al., 1999). These methodologies, incorporating lessons learnt from the NEA, may become more important on the NWS as exploration moves northwestwards into deeper waters.

An interesting question arising from comparison of the NWS and NEA is whether the NWS volcanism can be attributed to a mantle plume. As indicated earlier, most of the phenomena associated with the Iceland Plume in the NEA are also observable on the NWS (underplating, marginal uplift, subaerial basalts, SDRs, hyaloclastites). Together, these characteristics seem to these authors to be powerful circumstantial evidence for a common origin. The most comprehensive regional study yet published on the NWS volcanism (Symonds et al., 1998) attributes these effects to "a broad, long lasting zone of elevated asthenospheric temperatures" but is equivocal as to whether these temperatures are plume-related. A hotspot is not, of course, a prerequisite for magmatism on a passive margin, since break-up necessarily involves the development of a spreading ridge and asthenospheric upwelling. Adiabatic (decompression) melting takes place as a result of crustal extension and thinning prior to separation, so therefore some volcanism should be expected. Bown & White (1995) and Minshull et al. (2001) have shown that magmatic intensity in this setting depends on the rapidity of the extension, with faster extension producing the more voluminous melts. Melting may also be enhanced by more rapid extension of the lower crust and upper mantle compared to that of the upper crust (Karner & Driscoll, 1999; see also section on Rift Models).

On plate tectonic reconstructions up to break-up time (Fig. 5) the NWS lay fairly close to the point of origin of the Kerguelen Plume, a superplume even larger in scale than that beneath Iceland (Coffin & Eldholm, 1994). The present plume is located at Kerguelen Island in the southeast Indian Ocean. The palaeo-plume is represented by the lavas of the Kerguelen Plateau, by the Broken Ridge west of Australia, and by a 6000 km N-S hotspot trail (the Ninetyeast Ridge) terminating in the Rajmahal igneous province in eastern India (Kent et al., 2002) (Fig. 6). Formation on the fringe, but not the epicentre, of this plume would provide a convenient explanation for the NWS volcanism, but both timing and geochemistry initially seem to argue against this premise. The earliest recorded volcanism on the Kerguelen Plateau is about 119 Ma (Aptian) (Weis & Frey, 1996; Coffin et al., 2002), an onset probably generically associated with the formation of a triple junction between India, Australia and Antarctica (Fig. 5). If this dating truly represents the first plume activity, then it clearly postdates the NWS break-up volcanism. Furthermore, ocean crust on the Argo Abyssal Plain only carries the distinctive isotopic and element abundance signature of the Kerguelen Plume in samples younger than 125 Ma (Weis & Frey, 1996). Therefore, attributing the Argo volcanism to the Kerguelen Plume would require the existence of an undiscovered and undated precursor plume dating back to 155 Ma, probably with different geochemical characteristics.

Mihut & Müller (1998) have suggested a hotspot model for the Exmouth Plateau volcanism. In this model a small plume beneath the Exmouth Plateau at the time of break-up gave rise to a hotspot trail in the adjacent Cuvier Abyssal Plain, represented by two volcanic edifices, the Wallaby and Zenith plateaus. We note that the timing of the Exmouth-Carnarvon break-up and volcanism (Valanginian, c. 136 Ma) is close in time to the first recorded instance of the Kerguelen geochemical signature on the Argo Abyssal Plain. It is therefore tempting to speculate that, rather than emanating from a separate hotspot, the Exmouth Plateau volcanism could have been the earliest manifestation of magmatism on the fringes of a proto-Kerguelen Plume.

In the earliest Cretaceous the hotspot would have been located off SW Australia where onshore basalt flows (the Bunbury basalts) have been recently dated as 130 Ma and linked with the Kerguelen plume (Coffin et al., 2002). These basalts are probably (albeit not unequivocally) associated with the offshore Naturaliste Plateau (an ocean-floor construction of probable volcanic origin) and with volcanic phenomena recorded in the offshore Perth Basin (Gorter & Deighton, 2002). Increasing circumstantial evidence is therefore closing the gap in time and space between initial activity on the Kerguelen plume and the Exmouth-Carnarvon volcanism (Fig. 5). If one considers the huge radius of influence of the comparable Iceland Plume both in the past (White & Lovell, 1997) and at present (Jones et al., 2002), this gap seems comparatively modest.

Rift Models and Extensional History

The extensional episodes that formed the NWS and NEA, and their geographical distribution, are illustrated by tectonic element maps (Figs 1 and 2). Basin-fill characteristics and rift geometries are illustrated by cross-sections along each margin (Figs 8 and 9).

North West Shelf

The NWS is dominated by a NE-SW chain of broad basins (the Bonaparte, Browse, Roebuck, North and South Carnarvon basins) that has been termed the Westralian Superbasin (e.g. Yeates et al., 1987; Hocking et al., 1994; Baillie et al., 1994). Opinions differ as to precisely when extension occurred, but this activity can at least be constrained between Late Carboniferous and Late Permian (e.g. Hocking et al., 1994; Baillie et al., 1994; Struckmeyer et al., 1998; Karner & Driscoll, 1999). It can be viewed as a precursor to the detachment of a continental terrane (the Cimmerian Blocks) and Neo-Tethyan spreading in the Late Permian. The Westralian Super-basin strongly cross-cut a series of older NW-SE basins (Fig. 1), represented landwards by the Canning Basin and Petrel Sub-Basin, which were formed by widespread rifting and rupture of the Australian craton in the Cambrian-Ordovician and Devonian-Early Carboniferous (e.g. O'Brien et al., 1996; King, 1998). Rotation of the extensional vector from NE-SW to NW-SE between the Late Carboniferous and Late Permian was a fundamental event in the development of the NWS (Smith et al., 1999).

Post-rift subsidence in the Westralian Super-basin resulted in the accumulation of a rather uniform, pervasive fill of Late Carboniferous and Permo-Triassic sediments attaining thicknesses of tens of kilometres (Fig. 8). Subsequent rifting of this sedimentary blanket was associated with later stages of continental break-up along the NWS. An extensional episode along NE-SW lines took place in latest Triassic-Middle Jurassic times, culminating in widespread peneplanation in the Callovian and the separation of Argoland from the Browse-Bonaparte margins in the Oxfordian. The most intense extension occurred in localised depocentres such as the Exmouth, Barrow and Dampier Sub-basins in the North Carnarvon Basin (Karner & Driscoll, 1999) and, farther northeastwards, within the Vulcan Sub-Basin and Malita Graben (e.g. Bradshaw et al., 1988). The most significant source rock on the NWS, the Jurassic Dingo Shale and its equivalents, accumulated in restricted marine conditions in these depocentres.

Further extension, distributed over a wide area but particularly important in the North and South Carnarvon Basins, took place in the Tithonian-Valanginian as a concomitant of break-up between Greater India and Australia (Karner & Driscoll, 1999). Thermal subsidence into the extended zone in the Neocomian provided accommodation space for the economically important fluvial-deltaic to marginal marine sandstone reservoirs of the Barrow Group. Only minor extensional reactivation along pre-existing fault lines took place after the Neocomian, with sedimentation dominated by sag into earlier depocentres and the progradation northwestwards of a carbonate shelf in the latest Cretaceous-Cenozoic (Fig. 8).

Northeast Atlantic Margin

Post-Pangean rifting began by foundering of the fused Pangean orogenic belts, with the dominant element in the NEA being the NE-SW Caledonian mountain chain. In the Permo-Triassic this extension was manifested as a series of intermontane half-grabens infilled with terrestrial sediments (e.g. Doré et al., 1999; Roberts et al., 1999). Triassic basin-fill included sporadic evaporites introduced by marine incursions, for example offshore Mid-Norway, which were locally important as detachment zones for later rifting (Pascoe et al., 1999). An important phase of rifting took place in late Middle-Late Jurassic times, probably associated with spreading and plate divergence in the Central Atlantic and Tethys. Basins formed by this phase on or adjacent to the NEA reflect a dominant E-W extension direction, resulting in a series of N-S grabens typified by the Viking Graben in the northern North Sea, but also including the East Greenland Rift, the Halten Terrace off Mid-Norway and the Porcupine Basin off western Ireland (Doré et al., 1999) (Figs 2 and 4). Anoxic Upper Jurassic shales deposited within the rifts (Kimmeridge Clay and equivalents) are the origin of the dominant hydrocarbon system on the NEA (Spencer et al., 1999).

In the Neocomian the principal extension direction rotated to NW-SE, and rifting activity became focused on what was to become the NEA (e.g. Rattey & Hayward, 1993). The result was a broad NE-SW zone of extension stretching from the western Barents Sea to west of Ireland, overprinting and cross-cutting the pre-existing Triassic and Jurassic fabrics (Fig. 2). Post-rift subsidence resulted in the accumulation of thick Cretaceous successions in the Tromsø, Vøring, Møre, Faroe-Shetland basins and Rockall Trough (Fig. 9). Further extension, somewhat variable geographically and in timing, took place throughout the NEA in the mid-Cretaceous (Aptian-Cenomanian) and was probably associated with the Atlantic spreading axis propagating northward to the Galicia margin, Bay of Biscay and Charlie Gibbs Fracture Zone (Lundin & Doré, 1997; Bjørnseth et al., 1997; Johnston et al., 2001; Baxter et al., 2001).

