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Tectono-stratigraphic geometries at volcanic passive margins – some observed phenomena in the Norwegian Sea and elsewhere on the NE Atlantic margin

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Extension leading to Early Eocene break-up of the NE Atlantic can be viewed to have already started in Late Devonian time, with gravitational collapse of the Caledonian Orogen. Gradually more organized rifting, reflecting far-field plate stresses associated with continental break-up, developed and eventually culminated in plate separation. While the total time of rifting was very long (c. 300 Ma), the rifting was multiphase and episodic in nature (e.g. Doré et al, 1999). From Late Jurassic time and onwards, the rifts followed a systematic pattern and reveal a progressive clockwise rotation of extension direction. As a consequence, a pattern of younger rifts transecting older rifts is observed. In addition to the transecting pattern, the rifts tended to become focussed toward the future zone of break-up.

Magmatism was locally associated with rifting at least from the mid-Jurassic time and onwards. The mid-Jurassic North Sea dome and the associated Forties igneous province is considered an example of "active" rifting above a mantle plume (Underhill & Partington, 1993*)*. Magmatism ahead of propagating spreading axes is observed in several locations in the evolving NE Atlantic. Subaerial construction of the oceanic Spur Ridge south of Grand Banks and the conjugate Madeira-Tore Rise (Chron M0-M4, c. 120-125 Ma), occurred prior to northward propagation of the Mid-Atlantic spreading axis between Grand Banks and Iberia. Further north in southern Rockall Trough, the Lower Cretaceous Barra Volcanic Ridge formed at the tip of the advancing Mid-Atlantic spreading Ridge, probably near Chron 34 (c. 84 Ma). Seamounts formed southwest of Hatton Bank around Chron 33-30 time (c. 80-67 Ma). Similar examples are seen for the Arctic system. Although of debated age, seamounts in the northern Rockall Trough may relate to extreme mid (?) - Late Cretaceous extension.

However, it was not until latest Cretaceous to Early Tertiary time that the NE Atlantic margins received their pronounced magmatic signature and started developing into volcanic passive margins. The key factor in transforming these margins into volcanic passive margins was the so-called "arrival" of the Iceland plume. Dated magmatism associated with the North Atlantic Igenous Province (NAIP) (and the Iceland plume) reveals two main pulses of magmatism, c. 62 to 58 Ma and 56 to 54 Ma respectively (e.g. Saunders et al., 1997). The older phase of magmatism is observed in Baffin Bay-W Greenland, SE Greenland (ODP 917), and the British Volcanic Province to Faroes area, while the younger phase relates primarily to the seaward-dipping reflector sequence (SDR) bordering the continent-ocean boundary along most of the NE Atlantic margins. It is generally accepted that Paleocene magmatism was focussed along zones of weaknesses in the lithosphere.

Some workers have proposed that the ancient Iceland plume was located under the Greenland craton during Paleocene time (e.g. Lawver & Müller, 1994). Such estimates of the plume centre position are derived from plate models, whereby the plates move over a fixed plume referenced to the Earth's core. However, other workers have proposed that the initial plume centre was located near Kangerlussuaq in E Greenland (e.g. White & McKenzie, 1989). In general, there is little first hand evidence of a migration of the plumehead across the plate from a position beneath Greenland to its present position beneath Iceland. We propose here that the plume either formed in situ or has been captured in the NE Atlantic spreading system, and has not "migrated" from beneath Greenland into its current position. Such an interpretation readily explains the Greenland-Scotland Ridge as a symmetric hot spot track, and fits with the near equidistant position of the most far-flung NAIP igneous centres from the present plume centre. More speculatively, the plume may have acted as the focal point of propagating rifts (i.e. may also be an example of active rifting) for the suggested overlapping and opposed Arctic and Atlantic rifts (Lundin et al, this volume). The NNW-trending British Volcanic Province may represent a third arm of weak extension related to the plume uplift, a phenomenon suggested in early models of plate tectonics (e.g. Burke & Wilson, 1976).

While the NAIP plume-related surface magmatism, uplift and sedimentation is confined to the Paleocene, magmato-tectonic structuring appears to have started in Maastrichtian time. Early effects of underplating may be indirectly dated by the timing of structuring of the Gjallar Ridge core complexes, the palaeo Vema Dome, and arguably the Hel Graben along the outer Vøring margin. The dome-shaped Gjallar Ridge core complexes, defined by the base Tertiary unconformity, lie directly above a dome-shaped deep-seated reflector that coincides with the top of underplating (e.g. Wheeler et al., 2002). Underplating in these locations is thick and distributed in an uneven "blob"-like fashion. While the Gjallar Ridge was already experiencing brittle faulting in Campanian time, a more ductile style dominated in Maastrichtian to Paleocene time, when the core complex structuring occurred.

