

EUG XI



Symposium RCM2

The Formation of the Continent-Ocean
Boundary Zone: Structure and Processes

Convenor

Nick Kuszniir
Garry Karner

Wednesday PM Session

RCM2 : WEpm25 : F3
Cretaceous Ultra-Slow Spreading in the
Ocean-Continent Transition along the
Southwest Australian Passive Margin:
Constraints from ⁴⁰Ar/³⁹Ar Dating

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The mode and age of formation of the ocean-continent transition (OCT) of the non volcanic SW Australian passive margin is still a matter of debate, partly due to the difficulty of identification of the oldest magnetic anomalies along the margin. Samples of crystalline basement dredged during the Margau cruise (May 1998, R/V Marion-Dufresne) at the western end of the margin (between 108°E and 120°E) documents the nature, age and evolution of the oldest Australo-Antarctic Basin sea-floor.

The 11 dredge sites, located on basement structural highs in the 3 E-W oriented morpho-structural units that define the margin, have sampled rocks which consist, from north to south, of: (1) continental high-grade sheared metamorphic rocks on the continental slope, together with gabbros on the Naturaliste Plateau slope, (2) partly serpentinized plagioclase-bearing peridotites in a flat and sedimented 150 km-wide magnetic quiet zone (MQZ), and (3) a peridotite/gabbro/basalt assemblage in a rough 100 km-wide zone in the prolongation of the Diamantina Zone (DZ).

The evolution of the peridotites, and of the associated intrusive gabbros in the DZ, is compatible with an uplift under a rifted area. The peridotites are mainly poorly depleted lherzolites that locally underwent mylonitization before late serpentinization and fracturing in sub-surface conditions. The associated gabbros were submitted to a retrograde evolution with an extensional deformation in decreasing amphibolite to greenschist conditions. They are cut by magmatic intrusions expressed by locally ductily sheared hornblende, dolerite and basalt. ⁴⁰Ar/³⁹Ar dating was carried on amphibole and biotite single grains from five samples from two dive sites located on both sides of the Leeuwin Fracture Zone (LFZ). The results indicate that ductile deformation of the intrusives and their host rocks occurred between 87.4 ± 0.7 My (plateau age, 1σ) and 90 Ma. This deformation was sealed by later intrusions emplaced between 84.6 ± 0.5 and 84.3 ± 0.7 My.

Plateau ages of 508.2 ± 1.0 My (amphibole) and 507.7 ± 1.0 My (biotite) on high-grade gneisses from the continental slope confirm that these rocks well belong to the Australia craton, and that they stayed in the upper crust during the syn-rift remobilization on the margin. The plateau age of 494 ± 1.0 My (amphibole) from a gabbro of the Naturaliste Plateau indicates that the Plateau is made at least partly of pre-rift continental rocks.

The nature, evolution, and structural setting of the ultramafic and associated mafic rocks are compatible with a DZ formed during an episode of ultra-slow spreading, responsible for the exhumation of mantle and intrusive mafic rocks, around 88 Ma on both sides of the LFZ. The discovery of mantle rocks in the MQZ suggests that the continental breakup was older. A model of formation of the margin and the OCT is proposed.

RCM2 : WEpm26 : F3
Images of a Continent-Ocean Boundary:
A New Seismic Reflection and Refraction
Survey Offshore Newfoundland,
SCREECH Transect 1

