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The southeast Greenland Volcanic Rifted Margin: Nature of Breakup and Interaction with the Iceland Plume.

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The process of continental breakup is a fundamental component of the plate tectonic paradigm and the associated basin formation is an important target for hydrocarbon exploration. This common academic and industry desire to understand the breakup process has led to significant advances in the understanding of rifted margins over the last 1-2 decades. Primary data sets that have facilitated this progress include academic deep crustal studies, scientific ocean drilling, exploration drilling and geophysical mapping mainly by industry. The rifted margins of the Atlantic previously were considered type model for a breakup process developing over geological time from modest continental rifting through an East African Rift stage and eventually into continental separation and formation of normal oceanic crust. The surprising result is that very large parts of both South- and North Atlantic rifted margins seems to have developed quite different and in association with extreme igneous activity. A new class of rifted margins, the volcanic rifted margins, have been defined on the basis of these findings. And even more surprising, segments of almost entirely amagmatic rift development including tectonic exhumation of the mantle lithosphere are sometimes found close to volcanic rifted margins.

A key reference frame in which to understand the geodynamic aspects of volcanic rifted margin formation is the concept of hot mantle plumes impinging at the base of the continental lithosphere shortly before or during breakup. The prime natural laboratory for studying this type of margin formation has so far been the North Atlantic margins, primarily the margins along North-western Europe and East Greenland where the initial discoveries were made, but also the margins along the Labrador Sea and Davis Strait between North America and Greenland. The setting is quite ideal with the Iceland plume centered (almost) below the spreading ridge in Iceland and some clearly defined basement ridges (Faeroe-Iceland-Greenland Ridge, FIGR) tracking the plume history back to the time of breakup. The North Atlantic volcanic rifted margins north of the FIGR developed within rift settings with a late Palaeozoic through Mesozoic history of basin formation, and the resulting margin structure is, at least within the upper crust, quite different from areas where apparently only limited rift basin formation took place prior to rifting. With perhaps a few exceptions, petroleum exploration potential is related to these pre-breakup basins north of the FIGR; they have been affected more or less strongly by the igneous activity during breakup.

Running the risk, however, of the explorationists taking a break from the conference lectures this presentation will focus on the less prospective southeast Greenland margin where apparently only limited (middle-late Cretaceous) basin formation took place prior to breakup. This focus is not to demonstrate academic negligence of industry priorities, but reflects a desire to study the breakup process in its simplest possible setting in order to isolate and understand the basic geodynamic mechanisms operating during breakup. A further complexity about the more prospective region north of the FIGR is the mid-Tertiary relocation of the spreading from the now extinct Aegir spreading ridge between the Møre Margin and the Jan Mayen Ridge to a location north of Iceland. During this process the Jan Mayen Ridge, believed to be at least partly floored by continental crust, was torn off the central east Greenland margin by mid Tertiary northward propagation of the spreading ridge from the Iceland hotspot. Major half-graben formation, possibly with some hydrocarbon potential, took place along the central East Greenland margin and overprinted the initial breakup structure along this part of the margin. However, landward of this Tertiary basin formation and its major, coast-parallel boundary fault, a vast area of thick (6 km+) flood basalts, the East Greenland flood basalts, are exposed and accessible for detailed investigations allowing detailed correlation to the Faeroe Island basalts on the conjugate margin.

While flood basalts are a nuisance to hydrocarbon exploration in almost all regards, they are highly useful for offering high-resolution records of geodynamic events. No less so because our offshore seismic and drilling work including Ocean Drilling Program legs 152&163 allow us to tie this flood basalt province to the offshore margin structure from the Denmark Strait (i.e., the hot spot track) and southward along the entire southeast Greenland margin. The volcanic margin structure can be followed as far as just south of Greenland to the area of the former triple junction from which simultaneous spreading extended northward from the mid-Atlantic ridge and into the Labrador Sea (until ca. 40 Ma) west of Greenland and east of Greenland northward into the Norwegian-Greenland sea from ca. 56 Ma. During breakup off east Greenland around 56 Ma, the north-western ridge segment extending from this triple junction into the Labrador Sea operated as a non-volcanic to even magma starved rift: By contrast the ridge segment extending northeast between the East Greenland and Hatton Bank margins for 2-3 myrs was highly volcanic and thick (> 14 km) igneous crust formed from a subaerially exposed rift.