Rise of the palaeo-Vema Dome started in Late Maastrichtian time and culminated with major erosional truncation in Late Paleocene time, followed by collapse and infill in earliest Eocene time. Cauldron-like collapse of Hel Graben, in the northwest corner of the Vøring margin, occurred concurrent with collapse of the Vema Dome. The Hel Graben is also underlain by a local build-up of underplated material and the sedimentary basin is heavily intruded by high-velocity sills.

Several workers have documented a significant discrepancy between observable Paleocene extension and subsidence along the outer Vøring margin (e.g. Kusznir et al, this volume). Basically, the margin has subsided far more than expected from observable extension, applying a "McKenzie" model for passive margin subsidence. The most plausible causal mechanism for this anomalous subsidence is depth-dependent stretching, a process whereby the whole lithosphere is thinned more that the seismically observable upper crust. Anomalous Paleocene subsidence is also apparent in e.g. the Faroe-Shetland basin (Dean et al. 1999). It may be a general phenomenon around the NE Atlantic margins (Hall & White, 1994) and other passive margins worldwide.

The boundary between the continental Vøring margin and oceanic crust is marked by the Vøring Marginal High, here considered to be a magmatic construction. ODP 642 on the marginal high drilled through the SDR wedge of basalt and reached continentally derived intermediate composition magmatic rocks of Late Paleocene age, including ignimbrites. We argue that the marginal high development can be viewed as a response of plastic material (lower crust –mantle) to extension, whereby the plastic material flows into the most thinned area, a process enhanced by plume-related heating. The response of plastic materials overlain by brittle materials to extension is well established from analogue modelling aimed at understanding salt tectonics (e.g. Vendeville & Jackson, 1992). Such modelling has more recently been aimed at volcanic passive margin development (e.g. Callot et al. 2001; Bonini et al. 2001), and provides a number of instructive results. While analogue models cannot mimic subsidence well, we suspect that lateral withdrawal of lower crust forms at least an element of depth-dependent stretching. We interpret a genetic relationship between 1) elevated mantle temperatures due to the plume, 2) decompressional melting and rise of the melts, 3) underplating beneath the crust and heating of the lower crust, 4) structuring of the upper crust, 5) plastic flow of the lower crust, 6) development of marginal highs, and 7) possibly the anomalous subsidence.

Upon rupture of the plates, it appears that the marginal high constructions ended up on one of the conjugate margins. The margin receiving the marginal high became isostatically held up by the marginal high, consequently subsided less, and was therefore not significantly flooded by breakup-related basalt (so-called inner flows). At least for the Norwegian Sea margins such a pattern can be proposed. In the far north the Lofoten margin lacks a marginal high and is flooded by basalt while its conjugate NE Greenland margin is not significantly flooded and has a marginal high. Next to the south, the Vøring margin has a prominent marginal high and is not basalt flooded, while the conjugate central E Greenland margin appears to lack a marginal high and clearly is basalt flooded. The Møre margin is basalt flooded while the conjugate Jan Mayen is not. The Jan Mayen microcontinent is complicated however, due its position between two propagating rifts/spreading axes. South of the Greenland-Scotland Ridge the pattern is unclear, but the entire Hatton Bank margin (and beyond) is basalt flooded while SE Greenland is not.

A general view is that the NE Atlantic margin ceased to be a volcanic passive margin during the Eocene. However, it is possible to argue that many subsequent phenomena relate to the magmatism and to the plume. Inversion structures within the deep Cretaceous depocentres such as the Ormen Lange Field (a major gas discovery) may have been formed or enhanced by plume-enhanced spreading during periods of high plume flux. Broad, widely-spaced Neogene uplifts on the margins bordering the NE Atlantic (e.g. Japsen & Chalmers 1999) appear to have mantle involvement and could have been formed by the rise of mantle diapirs related to the plume (Rohrman & van der Beek 1996). The uplifted areas acted as nucleation sites for ice caps during the Late Pliocene, and influenced the position of thick build-outs of glaciomarine sediments, which in turn governed the locations of massive slides and debris flows such as the Storegga Slide and Traenadjupet Slide. Thus, even the recent history of the NE Atlantic Margin may be linked by a chain of cause-and-effect to its development as a volcanic passive margin.

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