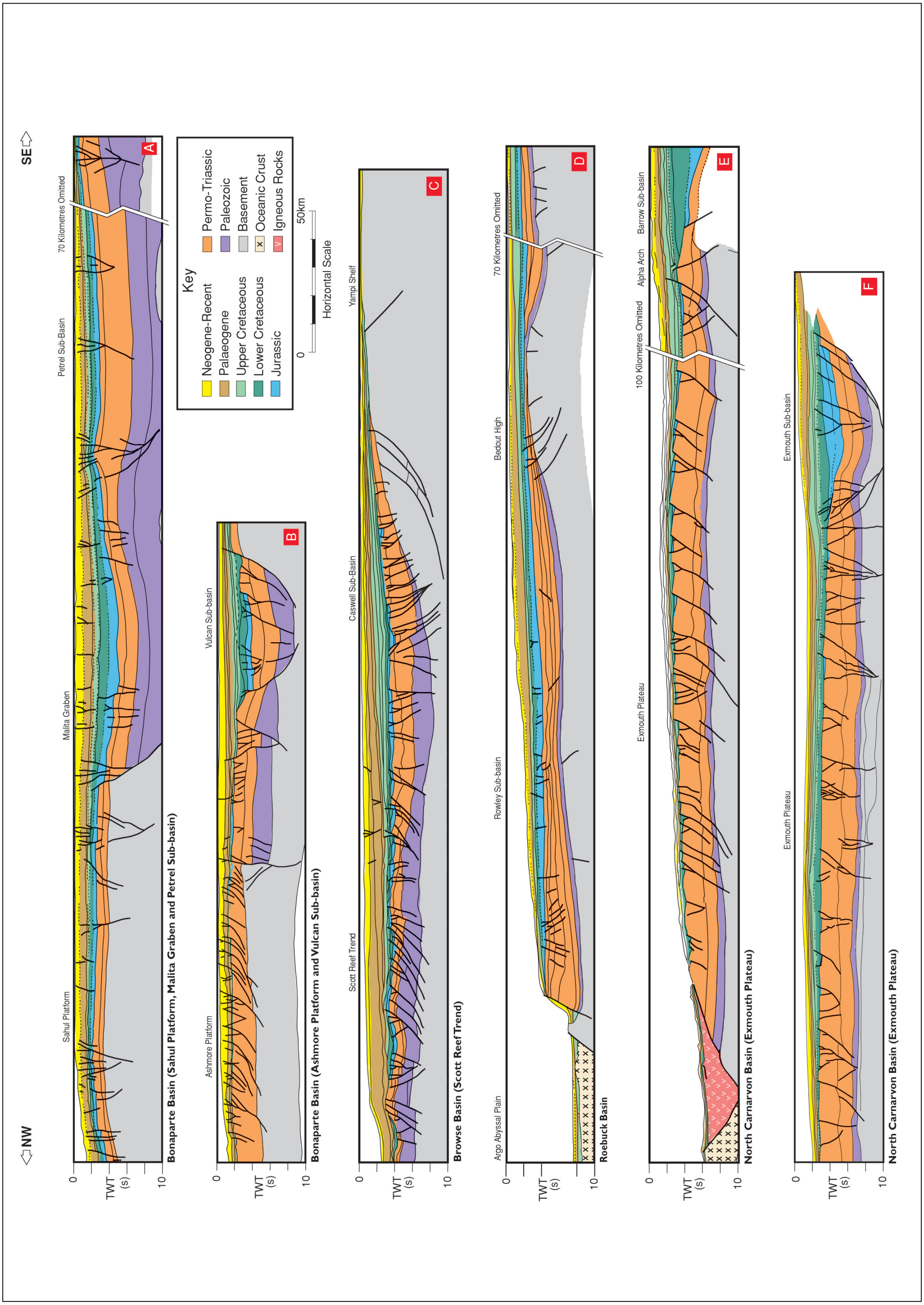

Figure 8: Geoseismic sections over the North West Shelf, Bonaparte Basin to North Carnarvon Basin. For location of sections, see Figure 1.

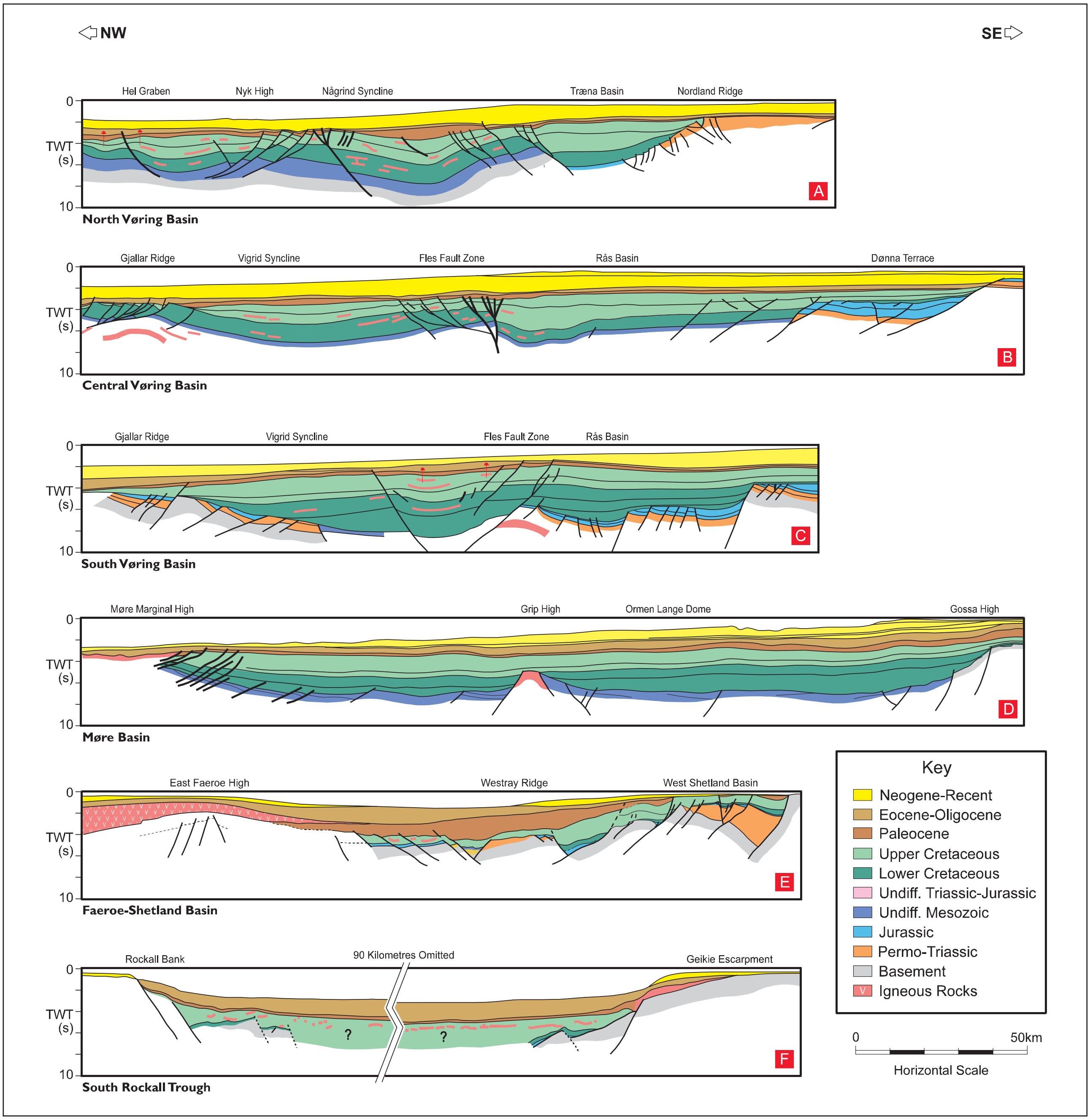

Figure 9: Geoseismic sectons over the Northeast Atlantic Margin, Vøring Basin to Rockall Trough. For location of sections, see Figure 2.

Break-up was preceded by a Maastrichtian-Paleocene episode of NE-SW extensional faulting located close to the present margin. Although probably present over the whole margin, rift geometry is frequently obscured by the extensive contemporaneous volcanics. It is best seen in the Vøring margin off mid-Norway (Figs 2 and 9). Locally important Paleocene depocentres formed in the Møre Basin, Faroe-Shetland Basin and northern North Sea, reflecting abundant sediment supply from hotspot-related uplift of provenance areas (see section on Volcanism). These sediments included the deep marine coarse clastics that currently form the principal reservoir target on the NEA (e.g. Leach et al., 1999). The last recorded extensional episode of any significance on the NEA was of Oligocene-Miocene age. It was confined to southern East Greenland, the western flank of Jan Mayen and the northern Vøring Basin, and was associated with the separation of the Jan Mayen microcontinent along the Kolbeinsey spreading ridge (Kuvaas & Kodaira, 1997; Lundin & Doré, 2002).