ODP drilling and a deep crustal seismic survey off south-east Greenland from the most plume centre distal location south of Greenland to the plume track proximal location within the Denmark Strait – a distance of more than 1000 km – show that along this margin: (1) close to normal thickness continental crust (i.e., ~30 km) with a velocity structure consistent with that of the Precambrian basement exposed along the coast is replaced seaward by thick igneous crust over a transition zone only 40-50 km wide; (2) the upper part of this igneous crust comprise 4-6 km thick sequences of seaward-dipping lavas of basaltic composition and subaerially erupted; (3) the maximum thickness of igneous crust is fairly constant around 18 km at offsets greater than ca. 500 km from the plume track and significantly thicker (28 km to likely more than 32 km) close to the hotspot track; (4) igneous crustal thickness along the hotspot track is quite uniform around 30 km+ and comparable to that of north-western Iceland; and (5) except for the region very close to hotspot track, subaerial (Icelandic type) spreading and formation of thick igneous crust is transient and limited to a period of only 2-4 myrs after final breakup. No significant underplating below the continental crust is resolved, and nearly all high velocity lower crust normally referred to as underplating can be interpreted as cumulus material within an entirely igneous (oceanic) crust.

There are basically two different mechanisms that can create igneous crust 3-5 times thicker than normal oceanic (igneous) crust. These are: (1) higher than normal asthenospheric mantle temperature; and (2) active asthenospheric mantle up-welling below the rift. The latter implies that the rate of vertically ascending asthenospheric mantle is in excess of the extension rates (half spreading rate) and therefore in excess of the accommodation space provided by plate separation. This has the effect that more asthenospheric mantle per time unit can ascend through the decompression melting zone than would have been the case by passive mantle up-welling, i.e., when vertical ascend rate equals half spreading rate. Passive mantle up-welling is generally believed to take place below mid-ocean ridges and has often been assumed to also characterize volcanic rifted margins. Assuming passive up-welling, excess mantle temperatures can be calculated to meet the excess igneous crustal thickness observed. In the case of the south-east Greenland margin, this leads to leads to estimates of excess temperatures in the plume mantle of between ca. 100°C (far offset, ca. 18 km thick crust) and ca. 250°C (plume proximal, 30-40 km thick crust), i.e., a temperature zoned plume head.

Anything else equal, such a strong temperature zonation within the plume mantle underlying the margin during breakup should result in a strong geochemical zonation within the erupted basalts. In short, increased geochemical depletion towards the plume centre should be seen as a result of the higher degrees of mantle melting required; this is because dilution of incompatible elements leaving the mantle peridotite during initial, low degree melting will take place. However, exactly the opposite is seen: Enriched basalts dominate the plume proximal regions (though we locally have identified depleted compositions as well), and the far offset regions (e.g., ODP Site 917 and 918) are characterized by depleted compositions. A few samples from the very most distal positions (e.g., DSDP sites 552-555) are in fact highly depleted. While a primary geochemical enrichment of the plume mantle in part may explain this enigmatic relationship, it seems far from able to provide a satisfactory explanation. Rather, it seems that pretty uniform, and not too high, excess plume mantle temperature (100-150°C) along the entire margin is much more plausible for a number of reasons. The excess igneous crustal productivity close to the plume centre compared to the distal margin setting is in this interpretation related to local, active mantle upwelling within the central feeder channel - the so-called plume stem.

From detailed flood basalt stratigraphy and high precision chronology we can estimate igneous productivity with time during breakup and compare this to the estimates made on the basis of igneous crustal thickness within the Denmark Strait and known spreading rates. The correlation is remarkably good (both indicate max. ca. 2000 km3 melt/myr/km rift length). Interestingly, detailed analysis of the velocity structure of the igneous crust within the Denmark Strait region show that its average (igneous) crustal velocity is only very slightly higher than that of the more distal margin with significantly thinner igneous crust. If indeed this highly excessive crustal thickness close to the plume track was caused entirely by high mantle temperatures and associated very high degree of melting, the gross crustal composition should be considerably more (ultra) mafic than the distal parts of the margin. Because the seismic velocity is sensitive to Si and Mg content (slower and faster, respectively) the average crustal velocity of the thick igneous crust along the plume track should be higher than it is. The non ultra-mafic nature of this plume proximal igneous crust indicated by this lack of a distinct crustal seismic velocity anomaly is also supported by estimates of the original melt composition for the flood basalts (i.e., before fractionation). Together with the geochemical zonation along the margin, there is therefore ample evidence for a combination of a more moderate excess plume mantle temperature and active up-welling (3-5 times) in the plume stem proximal location.