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During July and August 2000, we conducted new deep seismic surveys (multichannel seismic and ocean-bottom seismometer) in three primary transects across the eastern Grand Banks to Flemish Cap margin. The transects were designed to determine margin structure reaching from full- or near-full-thickness continental crust across the continent-ocean transition to magmatically produced oceanic crust. The surveys are conjugate to detailed geophysical work and drilling on the well studied Iberia margin and thus will allow for interpretation of a complete non-volcanic rift system. In this abstract, we present data from the northernmost of three main transects, which is conjugate to the Galicia Bank portion of the Iberia margin. The transect crosses the full width of Flemish Cap from northwest to southeast and continues seaward into what is by all appearances magmatically produced oceanic crust. The Flemish Cap is a 60 km wide zone of ca. 30 km thick continental crust with maximum lower crustal velocities of 6.8-6.9 km/s that thins gradually seawards over 100 km. Where the crust first begins to thin, an unusually strong upper- to mid-crustal reflector is seen in the wide-angle data. A deeply subsided basement high capped by an isolated reflection sequence may be a submerged reef and marks a distinct change in the reflection character of the basement. From here to the seaward end of the line, a highly unusual velocity structure is seen with extreme lateral variability. First is an anomalous zone where velocities typical for upper crust are present, but velocities typical for lower crust are absent. This zone terminates seaward in a region with exceptionally high lower crustal velocities. This latter region is very likely a narrow (< 30 km) zone of serpentinized upper mantle confirming the amagmatic nature of rifting and final breakup here. The MCS data here show strong reflectors that may be shear zones related to unroofing of the lower crust and mantle like those that have been interpreted on the conjugate Iberia margin. At the seaward-most end of the transect we find what appears to be oceanic crust produced by mantle melting. However, the crust here has a velocity structure like that of oceanic layer 3 and there is only weak evidence for a layer 2. This crust is highly tectonized and has normal faults with several 100's of meters of throw.

RCM2 : WEpm27 : F3
A Regional Comparison of the Conjugate
Ocean Continent Transitions of the
Newfoundland Basin and Iberia Abyssal Plain

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Extensive geophysical investigations of the Iberia Abyssal Plain (IAP) and Newfoundland Basin (NB) non-volcanic margins allow us to contrast the full structure of their conjugate ocean-continent transition zones. For the first time we will be able to analyze a number of conjugate profiles within the context of the complete regional variability of the OCT. Recently, three deep multichannel reflection (MCS) and refraction transects were shot in summer 2000 across the northern NB from full thickness continental crust of the Grand Banks and Flemish Cap to oceanic crust seaward of magnetic isochron M0. These profiles form conjugate sections with reflection-refraction profiles previously shot across Galicia Bank and the IAP.

This paper will present the geophysical framework of the NB OCT using gravity, magnetic and depth-to-basement maps compiled from the previous datasets. These maps will be used to position the new MCS and refraction profiles with respect to major structural trends, and to contrast these

boundaries with similar images from recent studies of the IAP and Galicia Bank. Specific properties of the OCT that emerge from this comparison are: (1) OCTs are characterized by landward zones of rifted continental fault blocks and seaward zones of subdued basement topography. The seaward zones both decrease in width from south to north, but the nature of the basement reflectivity within these zones is quite distinct. In the NB, a strong reverberative reflection 'U' covers most of the basement; while 'U' is completely absent in the IAP. (2) Magnetic lineations exist within both OCTs but are very weak and difficult to correlate for isochrons older than M0-M3. A strong magnetic J-anomaly exists in both basins, but for the NB it terminates much farther south than in the IAP relative to their plate-reconstructed positions. (3) Gravity anomalies in both OCTs show some features clearly related to major basement structure. However, unique features of the NB not found on the Iberia margin are a series of gravity lows related to major rift basins that bound the continental blocks, and a regional gravity high within the OCT. (4) Depth-to-basement in the Newfoundland basin is systematically shallower than in the Iberia basin. Heat flow values off Iberia are normal for its age, while preliminary analysis of new measurements in the NB suggest up to 20% higher values. (5) Results of ODP boreholes have been important to understanding basement structures off the Iberia margin, but are still absent in the NB. Future drilling efforts to penetrate basement in the NB and sample syn-rift sequences will be of great importance.

Unique geophysical anomalies exist along each of the three main transects. Thus the OCT is quite variable in detail and cannot be described by a single two-dimensional section. To understand how these complexities are formed will be a significant challenge.