Discussion

There are strong similarities between the NEA and NWS in the way older structures appear to have been reactivated in the younger development of the margin. This is particularly evident on the NWS, where bounding faults on localised depocentres such as the Barrow, Dampier, Vulcan and Malita sub-Basins have been rejuvenated in a succession of rift episodes (Fig. 8). Even more impressive in both areas, superficially at least, is the control of very old (Proterozoic or older) basement structure on the Late Palaeozoic and Mesozoic rift basins. As indicated earlier, both margins are strongly segmented by NW-SE transfer zones. These features are usually not represented by well-defined fault lines, having instead a more diffuse character manifested as changes in structural style across doglegs in the graben system. The largest of the zones have a circumstantial link to basement inhomogeneity. For example, while the Canning Basin trend appears to influence the segmentation of the Westralian Superbasin, the Canning Basin itself exploits a series of NW-SE Proterozoic mobile belts (Li & Powell, 2001) bounded by the Paterson-Petermann Tectonic Zone, an ancient lineament extending SE to the Amadeus Basin (Fig. 10). On the NEA, both the Senja Fracture Zone and Anton Dhorn Transfer (Fig. 11) have been correlated with fundamental basement structure (Faleide et al., 1993; Dicken, 1992; Doré et al., 1997a). On both margins there is possibly a more general relationship between the NW-SE cross-cutting grain and onshore Proterozoic fracture systems, interpreted as extending offshore at a variety of scales, as hard and soft transfer linkages in the younger sediments (see for example Rumph et al., 1993 for the NEA, and O'Brien et al., 1996 for the NWS). The interesting issue brought up by this comparison is the true degree to which basement structure is implicated. Is it usual for basement lineaments trending parallel or sub-parallel to the extension direction to reactivate as transfer faults, or do only a few large lineaments reactivate? It is known that transfers form as a means of accommodating displacement between adjacent rift segments (Etheridge et al., 1988; Morley, 1990), a mechanism that would occur without pre-existing inhomogeneity. However, work on other extensional terranes has shown that the position of hard-linked transfers may be predetermined by basement grain (e.g. Cartwright, 1992).

The relative importance of basement control on the main extensional faults of the rift basins is also an issue. This is particularly the case on the NEA, where the NE-SW strike of most of the rift systems is approximately the same as that of the Caledonian basement substructure (Fig. 11). Many workers have assumed that the NEA extensional faults are reactivated structures, based solely on trend, when it is equally likely that the faults developed as new extensional structures (Roberts & Holdsworth, 1999). As indicated earlier, on the grand scale the NEA exploits the Caledonian Orogen. Some major NE-SW Caledonian shears such as the Møre-Trøndelag Fault Complex and Outer Hebrides Fault were clearly reactivated and formed basin-bounding faults in the Mesozoic (Doré et al., 1997a). Such faults tend to be long, sub-vertical, crustal-scale fractures.

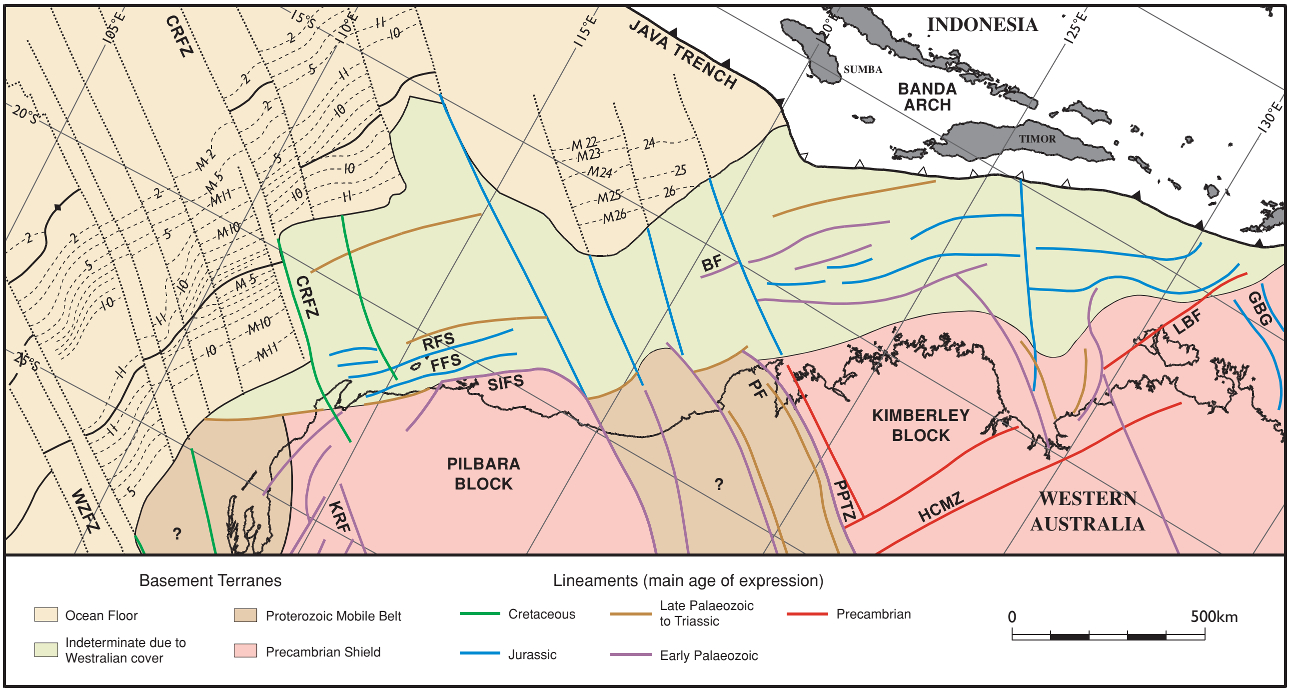

Figure 10: Basement terranes and lineaments on the North West Shelf. BF- Barcoo Fault, CRFZ- Cape Range Fracture Zone, FFS- Flinders Fault System, GBG- Goulburn Graben, HCMZ- Halls Creek Mobile Zone, KRF- Kennedy Range Fault, LBF- Lyndoch Bank Fault, PF- Pender Fault, PPTZ- Paterson-Petterman Tectonic Zone, RFS- Rankin Fault System, SIFS- Sholl Island Fault System, WZFZ- Wallaby-Zenith Fracture Zone.

Most other faults, however, cannot be tied in to basement by any direct means. There seems to be a need, on the NWS, NEA and rift systems in general, to quantify the degree of reactivation. Studies where field and remote sensing data onshore are combined with detailed interpretation of 3D data sets offshore (such as that carried out for the Petrel Sub-Basin and Timor Sea by O'Brien et al. (1996)) are particularly useful in this respect.

A further common factor between the NWS and NEA is that both were repeatedly rifted and show evidence of successive extensional episodes on the margin. The results of the rifting were, however, different between the two areas and this is reflected in the overall preservation of rift geometries. On the NWS every significant post-Pangean extensional phase (Permian, Late Triassic-Middle Jurassic and Late Jurassic-earliest Cretaceous) led to continental break-up. Consequently a substantial portion of each rift, including the axial area with most intense rifting, has probably been lost in the departing continental fragment and the evidence subsequently destroyed by orogeny. This observation may explain the very minor extensional faulting associated with Valanginian break-up off the Exmouth Plateau (Fig. 8) although, as we shall see later, depth-dependent extension provides an alternative explanation for this disparity. In contrast, the NEA preserves on both sides of the NE Atlantic a long record of rifting without continental drift which, if taken back to post-orogenic extensional collapse of the Caledonides in the Devonian, spans some 350 m.y. The observed pattern is generally that of sidestepping, rather than repeating rift axes with migration of the axes through time towards the line of eventual Cenozoic break-up – that is, the formation of new rifts with only partial reactivation of the existing ones (Lundin & Doré, 1997). A parallel to this pattern may occur in the North Carnarvon Basin, where Jurassic and Cretaceous rifting appears to have been most intense on the edges of the area of Westralian extension (Gartrell, 2000) (Fig. 1). Cooling time between successive failed rifts, with consequent strengthening of the mantle lithosphere, may explain the sidestepping pattern (e.g. Steckler & ten Brink, 1986).

The age difference between the plate tectonic "maturity" of the two areas is also reflected in the rift timing and basin fill, as even a cursory glance at cross-sections over the margins shows (Figs 8 and 9). Despite some important local Jurassic and Cretaceous depocentres, the dominant stratigraphic unit on the NWS is the Westralian Permo-Triassic succession. The direct analogy on the NEA is the thick Cretaceous fill occupying the Tromsø, Vøring, Møre, Faroe-Shetland basins and Rockall Trough, which together can perhaps be viewed as a "Westropean Superbasin". Both superbasins are the dominant structural feature of their margin, cross-cutting and burying pre-existing rift fabrics. Since both areas have important Jurassic source rocks, the much higher Cretaceous (and locally Cenozoic) sedimentation rates on the NEA compared to the NWS (Figs 8 and 9) make for very different thermal maturation and timing issues (see section on hydrocarbon systems).

