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Volcanic rifted margin structure and development: A comparison between the NE Atlantic and western Australian continental margins

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Introduction

Continental rifting and breakup is often associated with voluminous volcanism. Volcanic processes and deposits may have a strong impact on the structure and geodynamics of continental margins and associated sedimentary basins. The identification of volcanic deposits and the evaluation of its impact on the margin history are thus two important aspects of the petroleum exploration along continental rifted margins.

The melt potential of the mantle is controlled by its composition, volatile content and temperature. Voluminous volcanism is often associated with a mantle temperature anomaly, possibly caused by a mantle plume. However, there is also a strong link between tectonics and volcanism, for example lithospheric rifting may cause decompressional melting. Magma formed by partial melting of the mantle may migrate towards the surface through a plumbing system. The melt may subsequently be emplaced as intrusive bodies near the crust-mantle boundary and within the crust, or it may be extruded at the surface.

We have studied volcanic deposits and processes along the western Australian and the NE Atlantic margins. These studies have focused on the identification, mapping and understanding of volcanic deposits and processes at shallow crustal levels where high-quality seismic data, potential field data, borehole data and field analogues provide us with detailed maps, 3D images and geological data that can be used to develop and constrain geodynamic models of scientific and exploration importance.

Imaging and Interpretation of Volcanic Deposits

The nature of volcanic deposits strongly depends on the eruption and emplacement environment. The presence or absence of water in both the eruption and the emplacement environment are of particular importance. In addition, the paleo-topography and the presence and structure of sedimentary basins may also have important impact on the construction of volcanic complexes.

The seismic velocity of extrusive volcanic deposits can vary from 1.5 km/s (water-saturated tephra layers) to more than 6.0 km/s (interior of massive basalt flows). Mafic intrusive bodies have normally higher seismic velocities, typically in the range from 5.0 to 7.5 km/s, depending on their composition, thickness and intrusive depth. The volcanic sequences may be homogenous (e.g, sheet intrusions), layered (e.g, subaerial basalt flows and foreset bedded volcaniclastic sequences), or chaotic (e.g, debris flows).

We have developed and used the concept of seismic volcanostratigraphy to study the nature, geological history and emplacement environment of extrusive volcanic rocks from seismic reflection data. This work has been complimented with 1) seismic time horizon interpretation; 2) seismic anomaly interpretation (high-amplitude and high-velocity units, disrupted seismic data in hydrothermal vent complexes, and deep crustal line segment interpretation); 3) integrated seismic, gravity, and magnetic (SGM) interpretation; 4) borehole studies; 5) fieldwork campaigns; 6) analytical geology; and 7) numerical modeling.

Extrusive Sequences

The central Norwegian Vøring and Møre margins are classical volcanic rifted margin segments. These margins where formed subsequent to continental breakup between western Europe and Greenland in the early Paleogene. The rift phase was associated with voluminous volcanism. The construction of the extrusive volcanic sequences on these margin segments can schematically be divided into five main stages:

Stage 1: Initial explosive volcanism in an aquatic or wet sediment environment forming basalt-sediment complexes.

Stage 2: Effusive subaerial volcanism, including coastal hydrovolcanic and sedimentary processes.

Stage 3: Continuing effusive subaerial volcanism infilling the rapidly subsiding rift basins along the incipient breakup axis.

Stage 4: Explosive shallow-marine volcanism.

Stage 5: Voluminous, effusive deep marine volcanism.

Even more voluminous volcanic complexes are identified landward of the Faroes. Here, subaerially erupted basaltic melts are interpreted as a > 5 km thick basin-filling sequence of hyaloclastites, interfingered volcaniclasitc and massive basalts, and a lid of subaerially emplaced layered basalt flows infilling a low-relief basin.

Extrusive volcanic sequences were also deposited during both the Callovian-Oxforian breakup and the Valanginian breakup episodes on the Australian NW Shelf. We have mapped extensive volcanic sequences along the eastern Argo Margin and on the Gascoyne and Cuvier margins. The seismic characteristics are similar to the ones imaged in the NE Atlantic. However, the Lava Delta seismic facies unit has not been identified regionally. The volcanic deposits on the Argo and Gascoyne margins are also generally thinner than in the central NE Atlantic.

Sheet Intrusions

Extensive magmatic intrusive complexes are mapped landward of the extrusive complexes. These complexes are particularly well imaged on margin segments with limited extrusive cover, e.g., in the Vøring Basin and on the Exmouth Plateau.