RCM2 : WEpm28 : F3
Microstructures and Differential Stress
Estimates at an Active Low-Angle
Detachment Fault (Moresby Seamount-
Offshore Papua New Guinea)

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Drilling east of the Papuan Peninsula (ODP Leg 180) was performed to increase understanding of the mechanics and kinematics of a low-angle normal fault situated in a transition zone between oceanic spreading and continental rifting. In seismic profiles the fault plane is traceable to a depth of 9 km below the strongly asymmetric sediment-filled rift basin. Moresby Seamount is the uplifted footwall to the detachment dipping with 28° to the north. The northern flank of the submerged seamount downwall depicts the outcrop of the fault plane until it is covered by a thick sequence of synrift sediments (Taylor et al. 1999).

Recovered drillcores show hangingwall sedimentary rocks and footwall basement rocks which display a broad range of deformation fabrics resulting from relative movement of the fault blocks along the detachment's plane. Besides the main detachment, an antithetic normal fault and further minor fault zones were sampled. Hangingwall deformation is exclusively brittle with a variable and lithology-dependent number of extension- and shear fractures. Footwall rocks are far stronger affected by deformation and show a transition from ductile to brittle deformation fabrics to depth. Overprinting relationships result of temporal and spatial uplift of the footwall rocks and presumably simultaneous passing the ductile-brittle transition zone.

Palaeopiezometric methods were applied to calcite and quartz minerals filling a vast number of vein populations in the vicinity of the major and minor fault zones. Using Jamison & Spang's (1976) palaeopiezometer for twinned calcite, differential stresses range from 22 to 62 MPa. At least for the hangingwall this corresponds to calculated values resulting from simple lithostatic overburden. Data evaluated from recrystallized quartz grains was treated with different piezometers. However, among the conventional calibrations, the one of Koch (1983) should provide best values for flow stresses in naturally deformed rocks, as both data from dry and wet experiments were involved in determination of the equations and the constants. The values for the stresses vary between 100 and 200 MPa indicating a great depth and a high strain rate during the generation. Examination of recrystallized quartz domains under the TEM provided insight on submicroscopic scale. Intracrystalline structures reflected by arrangement of

dislocations are strongly heterogeneous indicating a complex deformation history of hot and cold worked quartz ending with a phase of recovery.

Jamison WR & Spang JH, *Geol. Soc. Am. Bull.*, **87**, 868-872, (1976).

Koch PS, *Rheology and Microstructures of experimentally deformed quartz aggregates*; PhD dissertation; Univ. of Los Angeles, pp 464, (1983).

Taylor et al, *Proceedings of the ODP; Initial Reports*, **180**, (1999).

RCM2 : WEpm29 : F3

Detachment Faulting, Mantle Serpentinization, and Serpentinite Mud Volcanism beneath the Porcupine Basin, SW of Ireland

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Axial stretching factors deduced from subsidence within the Porcupine Basin SW of Ireland increase gradually from values typical of the North Sea (c. 1.5) to those associated with rifted margins adjacent to the continent-ocean transition (greater than 6). As such, a study of the three-dimensional structure of the basin provides an opportunity to study processes that occurred during continental breakup. Furthermore, unlike many conjugate margin pairs, both sides of the rift are easily accessible during one survey and there is no uncertainty about the pre-drift configuration. Thus the Porcupine Basin allows investigation of the symmetry of rifting at stretching factors approaching continental breakup. Industry profiles across the basin image a bright reflection within the basement that appears to act as a detachment to overlying faults. This structure may in part be a decollement at the top of partially serpentinized mantle. Although overall the basin appears symmetric, the consistent westerly structural dip of the detachment implies that at high stretching factors extension was asymmetric. Further south, the 'Porcupine Median Volcanic Ridge' overlies apparent tilted fault blocks and is overlain by postrift sediment. Despite no evidence for synrift magmatism, this has previously been interpreted as a basaltic structure. However, it may also represent a serpentinite mud volcano or diapir: such features may produce the serpentinite breccias found within the rifted continent-ocean transition of non-volcanic margins. Based on the observations from the Porcupine Basin, we present an evolutionary model for the formation of the continent-ocean transition at non-volcanic rifted margins such as West Iberia.