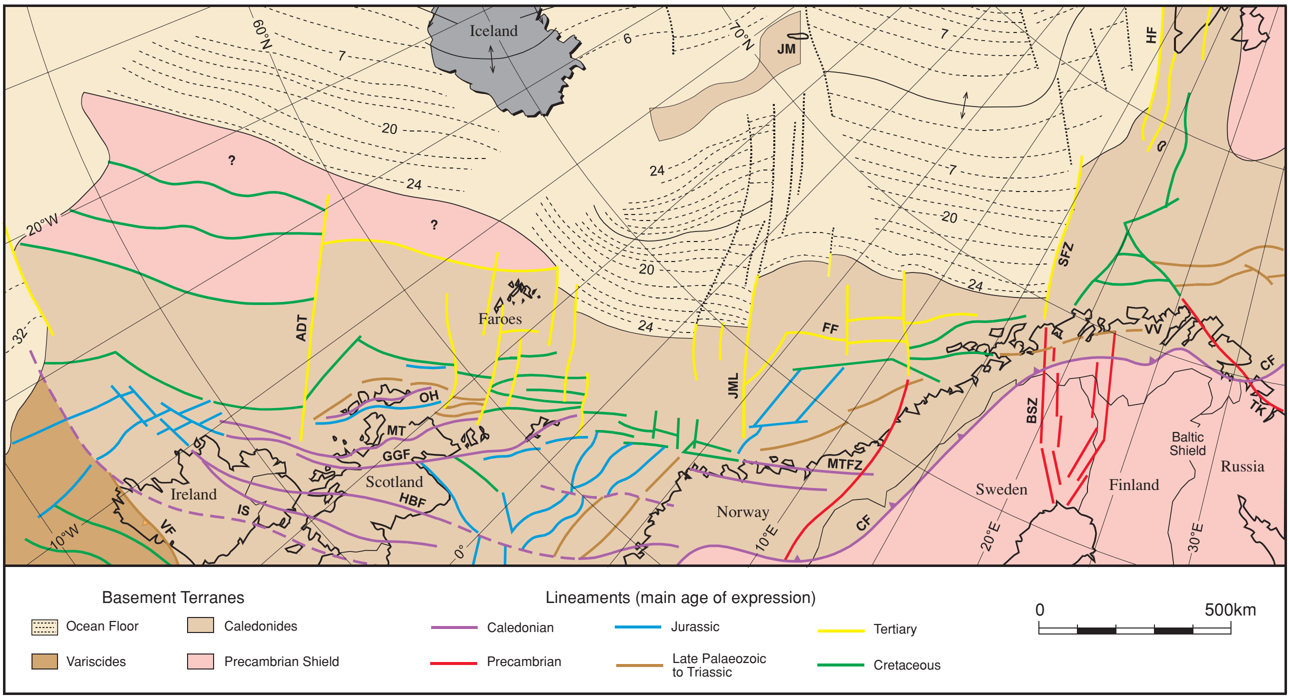

Figure 11: Basement terranes and lineaments on the Northeast Atlantic Margin. ADT- Anton Dhorn Transfer, BSZ- Bothnian-Senja Shear Zone, CF- Caledonian Front, FF- Fles Fault Zone, GGF- Great Glen Fault, HBF- Highland Boundary Fault, HF- Hornsund Fault Zone, IS- Iapetus Suture, JM- Jan Mayen, JML- Jan Mayen Lineament, MT- Moine Thrust, MTFZ- Møre-Trøndelag Fault Zone, OH- Outer Hebrides Fault Zone, SFZ- Senja Fracture Zone, TK- Trollfjord-Komagelv Fault Zone, VF- Variscan Front.

Both margins are characterised by excessive post-rift thermal subsidence compared to that predicted using simple stretching models and the amount of brittle faulting in the upper crust. Such mismatches appear to be characteristic of pre-break-up rifting on passive margins, and have also been documented on the Iberian margin (Boillot & Froitzheim, 1999; Manatchal et al., 2001) and West African margin (Karner et al., 2002). The most satisfactory explanation for the phenomenon involves excess stretching in the lower crust and lithosphere mantle compared to that in the upper crust, a process whereby plastic deformation in the lower crust is facilitated by increase in heat prior to break-up. This depth-dependent stretching or coaxial stretching model requires the existence of a plane at which strain is partitioned between the brittle upper crust and ductile lower crust (e.g. Karner & Driscoll, 1999; Boillot & Froitzheim, 1999; Gartrell, 2000).

On the NWS, disparities between brittle faulting and thermal subsidence appear to be the rule rather than the exception, probably because all of the main rift phases preceded break-up events. On the North Carnarvon Basin, models incorporating low-angle detachments (Karner & Driscoll, 1999) and/or lower crustal flow (Gartrell, 2000) have been used to explain the mismatch between the Tithonian-Valanginian pre-break-up faulting and the large post-Valanginian thermal subsidence that accommodated the Barrow Group. Similar depth-dependent stretching has been postulated for the Browse Basin, both for the Carboniferous-Permian Westralian rifting (Symonds et al., 1994) and the Jurassic rifting leading to the formation of the Argo margin (Struckmeyer et al., 1998). On the NEA the Jurassic-Early Cretaceous rifting can be modelled using uniform lithospheric extension, while modelling of pre-break-up rifting is made complex by the significant thermal and dynamic effect of the Iceland Plume. Even allowing for this factor, however, there is a significant disparity between the intensity of the Paleocene faulting in the upper crust and subsequent subsidence. This has led to the adoption of a depth-dependent stretching model for the Vøring Basin (Roberts et al., 1997). In the Porcupine Basin at the extreme southwest of the NEA (Fig. 2), a similar model has been used to explain large-scale subsidence without faulting in the Early Cretaceous, an event probably associated with the Albian onset of break-up southwest of the basin (Baxter et al., 2001).

This important phenomenon, fundamental to the development of passive margins, would benefit from continued study of the NEA and NWS, and continued comparison between these and other margins where the relationship between rifting, passive margin formation and thermal subsidence can be clearly seen. Key issues include the nature of mid-crustal partitioning (for example, the role of pure versus simple shear), role in excessive melt generation

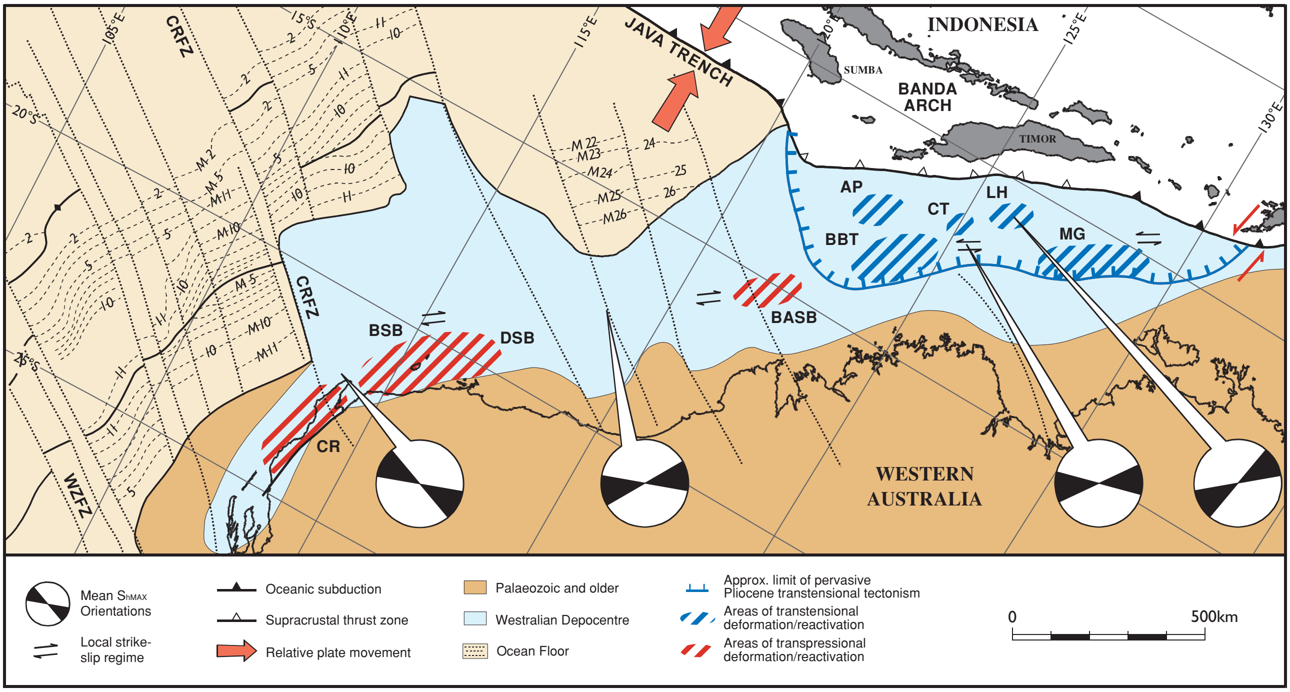

Figure 12: Map showing location of Neogene inversion and reactivation on the North West Shelf. Areas of transtensional and transpressional deformation mainly provided by M. Keep (personal communication 2002). Averaged present day horizontal stress directions taken from Hillis & Reynolds (2000). AP- Ashmore Platform, BSB- Barrow Sub-basin, BBT- Browse-Bonaparte transition, BASB- Barcoo Sub-basin, CR- Cape Ranges, CRFZ- Cape Range Fracture Zone, CT- Cartier Trough, DSB- Dampier Sub-basin, LH- Laminaria High, MG- Malita Graben, WZFZ- Wallaby-Zenith Fault Zone.

during break-up, degree of asymmetry in the continental margins and, from a commercial viewpoint, the implications of the thermal pulse for source rock maturation.

Inversion

As remarked by Dewey (1989), passive margin successions are prone to inversion after break-up as the dominant tectonic influence changes from extension to compression. This transition is a striking aspect of both the NWS and NEA, where the structural geometries on both margins have been significantly modified by late (Cenozoic) inversion (Figs 12 & 13).

North West Shelf

Numerous episodes of post-Permian inversion are recorded in literature on the NWS, suggesting that minor compressional, transpressional or transtensional adjustment on extensional faults in response to far-field stresses has taken place throughout the history of the province. Symonds et al. (1994) seem to be representative of the consensus view in listing four main episodes: 1) the Fitzroy movement of Late Triassic-Early Jurassic age, 2) Late Jurassic inversion, probably a local accommodation to continental break-up, 3) Broad Late Cretaceous uplift and reactivation of enigmatic origin in the North Carnarvon Basin (Stagg & Colwell, 1994; Bradshaw et al., 1998) and 4) Neogene deformation. Of these the Fitzroy and Neogene episodes have the most basin-wide significance.