Identifying the exact time of breakup on the basis of either breakup unconformities or magnetic stripe zones in the oceanic crust adjacent to the continental margin at best provide low resolution constraints on the breakup process. Detailed studies and geochronology of the extensive basalt sequences erupted during breakup, however, hold potential for additional and higher resolution constraints. ODP site 917 provides the most compelling record of the breakup process so far recovered. A pre-breakup sequence of 61-59 Ma old basalts and more developed lavas overly pre-rift sediments (late Cretaceous?) and themselves underlies a thin sequence of highly Mg rich basalts (picrites) quickly translating into normal, (depleted) Icelandic type basalts of which the oldest are constrained to be 55.8 Ma old (very earliest part of magnetic Chron 24r). Examination of the flood basalts in the Faeroe region and in central East Greenland points at exactly the same time of breakup, i.e., 55.8 Ma. We can therefore conclude that breakup, within our resolution of a few hundred thousand years, was synchronous along large parts of the margin, perhaps along the entire margin. These results are consistent with data from ODP Site 642 on the outer Vøring Plateau off Norway, though age constraints here provide somewhat less resolution. But perhaps even more astonishing than a possible synchronous breakup along the entire margin, is the rate at which we find the continental lithosphere is indicated fail and rupture.

We asses the rate of rupturing from two independant sets of observations: (1) The influence on geochemical composition within the melts produced by the gradual removal of the lithospheric lid over the upwelling asthenosphere; (2) the effect on melt productivity by active plate separation. Both of these constraints suggests extremely fast rupturing of the lithosphere, in the order of 0.5 myrs or less from fairly intact crust and lithosphere (~100 km thick) to complete rupture and generation of new igneous crust. This suggests that the continent-ocean transition related to the final breakup is a very narrow zone primarily generated by magmatic dilation of a subvertical zone of lithospheric weakness, rather than a gradual, and over geological time, thinning of the crust and lithosphere by tectonic processes.

The fact that Iceland plume activity was present across the entire North Atlantic region as much as five million years before final breakup suggests that breakup, though supported by the presence of the plume mantle, was not directly caused by the dynamic impact of the mantle plume. It remains in part enigmatic, however, that: (1) plume head mantle can underlie a region more than 2000 km times 2000 km wide, from the British Isles to West Greenland/Baffin Island and from south of Greenland to north-east Greenland/Lofoten margin off northern Norway; and (2) at the same time, amagmatic rifting and spreading in the southern Labrador Sea along the south-west Greenland and very close to the south-east Greenland volcanic rifted margin can take place. However, recent modelling shows that if a model of a much more focused (< 500 km in diameter) plume head impact is combined with rapid lateral, buoyancy driven spreading of the plume mantle at the base of the lithosphere, lateral spreading of plume mantle along lithospheric thin spots can be highly effective as long only limited melting takes place. A consequence of this is that actively extending rifts like the one in operating in the Labrador Sea during plume impact at ca. 61 Ma in fact is very ineffective for distributing plume mantle because it effectively freezes due to melting. The pre-existing, but non-extending lithospheric thin spots (i.e., Mesozoic and older rifts) between east Greenland and north-western Europe, on the other hand provided highly effective channels at the base of the lithosphere along which plume mantle prior to final breakup was channelled to far offsets without major melting.

Emplacement of a more moderately sized, and less high temperature mantle plume spreading laterally below the lithosphere in a relative thin layer (50-100 Km?) is consistent with the apparent lack of large degree of regional uplift prior to breakup. Considerable margin uplift later took place. The amplitude, timing and cause of this, however, remain partly speculative.