RCM2 : WEpm30 : F3

Serpentinisation and Magmatism during Extension at Non-Volcanic Margins – The Effect of Initial Lithospheric Structure

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At several non-volcanic margins serpentinized peridotites occur within a wide continent-ocean transition (COT) and beneath the edge of the thinned continental crust. However, other margins such as the Woodlark Basin appear to have a sharp COT and no reported serpentinities. We investigate the thermal, magmatic and rheological evolution of margins during extension as a function of initial lithospheric structure, rift duration and stretching factor. For cratonic and old orogen models, the entire crust should become brittle at stretching factors c. 3-4. The resultant crust-cutting faults allow water to reach and serpentinize the mantle, leading to the development of serpentinite decollements at the crust-mantle boundary and exhumation of mantle at the COT. Our predictions are consistent with the spatial limit and thickness of serpentinities at the SW Greenland, W Iberia margins and the Rockall Trough. They also explain the absence of a broad zone of unroofed, serpentinized mantle at the COT of the Woodlark Basin: here the crust was too thick and hot for serpentinities to form prior to breakup. Larger melt production than in the W Iberia type margins and concentration of the lithospheric strength in the crust leads to synchronous crustal separation and lithospheric failure, yielding a sharp COT.

RCM2 : WEpm31 : F3

Evolution of a Magmatic Passive Margin: The Red Sea Escarpment, Ethiopia

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The transition from continental stretching to pre-seafloor spreading is exposed at the western Escarpment of the southern Red Sea volcanic margin in Ethiopia. The faulted and rotated volcano-sedimentary strata show the change from border faults to a new magmatically-controlled along-axis rift segmentation. The pre-rift flood basalts and syn-rift basalts provide a time record of deformation along the margin. This locality provides an ideal test of models for break-up above mantle plumes, and for the generation of seaward-dipping reflector sequences. New SCLF ⁴⁰Ar/³⁹Ar dates provide constraints on the timing and duration of rifting, and the rates and volumes of volcanic extrusions. The southern Red Sea rift is bounded by an eroded fault scarp with Oligocene pre-rift flood basalts cut by border fault segments defining dip and stratigraphic domains. Landsat-7 images show the along and across strike fault-controlled segmentation of the Miocene Red Sea rift, and fault intersections provide a relative chronology of faulting. Field studies along transects of the previously unexplored margin allowed us to calibrate structural and stratigraphic interpretations of imagery. Segments were delineated from border fault geometry and displacement and continuity of volcanostratigraphic units. These 30-35 km-long border fault segments and rift architecture are characteristic of mechanical (border fault) rift segmentation seen in continental rifts worldwide.

Within the hangingwall to the border faults, we found a new, magmatic along-axis segmentation defined by a 50 km-wide strip of riftward-dipping volcanic strata analogous to seaward-dipping reflectors (SDRs) on magmatic margins. These magmatic segments unconformably overlie the flood basalts, and mark a later stage magmatic overprinting of the border fault segmentation. The sub-aerial preservation of the 'SDR' province indicates either a) they developed on stretched and intruded continental crust prior to break-up or b) they mark a failed mid-ocean ridge that was abandoned in Mid-Miocene time. Plate kinematic reconstructions will allow us to distinguish between the two models.