The Fitzroy movements were first recognised in the Fitzroy Trough of the Canning Basin and have since been extended to most of the NWS (e.g. Stagg & Colwell, 1994; Symonds et al., 1994; Blevin et al., 1998). Structuring includes reverse reactivation of earlier (Palaeozoic) extensional faults, transpression, transtension and the creation of NE-SW trending folds that are the receptacle for hydrocarbons, for example in the Barrow and Exmouth sub-basins (Stagg & Colwell, 1994). Structures were frequently eroded and peneplained prior to recommencement of Jurassic deposition. Studies in the Browse Basin suggest that this hiatus marks the cessation of inversion and the beginning of Jurassic extension (Blevin et al., 1998; Struckmeyer et al., 1998), although other studies indicate some overlap in time between these events (e.g. Bradshaw et al., 1998). The origin of the Fitzroy structures is enigmatic, but is usually attributed to far-field plate tectonic causes. These could include the Late Triassic collision of the Cimmerian Blocks with the Asian margin (although it is an interesting question as to how stress propagated across a significant ocean basin which presumably included the Neo-Tethyan spreading ridge) or, more probably, contemporaneous subduction and mountain building on the eastern margin of the Australian craton (e.g. Baillie et al., 1994).

Neogene inversion can be attributed to the Early Miocene arrival of the northern margin of the Australian plate, north of Papua New Guinea, at the east-west trending subduction zone of the Eurasian plate (Banda Arc). As shown by Keep et al. (1998), sinistral movement at the eastern end of the subduction

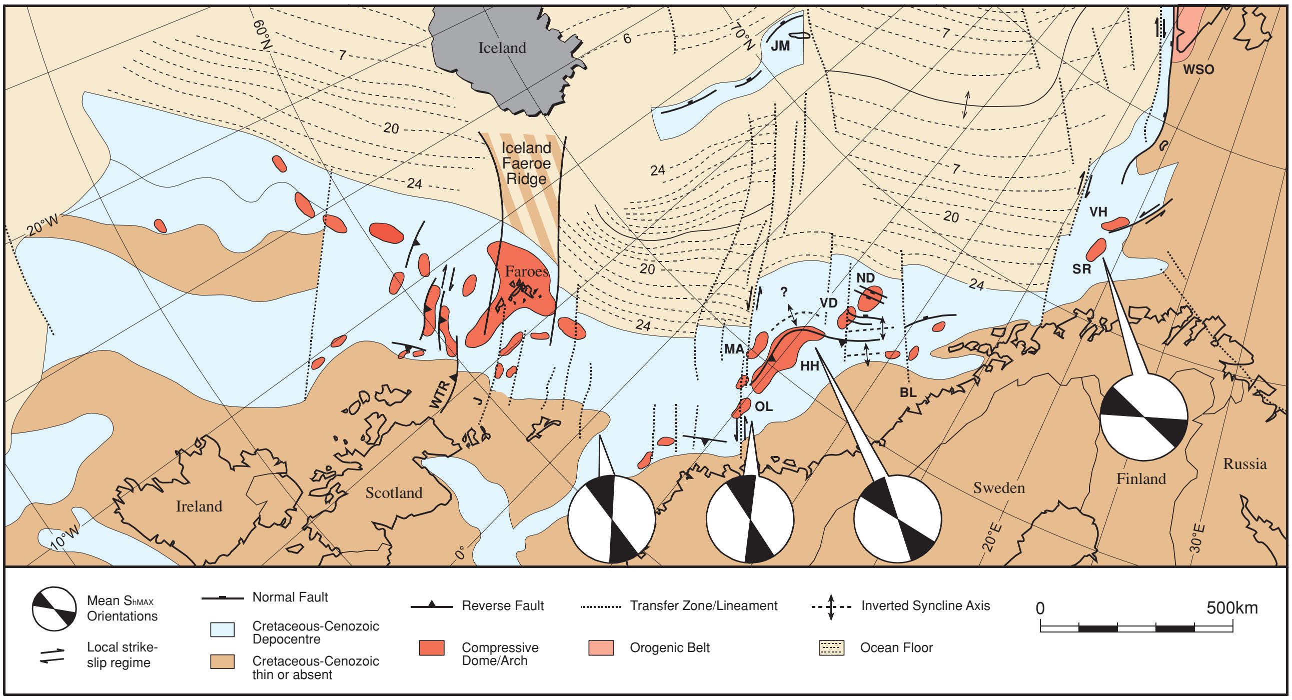

Figure 13: Map showing intra-Cenozoic inversion and associated structures on the Northeast Atlantic Margin. Present day horizontal stress directions simplified after Mueller et al. (2000). BL- Bivrost Lineament, HH- Helland-Hansen Arch, J – Judd Transfer, JM- Jan Mayen, MA- Modgunn Arch, ND- Naglfar Dome, OL- Ormen Lange Dome, SR- Senja Ridge, VD- Vema Dome, VH- Veslemøy High, WTR- Wyville-Thompson Ridge, WSO- West Spitzbergen Orogen.

zone combined with orthogonal movement at its western end imparted a counter-clockwise torque to the Australian craton (Fig. 7), which in turn resulted in distributed inversion and reactivation along the NWS (Fig. 12). The stress field changed through time as the Australia-Eurasia collision evolved, with many features showing multiple reactivation, which are difficult to interpret. The character of inversion also changes along strike due to distance from the subduction zone and interaction of the stress field with local pre-existing structure.

In the Bonaparte Basin steeply-dipping NE-SW faults developed in a sinistral transtensional setting, postulated to be compound wrench duplex structures by Nelson (1993) and negative flower structures by Keep et al. (1998) (Fig. 8). To the SW in the Browse Basin deformation appears confined to the Barcoo Sub-Basin and includes wrench-related anticlines along NE-SW basin faults (Keep et al., 2000), while farther SW in the Carnarvon Basin inversion is again widespread. Here the development of inversion anticlines has been attributed to oblique wrench reactivation of basin faults where these faults show a marked strike-swing from NE-SW to NNE-SSW (e.g. Stagg & Colwell, 1994) (Fig. 1). The Neogene episode had both positive and negative effects on the trapping of hydrocarbons on the NWS (Keep et al., 1998, 2000), as will be considered in the section on Hydrocarbon Systems.

Northeast Atlantic Margin

The post-Pangean history of the NEA was dominated by extensional tectonics until the onset of N.E. Atlantic spreading in the Early Eocene. From the Eocene to the present, but particularly within the Oligocene-Miocene interval, a suite of compressional features developed within the thick, ductile Cretaceous-Cenozoic depocentres between the Vøring Basin and Rockall Trough (Boldreel & Andersen, 1993; Blystad et al., 1995; Doré & Lundin, 1996; Lundin & Doré, 2002) (Figs 7 & 13). The most commonly observed structures are elongate, gentle domes, orientated NE-SW or N-S. They are areally extensive with long axes of up to 200 km (observed at the Helland Hansen Arch in the Vøring Basin) and amplitudes of a km or more. Minor bulge of depocentre axes and half graben infill, and reverse reactivation of normal faults (for example the Fles Fault, a Cretaceous normal fault bounding the Helland Hansen Arch) are also associated with the compression. The structures updome prospective reservoirs of Paleocene age and are thus an exploration target. A significant gas field has been discovered in the Ormen Lange Dome off Mid-Norway, while inversion is implicated in trapping of the Foinaven and Schiehallion fields in the Faroe-Shetland Basin.

The origin of the structures has been attributed to ridge push from the adjacent Atlantic spreading centre (Boldreel & Andersen, 1993; Doré & Lundin, 1996), with the onset of deformation indicating the building of topography on the ridge. Periods of increased deformation have been related to sinistral reactivation of the NW-SE transfer zones during the change in spreading direction that took place in the Oligocene-Miocene (see section on Plate Tectonics) and to enhancement of ridge push during changes of flux on the Iceland Plume (Lundin & Doré, 2002). Other authors (e.g. Brekke, 2000) believe the structures developed in response to far-field stresses from the Alpine Orogeny, in particular the Miocene docking event between Africa and Eurasia. Plate vectors from NE Atlantic spreading and Alpine convergence are similar (Fig. 7), and at present day much of N.W. Europe is experiencing mild NW-SE compression (Zoback, 1992; Mueller, 2000), making it difficult to isolate the effects of the two potential mechanisms. However, observation of contemporaneous folds in East Greenland (Price et al., 1997), which should be decoupled from Alpine compression by a spreading ridge, lend support to the ridge push hypothesis.

Discussion

In this discussion we concentrate on the Cenozoic inversion phenomena on both margins, because both can be analysed in terms of present-day plate tectonics, stress fields and hydrocarbon systems.

The inversion on the NWS commenced in the Miocene and is still active today, particularly in the Timor Sea and Barcoo Sub-basin, where steeply-dipping faults intersect and sometimes offset the sea-bed (Nelson, 1993; Keep et al., 1998, 2000). Structuring on the NEA took place during the Oligocene-Miocene and appears to have waned through the Pliocene and is largely inactive today. These observations fit with present day in-situ stress measurements, which indicate higher differential stresses on the NWS than on the NEA (Hillis, 1998).