Classical saucer-shaped intrusions are found at shallow depths in unstructed basin settings both in the NE Atlantic and on the NW Shelf. The sizes of the saucers increase with increasing emplacement depth. New numerical models show that the saucer shape is caused by the development of stress anisotropy near the tip of the sills during the emplacement process. The geometry of the sheet intrusions is strongly modified by the basin geometry, where the intrusions tend to follow the trend of underlying structural highs.

The central Exmouth Plateau is one of the few volcanic rifted margin segments where it is possible to image the pre-breakup basin configuration almost all the way the continent-ocean boundary (COB). Here, it is worth to note that the intensity of shallow intrusions does not increase towards the COB. However, the thickness of the high-velocity lower-crustal 'magmatic underplated' body increases towards the breakup axis. Thermal and rheological modeling suggest that the underplated body may cause a transient shallowing of the brittle-ductile transition of about 5 km during a period of several million years after the underplating event.

Emplacement of shallow-level intrusions will lead to heating of pore fluids and metamorphic reactions, possibly leading to an explosive rise of fluids and fluidized sediments to the surface. Several hundred hydrothermal vent complexes have been mapped in the Vøring and Møre basins. One of them has been drilled. New geochemical and petrophysical data from this well shows a major thermal event in the latest Paleocene and indicates re-usage of the fracture system in the vent complex for later fluid migrating.

Similar vent complexes have been identified in the field (Karoo Basin), but presently not on the NW Shelf. However, high-amplitude seismic anomalies are identified above the tip of sill intrusion on the Exmouth Plateau, in a similar position as the hydrothermal vent complexes in the NE Atlantic. We argue that the seismic, field, and well observations show that fluid migration in volcanic basins is influenced by sill and vent complexes long time after their emplacement.

Rift Segmentation and Volcanism

The NE Atlantic can be divided into three main segments bounded by four major fracture zones or lineaments. The boundaries are defined by the Charlie-Gibbs Fracture Zone, the Fareo-Iceland-Greenland ridge, the Jan Mayen Fracture Zone, and the Senja Fracture Zone.

The central lineament, the Faroe-Iceland-Greenland ridge, is generally interpreted as the voluminous volcanic deposits formed along the Iceland Plume track. However, the ridge follows the trend of the major fracture zones in the NE Atlantic. A fracture zone has been suggested to be present along the ridge being related to offset between the adjoining Møre and Faroe margin segments. It is a general lack of high-quality data in this region, though, and it is thus difficult to identify and map any fracture zones on available data.

To the north, the thickness of the volcanic deposits decrease in the region southeast of the Jan Mayen Fracture Zone. Locally, no volcanic deposits have been identified on the Vøring Transform Margin. In contrast, the central Vøring Margin is an area with increased thickness of volcanic deposits, forming a well-defined marginal high. The thickness of breakup volcanic deposits gradually decreases towards the Lofoten Margin, where the entire volcanic extrusive sequence is interpreted as submarine deposits. Further north, no major volcanic deposits have been located along the Barents Sea Transform Margin except along the small rift segment associated with the Vestbakken Volcanic Province. The volcanic Yermak Plateau is finally located at the northern extension of the Barents Sea Transform Margin.

The western Australian margin reveals a similar segmentation as the NE Atlantic. The main fracture zones are the Wallaby-Zenith Fracture Zone and the Cape Range Fracture Zone. The transition between the Gascoyne and Agro abyssal plains is poorly defined. Furthermore, the classification of the Argo Margin segments is difficult. A north-northeast magnetic lineation direction has recently been published, suggesting that the northern Exmouth Plateau is dominantly a transform margin, whereas the Scott Plateau is dominantly located along a rifted margin segment.

There is none or limited thickness of volcanic rocks along transform margins both in the NE Atlantic and on the western Australian margin. We associate this decreased volcanic activity to a lower degree of lithospheric thinning during breakup and cooling of the oceanic lithosphere by the adjoining continental lithosphere during the drift phase.

Continental Crustal Fragmentation and Volcanism

Several major oceanic and marginal plateaus are found along the western Australian margin (Naturaliste Plateau, Wallaby Plateau, Zenith Seamount, Exmouth Plateau, Joey Rise, Scott Plateau) and in the NE Atlantic (Rockall Bank, Faroes, Iceland, Vøring Plateau, Jan Mayen Ridge, Yermak Plateau).