RCM2 : WEpm34 : F3

New K-Ar Constraints on the Silicic Volcanism in Central Afar, its Implications in the Rifting Process

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The Afar depression is a triple junction characterised by thinned continental crust, where three rift systems merge (Red Sea, Gulf of Aden and East African Rift). About 100 new K-Ar ages (Cassignol/Gillot technique) and geochemical analyses on Plio-Pleistocene lavas allow us to detail the volcanic activity in Afar. Our data reveal a clear evolution through time in relation with rifting. For the last 3 Myr, intense fissural volcanic activity causing the emplacement of the trap-like 'stratoid series' was more and less continuous. It now covers most of the depression, except the presently active rift segments. Through time, from Stratoid Series volcanism to rift segments one, contribution of depleted mantle increase producing more and more tholeiitic magma. New ages enhanced the correlation between the rhyolitic volcanism and the Red Sea and Aden continental rift zones initiation: Silicic activity mainly occurred during two phases, 1.3 and 0.6 Myr ago before each stage of rift propagation inside Afar depression. Furthermore, at a ridge scale as at a small rift segment one, silicic lavas are systematically older than the basaltic ones. Evolved lavas were erupted at the axis of a future rift segment prior to the main extensive phase when basaltic fissural activity develops. This explains why elements of silicic centers are presently located on the both sides of active rift. They seem to be a necessarily precursor feature. After that, the extension increasing, magma was directly erupted from the source to surface as basaltic lava without differentiation

process occurring. Differentiated volcanoes (and magma chambers associated) considered as zones of local weakness, would allow the development of fractures which generate then fissural magmatism. This mixed system of rifting, including volcanic and tectonic components can be compared to the continental break-up, including also active component (hot spot) and passive one (regional stress).

RCM2 : WEpm35 : F3

Continent-Ocean Boundary, Breakup Magmatism, and Segmentation along the Lofoten-Vesterålen Volcanic Margin off Norway

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The narrow and steep Lofoten-Vesterålen volcanic margin is a distinct margin province contrasting with adjacent provinces in terms of basement level, sediment cover and history of vertical motion. It also exhibits a well-defined along-strike structural segmentation. It includes three segments separated by Late Jurassic-Early Cretaceous transfer zones which have in turn pre-determined the location of early opening (early Eocene) fracture zones. A significant along-margin change in style and volume of the breakup magmatism occurs at the Bivrost Fracture Zone/Lineament at the transition between the Voring and the Lofoten-Vesterålen margin provinces. The Lofoten-Vesterålen margin is characterized by: (1) absence of a typical marginal high bounded landward by a major escarpment; (2) breakup lavas covering almost the entire continental slope and terminating near the shelf edge; (3) less prominent, and shallower seaward dipping reflector (SDR) seismic images without the typical wedge-like pattern observed on the Voring margin; (4) considerably reduced amount of sill intrusions; and (5) decrease in the thickness and volume of the 7+ km/s lower crustal body. The lavas, which inhibit seismic resolution below, preclude a clear seismic definition of the continent-ocean boundary (COB). Nonetheless, several structural lineaments are observed near the foot of the slope. In the south, a lava front-like feature or a small-offset fault scarp is mapped just east of small wedges of SDRs and the oldest sea floor spreading anomaly, 24B. Further north, the feature changes character and moves to the east. In particular, it changes dip polarity and is replaced by a west-dipping fault bounding SDR-like images. We place the COB along a weak magnetic gradient change between these structural lineaments and anomaly 24B. Thus, the COB is restricted to a <10-km-wide zone. The narrow lava-covered, and progressively northward steepening, continental slope suggests rapid initial post-opening margin subsidence to bathyal depths. We ascribe the difference in margin subsidence on either side of the Bivrost Fracture Zone to changes in crustal properties related to: (1) breakup in relatively thick crust on the eastern flank of the Cretaceous basin region between Norway and Greenland; and (2) diminishing melt potential with distance from the Iceland Plume. Hence, the Bivrost Fracture Zone and its landward structural prolongation constitute a barrier for breakup melts emplaced as high-velocity lower crust and intrusives farther south.