Both sets of structures represent only mild compression (on the NEA we estimate that crustal shortening over the folds is only 1-2%) and show some common features, such as reverse rejuvenation and buttressing against half-graben faults. In other respects the phenomena are very different. Wrench-related transpressional and transtensional structures are the norm on the NWS (Nelson, 1993; Keep et al., 1998) but are less easily identified on the NEA, although, as indicated above, sinistral motion on NW-SE transfer zones may be locally implicated in the structuring (Doré & Lundin, 1996) (Fig. 13). On the other hand, the major, areally extensive domes typical of the NEA have no equivalent on the NWS. The only candidate that we are aware of for such a structure is the broad uplift or arch affecting the central Exmouth Plateau (Fig. 8; see also Stagg & Colwell, 1994, fig. 5b), an older (Cretaceous) feature that may related to deep crustal factors (underplating) rather than compression.

The differences between the two inversion regimes can be understood in terms of their causal mechanisms and the stress fields these generated. The NEA inversions are most readily explained by topographic forces (ridge push), acting more or less orthogonally on the margin (Boldreel & Andersen, 1993; Lundin & Doré, 2002), while the NWS phenomena relate to boundary forces (subduction and collision) with transmission of stress approximately parallel to the margin (Castillo et al., 1998; Keep et al., 2000). In one of the few published comparative studies between the NWS and N.W. Europe, Hillis (1998) shows from borehole breakout data and earthquake focal plane mechanisms that the present day maximum horizontal stress (S_{hmax}) direction on the northeastern NWS trends NE-SW (Fig. 12), whereas in the North Sea S_{hmax} trends NW-SE, a situation also observed over most of the NEA (Zoback, 1992; Mueller, 2000) (Fig. 13). Interestingly, Hillis et al. (1997) observe that S_{hmax} rotates from 50-60° to N in the Bonaparte Basin to 90-100° (i.e. almost orthogonal to the margin) in the southwest Carnarvon Basin (Fig. 12), perhaps implying that boundary forces give way to topographical forces the more distal the area becomes from the collision zone.

An implication of the different stress fields is that deformation on the NWS will tend to focus on transtensional and transpressional reactivation of the basin-parallel faults, while on the NEA it will be manifested as squeezing of the margin-parallel depocentres with buttressing against basin faults and minor strike-slip reactivation of the cross-cutting transfer zones. This observation also has implications for fluid-flow and seal integrity. It has been observed from worldwide water-flood statistics that "open" faults acting as conduits for fluid movement tend to strike close to S_{hmax} (Heffer & Dowokpor, 1990), implying that margin-parallel fractures on the NWS, and transfer faults on the NEA, will have more tendency to be leaky (see also section on hydrocarbon systems).

An important common factor between both margins is the way in which strain is localised along specific faults and folds, while many intervening areas show little or no deformation. On the NWS Neogene sinistral transtensional phenomena are common in the Bonaparte Basin. In the otherwise unaffected Browse Basin, deformation is channelled through the narrow conduit of the Barcoo Sub-Basin, where the local mode is dextral strike-slip (Keep et al., 2000). Inversion features in the Roebuck Basin are located on specific structures (Smith et al., 1999) and are common in inboard parts of the Carnarvon Basin (Keep et al., 1998) (Fig. 12). On the NEA structuring is common in the Vøring Basin and the Faroe-Shetland Basin, but almost absent from the intervening Møre Basin (Fig. 13). The Møre Basin contains a thick Cretaceous-Cenozoic fill, so the lack of inversion structures in this readily deformable sediment pile is puzzling (Lundin & Doré, 2002). It is possibly attributable to the fact that the basin lies adjacent to an extinct spreading axis (the Aegir Ridge) and is shielded from the current ridge by the Jan Mayen Microcontinent. More probably, however, it relates to localisation of strain along the Jan Mayen Lineament separating the Vøring and Møre basins (Figs 2, 11 & 13) and/or the lack of significant buttressing faults in the basin.

The phenomenon of strain partitioning between basins and basin segments, and the localisation of deformation to specific structures, may be a paradigm for extensional terranes subjected to far-field compressive stress. It is a major topic for future study at both regional and local scale, with key issues being the mechanical properties of reactivating faults, the role of basement grain, the variability of stress fields in time and space and the interaction between stress directions and basin geometry. Comparative studies between different basins will be an important part of this process.

Hydrocarbon Systems

The tectonic events described above and summarised in Figure 14 have significant implications on the hydrocarbon systems of the NWS and NEA. Information was taken principally from Bishop (1999) and Longley et al. (this volume) for the NWS, and Fjaeran et al. (1997), Spencer et al. (1999) and Spencer & MacTiernan (2001) for the NEA. For more detail on hydrocarbon systems, the reader is referred to those papers.

North West Shelf

On the NWS source potential occurs in mudrocks (the Dingo Claystone and equivalents) all the way through the Jurassic succession. Overall these shales are of moderate quality and gas-prone, but a richer and more oil-prone interval occurs in the Oxfordian-Kimmeridgian. This Late Jurassic unit is the principal source rock on the NWS. Thicker and relatively more oil-prone syn-rift source rocks were concentrated in inboard depocentres such as the Vulcan and Dampier sub-basins, while in deeper waters away from the main rift zones (e.g. Exmouth Plateau) only a veneer of Jurassic shale is present (Fig. 8). Triassic deltaic shales of Scythian-Ladinian age (the Locker Formation and equivalents) are an important secondary source, and are mainly gas-prone. Other source potential occurs locally in the Palaeozoic (onshore Canning Basin and Petrel Sub-Basin) and in the Lower Cretaceous (e.g. Dampier Sub-Basin and Browse Basin).

Both the Late Jurassic and Early-Middle Triassic source rocks supply charge to deltaic-marine sandstones of Triassic to Early Cretaceous age, with Early Triassic (Mungaroo Formation and equivalents) and Lower Cretaceous (Barrow Group and equivalents) units being particularly important reservoirs. Traps include tilted fault blocks and horsts formed during the main Late Triassic to Valanginian extensional phases, Lower Cretaceous drape closures over the fault blocks, and anticlines formed during both early (Fitzroy) and late (Neogene) inversion episodes. The regional seal of the NWS, the Barremian–Aptian Muderong Shale and equivalents, were deposited during a basinwide marine transgression that reached its acme in the Aptian (Bishop, 1999). According to Longley et al. (2002) 97% of the hydrocarbons on the NWS are reservoired at the base of this seal, in subcropping Triassic-Lower Cretaceous reservoirs. Migration of hydrocarbons was by both vertical and lateral drainage.

Source rocks on most of the NWS are currently at their maximum burial depth due to the widespread build-out in the Cenozoic of a prograding carbonate shelf (Fig. 8). The hydrocarbon system is overwhelmingly dominated by gas. Oil accumulations occur together with gas in sweet spots,

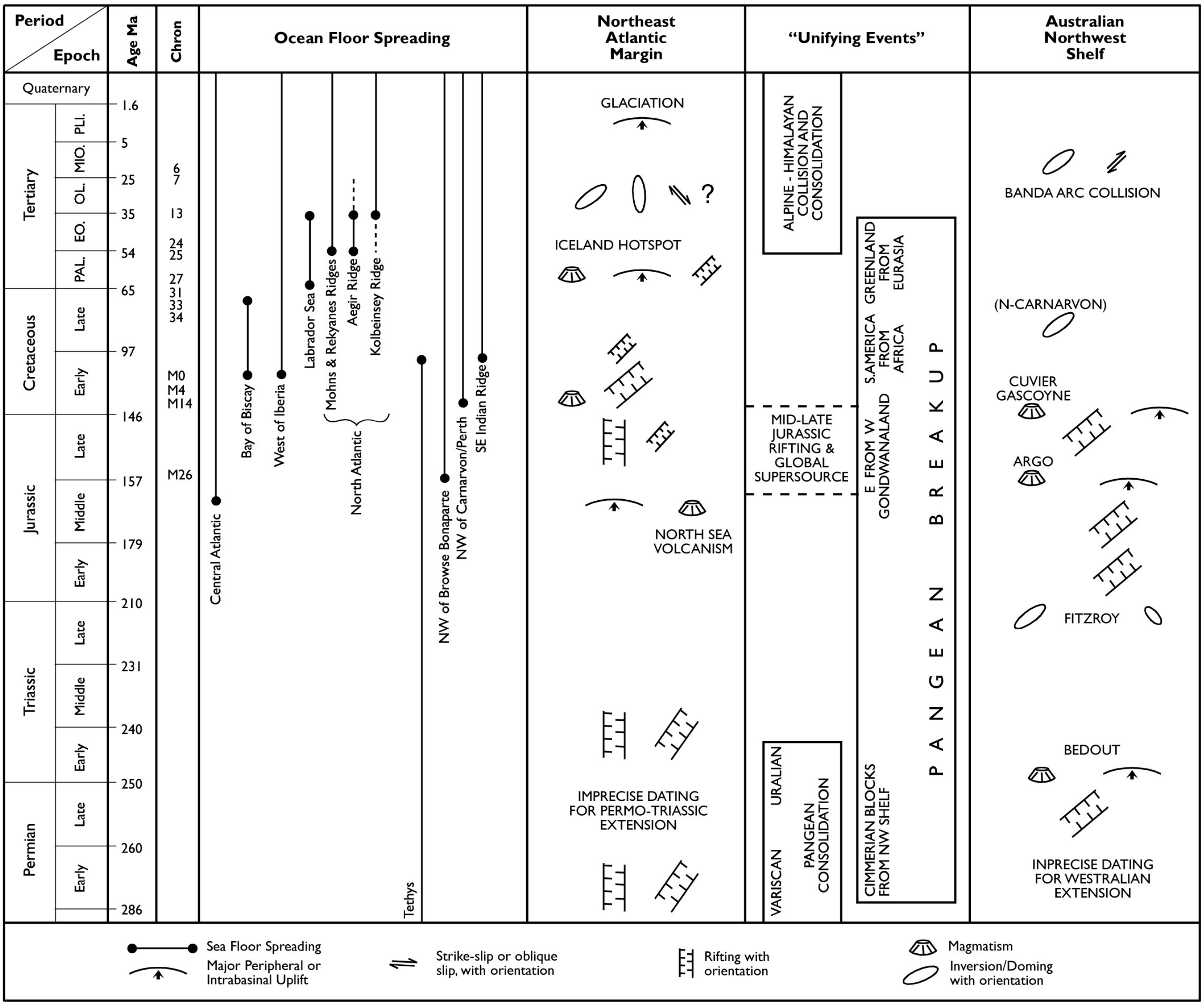

Figure 14: Comparison of generalized post-Carboniferous event chronologies for the Northeast Atlantic Margin and North West Shelf, showing plate tectonic controls and globally unifying events.