The origin of these plateaus ranges from certainly continental (Exmouth Plateau) to almost certainly magmatic (Iceland). However, our interpretations suggest that the plateaus are largely transitional in nature, consisting of continental fragments that are blanked and intruded by magmatic rocks. For instance, we interpret the Wallaby Plateau/Zenith Seamount complex as having a continental core based on new seismic data and dredge data.

Finally, the plateaus are spatially associated with major transform faults, e.g., the Wallaby-Zenith plateaus. We suggest that these plateaus were formed by rift propagation events possibly occurring prior to, during and/or after continental breakup. As an analogue, the Jan Mayen Ridge was likely formed during a rift propagation event and ridge jumping in the NE Atlantic.

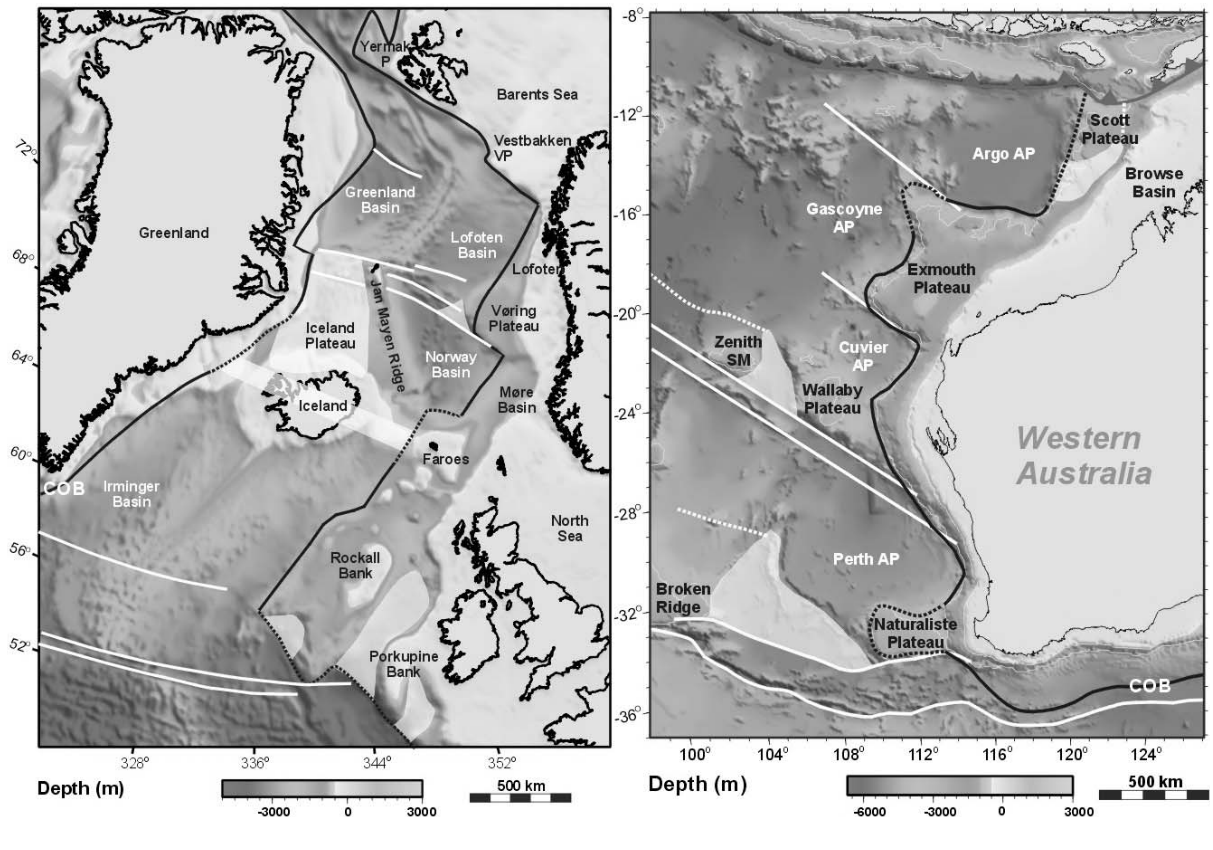

Figure 1. Bathymetry of the NE Atlantic (*left*) and western Australian (*right*) margins. Main fracture zones and structural boundaries are shown as white lines. Interpreted propagating rifts highlighted as white transparent areas. 0.5 and 2.5 km (*left*) and 0.5 and 3.0 km (*right*) depth contours shown.