RCM2 : WEpm36 : F3

Petrophysical-Petrologic Interpretation of Thick Igneous Crust at the Continent-Ocean Boundary of NW-Namibia

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Two recent onshore-offshore seismic transects across the Namibian passive margin show that the continent-ocean boundary is extremely abrupt, with a thick body of material of high seismic velocity ($V_p = 7.1 - 7.6$ km/s) abutting the continental crust. We interpret this material as basaltic igneous crust. To better understand the nature of this material and the process which formed it, we attempt to constrain the bulk chemical composition of the high-velocity crust by comparing its seismic velocity with a series of model basalts derived from experimental studies of peridotite melting. Observed seismic velocities in the igneous crust are consistent with basaltic material with about 14-18 wt.% MgO. This conclusion renews of

cumulate minerals because it integrates over the full thickness of the body, however the highest V_p -values of 7.6 km/s are consistent with the velocities expected for cumulate minerals produced by fractional crystallization of the 14-18% MgO parental melt. The subsolidus growth of garnet is unlikely to be a significant factor for the crustal velocity above the Moho depth of 30 km. In fact a magnesium-rich basaltic crust can be expected to limit the crustal thickness to about 30 km because bulk densities at deeper levels may exceed those of the peridotite mantle. The relationship between MgO of partial melts and potential temperature of a fertile peridotite source suggests that the estimated 14-18 wt.% MgO basalts were generated from mantle at about 1440°C-1560°C potential temperature, which may be a good estimate for the potential temperature of the ancestral Tristan mantle plume at the Namibian margin. The igneous crust has the greatest volume, the highest inferred MgO contents and mantle potential temperatures at the location of the northern transect, which is closest to the Walvis Ridge hotspot trace. Mantle potential temperature estimated for the southern transect is 50-100°C lower, suggesting cooling of the plume material during its flow southwards.

RCM2 : WEpm37 : F3 Petrogenesis of the Palaeogene Sorgenfri Gletscher Sill Complex at the East Greenland Volcanic Rifted Margin

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Sorgenfri Gletscher Sill Complex is intruded in the Mesozoic-Palaeogene Kangerlussuaq basin and the Palaeogene Lower Basalts. The sills have an estimated accumulated thickness of more than 1200 m that leads to a possible addition of 20% to the volume of the coeval flood basalts. The sills have been divided into four geochemical groups, none of which show signs of contamination. The most common, the main dolerites, and the low-silica dolerites are both evolved low-pressure fractionated microgabbros. The main dolerites have 48.60-52.75 wt% SiO₂, Nb=6-18 ppm and La/Sm_N=1.32, while low-silica dolerites have 45.98-48.59 wt% SiO₂, Nb=13-27 ppm, and La/Sm_N=1.84. Groups of olivine accumulative Mg-rich dolerites with >10 wt% MgO and La/Sm_N=1.11 and of alkaline dolerites with 42.31-60.26 wt% SiO₂ and La/Sm_N=4.50 are also defined.

Differences between the main dolerites and the low-silica dolerites are explained by melting models. Modelling of Nb-Zr-Y indicates that the main dolerites were formed from c. 10% melting of garnet-lherzolite and c. 1-3% melting of spinel-lherzolite, whereas the low-silica dolerites were formed by c. 5% melting of garnet-lherzolite and c. 1-2% melting of spinel-lherzolite. Possible correlations have been made to the lower Milne Land Formation and the Røsselashmer Fjord Formation flood basalts for the main dolerites and the low-silica dolerites respectively, although the relatively modest degrees of melting in the spinel-lherzolite field are slightly different from models proposed for the contemporaneous flood basalts.

The close temporal, spatial, and geochemical relationships of Sorgenfri Gletscher Sill Complex with the flood basalts indicate that they were part of the same melting and plumbing system. Because of differences in the melting models and the absence of internal magmatic contacts in the sills it is unlikely that the sills acted as low-pressure fractionation chambers for the flood basalts.