principally the inboard rift basins, while the deeper water areas, that lack a significant Jurassic source, are almost exclusively gas provinces. The gas dominance has been attributed to three principal factors; 1) the pervasiveness of lean and gas-prone source rocks, reflecting a strong terrestrial influence on deposition throughout the basin history, 2) Triassic and, in places, Jurassic source rocks being at gas-window maturity, and 3) leakage and gas flushing of a pre-existing oil charge (e.g. Lisk et al. 1998; Kennard et al. 1999). Longley et al. (2002) consider that the first of these factors (source quality) is the most important contributory factor to the gas dominance.

Reactivation of structures during the Neogene inversion phase has influenced hydrocarbon accumulation over most of the NWS, but particularly in northwestern areas such as the Vulcan-Sub-Basin and Timor Sea (e.g. Keep et al., 1998; Lisk et al., 1998; Kaldi et al., 1999; Kennard et al., 1999). Effects included breaching of seals (particularly in areas where the Lower Cretaceous shales are thinner), selective loss of gas caps through the seal, and flushing of oil by gas generated in newly-created depocentres. Residual oil shows in evacuated traps and palaeo-oil water contacts within current accumulations are common occurrences.

Northeast Atlantic Margin

Syn-rift marine shales of Late Jurassic age, roughly equivalent to the Kimmeridge Clay of onshore England and the northern North Sea, form the main source rocks of the NEA. They are rich and generally oil-prone, and are correlated to the major oil accumulations of the Halten Terrace and Faroe-Shetland Basin (Spencer et al., 1999). The Jurassic interval as a whole appears to have been prone to anoxic environments, with the result that source rocks occur throughout the section. Lower Jurassic source rocks contribute to the oil and gas accumulations off Mid-Norway (Koch &

Heum, 1995) and have been identified in the Slyne Trough off western Ireland, while a Middle Jurassic source contributes to the oils discovered west of Shetlands (Scotchman, 2001). Upper Carboniferous coals constitute a very local source for gas on the NEA, providing the charge for the Corrib Field in the Slyne Trough.

Jurassic shales are mature for oil generation in inboard areas, in particular the Halten Terrace where they directly charged pre-rift and syn-rift Jurassic reservoirs in extensional fault blocks, sealed by overlying Cretaceous shales (Koch & Heum, 1995). In the Faroe-Shetland Basin, where burial of the Jurassic section is greater, Paleocene reservoirs, in combination structural-stratigraphic traps, may have been charged with oil by a two-stage migration process involving an intermediate reservoir (Spencer et al., 1999). In the shallower adjacent West Shetland Basin, Upper Palaeozoic to Lower Cretaceous reservoirs were charged with oil and gas by pulsed lateral migration from the outlying depocentre (Parnell et al., 1999). The Halten Terrace and Faroe-Shetland Basin account for most of the hydrocarbons currently discovered on the NEA, and for the dominance of oil.

The hydrocarbon system is less well known in the chain of basins between the Vøring Basin and Rockall Trough. The distribution of the Jurassic source rock is indeterminate, due to the thick Cretaceous cover (Fig. 9), and the rapid burial would have caused any source rocks to generate oil in the Early Cretaceous and to be gas-mature or postmature at the present day. Early exploration of this basin chain therefore had to be predicated on multi-stage remigration from the Jurassic to younger reservoirs, or on regional evidence for younger and less mature source rocks (Doré et al., 1997b). To date, dry gas discoveries have been made in Paleocene and Campanian reservoirs, the largest being the Ormen Lange Field, a Cenozoic inversion dome in the southern Vøring Basin (Fig. 13). The origin of this gas is, at time of writing, unknown.

Paleocene uplift, associated with the Iceland Plume, and Neogene denudation associated with glaciation, caused exhumation of some marginal basins along the NEA: for example, the Western Barents Sea, the West Shetland Basin and the Slyne and Erris troughs (Fig. 2). In the Western Barents Sea, over 2500 m of overburden were removed. The exhumation had a radical effect on the hydrocarbon system, including the cooling of source rocks and seal failure. Decrease in fluid pressure caused gas exsolution from oil and brine and expansion of existing gas, resulting in flushing of oil from traps. Gas-dominated systems with residual oils, biodegraded oils and palaeo-oil water contacts are typical of these areas (Nyland et al., 1992; Doré & Jensen, 1996; Doré et al., 2002).

Discussion

There are quite remarkable similarities in source rock development between the NWS and NEA. Both areas feature multiple source rocks, and in both areas the entire Jurassic interval has a predisposition towards organic shale development. The richest and most oil-prone shales of both the NWS and NEA occur in the Upper Jurassic syn-rift section, reflecting the status of the Upper Jurassic as a global supersource (e.g. Baudin, 1995) (Fig. 14). However, as shown very clearly by Longley et al. (2002) the Western Australian source rocks are, taken as a whole, considerably leaner and more gas-prone than their Northwest European counterparts. It is almost certainly this factor, and not maturity differences, that accounts for the gas dominance on the NWS and oil dominance on the NEA based on currently discovered reserves.

Despite the difference in age and stratigraphy of the two margins, the ultimate result in terms of hydrocarbon distribution, and in the challenges this creates, is quite similar. On both margins, most discovered reserves are concentrated in rift basins or shoulders in the more inboard, shallower water areas with moderate Cretaceous and Cenozoic overburden. Gas appears to dominate in the more sparsely explored, deeper water areas of both margins, but for very different reasons. In the case of the NEA, Cretaceous subsidence occurred without break-up and accommodation space was rapidly filled by predominantly fine clastics from both the Greenland and European margins (Fig. 9). Jurassic source rocks were buried to postmaturity levels, leaving traps to be charged by residual remigrated gas, or by gas from lean shales in the younger section. On the NWS Cretaceous subsidence accompanied break-up, and despite some important progradations such as that of the Barrow Delta, large parts of the shelf were comparatively starved of sediment (Fig. 8). Younger source rocks, if present at all in these outboard areas, are therefore immature. Only deeper source rocks such as the gas-prone Late Triassic reached generation thresholds. Simplistically, the outboard NEA is gas-prone due to rapid deposition while the outboard NWS is gas-prone due to sediment starvation. Undiscovered resources for the NEA will mainly lie within outboard provinces and based on the available evidence will be predominantly gas (Fjaeran et al., 1997), suggesting that future exploration will tilt the oil-gas balance of the NEA more towards that of the NWS.

In both areas the deposition of a significant Cenozoic succession was a key factor in attaining present day maturation levels. On the NWS this process mainly consisted of the steady build-out of a carbonate shelf, with some depocentre readjustment due to Neogene inversion. On the NEA the process was much more dynamic due to the vertical movements of the Paleocene and Neogene, with some basins undergoing rapid burial and other basins being rapidly exhumed. In the Faroe-Shetland Basin anomalously high Paleocene sedimentation rates (Fig. 9) caused high generation rates in the Early Cenozoic while on the Halten Terrace major Neogene build-out from the margin resulted in rapid generation continuing to the present (e.g. Spencer et al., 1999). In the western Barents Sea, Neogene exhumation caused a complete cessation of hydrocarbon generation (Nyland et al., 1992).

Predicting the effects of pre-break-up rifting and volcanism presents a challenge for basin modellers working on both margins. Both margins are intruded, are underplated and were subjected to depth-dependent extension, all processes that add heat to the system and preclude analysis using simple rift-thermal subsidence models. For example, as shown by Karner & Driscoll (1999), high lower crustal extension rates prior to break-up on the Carnarvon Basin margin would have been accompanied by a heat pulse, with implications for timing of maturation on the Exmouth Plateau and other outboard basins. Plausibly, deep-seated heating from this mechanism and/or underplating could explain the predominance of dry gas accumulations on the Exmouth Plateau despite the fact that, at present-day geothermal gradients, the presumed Late Triassic source should not have entered the gas window (Bradshaw et al., 1998). Local heating around sills, dyke swarms and central intrusive complexes can also add complexity to the generation pattern, particularly on the NEA where the volcanism was more pervasive (Naylor et al., 1999). Migration of hot fluids from depth may also affect local maturation thresholds, as shown for the NEA by Parnell et al. (1999) and for the NWS by Kennard et al. (1999). For all of these phenomena, the key questions for maturation modellers are the intensity and duration of the heat spike, its geographical extent and how to model its decline with time. Modelling strategies remain a subject of "heated" debate (e.g. Green et al., 1999; Parnell et al., 1999).

Neogene inversion on the NEA has generally enhanced the potential for hydrocarbon discovery. The simple domes found throughout much of the deep basin chain (Fig. 13) form 4-way dip closures for Paleocene and Upper Cretaceous reservoirs, and are implicated in redistribution of hydrocarbons into major structural-stratigraphic traps in the Faroe-Shetland Basin (Iliffe et al., 1999). In contrast, despite the formation and enhancement of some traps, the inversion is widely blamed for seal failure on the NWS (e.g. Lisk et al., 1998; Kaldi et al., 1999). Seal failure occurs on the NEA, but relates to two different phenomena; the building of burial-related overpressure and its exact inverse, the creation of disequilibrium pressures during exhumation.

As discussed in the section on Inversion, empirical data suggests that the differing stress regimes may locally induce fractures sub-parallel to the basin trend to fail on the NWS but remain closed on the NEA. In reality, the situation is probably far more complex and relates to the type of caprock present (membrane vs. pressure seal), the intensity and orientation of the local stress field and the orientation of natural faults and fractures. As shown by Hillis (1998), where pore pressures and differential stress in the caprock are both high, shear failure will take place before tensile failure, resulting in the development of conjugate fractures at oblique angles to S_{hmax}. This describes the northern NWS (Fig. 12), where pre-existing faults corresponding to this shear couplet are associated with high risk of leakage (Castillo et al., 1998). Where pore pressures are high but differential stress is low, tensile failure of the caprock (hydraulic fracturing) can take place, resulting in the development of fractures roughly parallel to S_{hmax}. This describes the NEA (Fig. 13), where hydraulic fracturing due to burial and generation of overpressure has caused trap evacuation, and leakage of hydrocarbons to higher levels, in the Faroe –Shetland Basin (Iliffe et al., 1999) and Halten Terrace (Koch & Heum, 1995). In exhumed basins on the NEA such as the western Barents Sea, disequilibrium fluid pressures during rapid removal of overburden probably also promoted tensile failure and loss of hydrocarbon charge (Corcoran & Doré, 2002; Doré et al., 2002). Naturally-occurring tensile fractures striking close to S_{hmax} also have positive connotations for hydrocarbon production: for example in the Clair Oil Field in the West Shetland Basin (Fig. 2), where "open" NW-SE fractures in the low permeability Upper Palaeozoic sandstone reservoir have been targeted by directional wells as a strategy for increasing recovery (Coney et al., 1993).

Conclusions

The NWS and NEA are remarkably similar in terms of area, orientation, water depth, commercial importance and geological structure. An initial joint tectonic study demonstrates that many useful comparisons can be made, some of which reveal issues of general significance for passive margins. Overall, comparative studies between the NWS, NEA and other passive margins worldwide constitute a promising area for continuing research. Key observations from the present study are as follows:

1) The NWS evolved through continental fragmentation on the periphery of Pangea, while the NEA represented the final point of break-up in the supercontinental interior. In plate tectonic terms the NWS is about 80 Ma older than the NEA and is currently undergoing subduction. In many other respects, however, the two margins are similar. An example is in the way diffuse NW-SE transfer zones offsetting the marginal basins evolved into shear margin segments and then into transform faults extending from the margin. The plate tectonic history of the NWS involved the drifting off of a succession of elongate continental terranes from the extended margin, a behaviour that also appears typical of the Arctic Ocean and is beginning in the North Atlantic with the breaking away of the Jan Mayen microcontinent.
2) Both the NWS and NEA are volcanic margins, with a wide array of comparable phenomena including underplating, marginal uplifts, intrusions, basalt flows, SDRs and hyaloclastite constructions. The NEA was unequivocally affected by the presence of a superplume, evidenced by the greater scale of the Paleocene volcanism and by widespread permanent uplift. The Late Jurassic-Early Cretaceous NWS volcanism could be explained by high finite-rate extension or depth-dependent extension, but based on the plate tectonic setting and the range of phenomena a plume model, perhaps involving marginal influence from the Kergeulen hotspot, cannot be ruled out.
3) Sub-basalt imaging techniques developed and employed

on the NEA may become useful in future exploration in deeper waters of the NWS. In both areas modelling the intensity, distribution and duration of heating associated with pre-break-up magmatism is a key challenge for maturation modellers.

4) On both margins there is strong circumstantial evidence for a link between basement substructure, basin development and passive margin geometry. This link is particularly evident in the development of basin transfer zones at basement discontinuities. Margin-parallel faults are also often multiply reactivated and, particularly on the NEA, there is an assumed relationship with underlying basement grain. Direct evidence for basement reactivation is, however, sparse in both areas. To make further progress, future work must extend beyond lineament analysis into detailed comparison of onshore field measurements with offshore 3D data sets.
5) Both margins preserve a record of multiple rifting episodes representing successive stages in the disassembly of Pangea. On the NWS each major extensional phase led to break-up and drifting away of part of the basin, while on the NEA a succession of rift episodes spanning some 350 million years took place prior to final break-up in the Early Eocene. Both areas are characterised by a chain of contemporaneous deep sag basins, the Westralian Superbasin on the NWS and an analagous "Westropean Superbasin" on the NEA. The basin fill in each case is dominated by a major stratigraphic super-unit, the Permo-Triassic on the NWS and the Cretaceous on the younger NEA. Both super-basins strongly overprint older rift fabrics.
6) Jurassic extension, reflecting a globally important phase of Pangean break-up, was common to both areas. The rifting created the conditions for the deposition and preservation of the organic shales that form the dominant source rock of both provinces.
7) Depth-dependent extension models are required to explain disparities between upper crustal brittle faulting and thermal subsidence for all of the NWS rift episodes, and for Mid-Cretaceous and Paleocene phases on the NEA. Ductile extension of the lower crust and lithosphere mantle appears to be characteristic of these and other passive margins at time of break-up. Further study of this potentially important phenomenon will benefit from integrated global studies addressing, among other issues, the means of mid-crustal strain partitioning, the degree of asymmetry of continental margins, and the consequences for heating and source rock maturation.
8) Cenozoic inversion structures on the NWS were produced by distributed transtension and transpression longitudinal to the margin resulting from the oblique collision between the Australian and Eurasian plates. In contrast, inversion on the NEA resulted primarily from compression orthogonal to the margin, probably attributable to ridge-push. In both areas strain was localized along specific folds and faults, while other areas remained undeformed.
9) Inversion in both areas significantly affected trapping and modified hydrocarbon distribution. The intensity and orientation of the stress field differed significantly between the areas, and can be shown to have predictive value for determining which fault/fracture geometries in each area will seal, and which will conduct fluids. Comparison of present day stress fields and post-break-up inversion on different margins should be a particularly productive topic for future research.
10) Both margins contain source rocks at multiple levels with the Jurassic as the most important interval. As a whole, source rocks are more gas-prone on the NWS. This observation is reflected in the currently discovered reserves, which are gas-dominated on the NWS and oil-dominated on the NEA. Oil systems in both areas are more common in inboard rift basins where the Jurassic is at ideal generation depths. Cenozoic sedimentation was a key factor in the present day hydrocarbon distribution in both areas, but on the NEA the process was more dynamic, resulting in exhumation of some basins and rapid subsidence of others.
11) A transition from oily systems to dry gas-dominated systems occurs in deeper water parts of both margins. On the NWS this change is due to post-break-up sediment starvation and immaturity of the Jurassic source, which allows deeper gas-prone source rocks to dominate the system. On the NEA it is due to rapid Cretaceous subsidence and deep burial of the Jurassic syn-rift mudrocks. Future exploration of the deeper water NEA is expected to find more gas, tilting the oil-gas balance more towards that of the NWS.

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Biographies

Tony Doré obtained a Ph.D in Marine Geology from University College London, and joined the petroleum industry in 1977. He has worked as a geologist, function leader and manager for Britoil, Conoco and, for the last eight years, Statoil. His working experience has taken him to petroleum provinces all over the world, but with emphasis on NW Europe. His current position is Vice President Global Exploration, Americas, based in London. Tony has published on stratigraphic nomenclature, NE Atlantic geological evolution, basement reactivation, basin modelling, Cenozoic exhumation models and exploration risk analysis. He has edited books on basin modelling and resource quantification for the Norwegian Petroleum Society, acted as Geology Editor for First Break, and is currently editing a Geological Society Special Publication on Exhumation of the North Atlantic Margins. Tony has just completed a 2-year tenure as chairman of the Petroleum Group of the Geological Society and is Technical Chairman for the 2003 Petroleum Geology of NW Europe conference.

Iain Stewart graduated from the University of Liverpool in 1976 with a Bachelor of Science and from Reading University in 1977 with a Master of Science in Sedimentology. He was employed by Texaco and then Gulf Oil in London prior to moving to Kerr McGee in 1981. He held a number of positions with the company before becoming Exploration Director, responsible for all exploration matters relating to North West Europe. From 1990 to 1992 he worked firstly as a consultant and latterly as Exploration Manager for Pict Petroleum on UK and international projects in North Africa and the Far East. In 1992 he Joined Nimir Petroleum as Director of Exploration responsible for exploration acreage in the Yemen and Malta. From 1995-1997 he worked as an Independent Exploration Advisor on project in the UK and Pakistan before becoming Exploration Manager for Santos Europe Ltd where he was responsible for Santos's UK assets. He Joined TroyIkoda in 1998 as Manager of Exploration Studies and has worked on international projects in the Middle East, North Africa, Europe, West Africa, UK and the Former Soviet Union. He is a member of the PESGB.