RCM2 : WEpm38 : F3 ⁴⁰Ar/³⁹Ar Dating and Geochemistry of Taoudenni Basin Dikes (North Mali): Further Constraints for the Duration and Emplacement Process of the CAMP Related to the Central Atlantic Rifting

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Taoudenni sedimentary basin is located within the West African craton, 1000 km from the western African margin. Complex mafic dike swarm and related sills were injected mainly into carboniferous sedimentary rocks, often covered by quaternary sands. Dike length ranges from two to fifty kilometres. Seven dikes of approximately NW-SE trending group, 3 dikes of approximately E-W trending group, and 3 sills (two of them originate from a drilling) were analysed. All the dolerites are tholeiites similar to low-Ti CFBs. Two sub-groups differ from their Ti contents and LREE/HREE ratios, but they are isotopically indistinguishable. The enriched group belongs mainly to E-W trending dikes. ⁴⁰Ar/³⁹Ar step-heating method was performed on transparent grains of plagioclase (100 - 200 µm) separated from dike and sill samples. Age spectra show that Taoudenni tholeiites are unaffected by argon loss or excess argon. Age spectra yield plateau ages, which agree with isochron ages, clustering (1) from 194.0 ± 2.2 Ma to 197.9 ± 3.8 Ma, except for one dike at 187.6 ± 3.4 Ma (lower-Ti and mainly NW-SE trending group), and (2) from 196.8 ± 1.4 to 200.9 ± 2.5 Ma (higher-Ti and approximately E-W trending group). Sill Ar-Ar results display plateau ages from 197.7 ± 2.2 Ma to 201.1 ± 2.4 Ma. Duplicate analyses on sill sample give 198.5 ± 1.4 Ma and 198.3 ± 1.5 Ma. Taoudenni Ar-Ar ages are considered as emplacement ages, regarding Ca/K ratios (deduced from ³⁷Ar/_{Ca}/³⁹Ar_K) that are not related to secondary alteration phases. These ages are younger than a Taoudenni previous data of 203.7 ± 2.7 Ma (Sebai et al., 1991). However, these ages (except one younger data) are in accordance with previous dating obtained throughout the CAMP province (Sebai et al., 1991; Deckart et al., 1997; Marzoli et al., 1999; Hames et al., 2000). The geochemical variations fit those observed in the main part of the lava pile filling rift basins in Morocco, which gave similar ages. These results indicate that the dense dike swarm from Taoudenni basin belongs to the CAMP province. This is an additional evidence for the brevity of CAMP magmatism over a gigantic spatial extent, including areas far away from the continental margins.

Sebai A, Féraud G, Bertrand H & Hanes J, *Earth and Planetary Science Letters*, **104**, 455-472, (1991).

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Wednesday PO Session

RCM2 : WEpo01 : PO Three-Dimensional Structure of the S Reflector, West of Galicia

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The S reflector west of Galicia is thought to be a detachment fault active during rifting leading to final crustal separation and breakup at the west Galicia rifted margin. It is a gently-dipping bright positive polarity reflection, onto which the overlying block-bounding faults appear to detach. Using a combination of old MCS data and more recent data collected a cruise with the RV Maurice Ewing during 1997, we have studied the 3-D geometry of the S reflector. Through the use of iterative prestack depth migration, coupled with depth-focussing error analysis between iterations, we have built up a detailed velocity model above S and hence depth image of the structure along a series of dipline profiles. These have allowed us to map out the S reflector in depth. The improved images have also clarified its relationship to other structures of the margin, such as the overlying fault blocks and the Peridotite Ridge further to the west. S does act as a detachment to the overlying fault blocks and appears to cut down to the west from a breakaway in the east. It intersects and subsequently follows the crust-mantle boundary (CMB), making it likely that over much of its extent, the S reflector follows a serpentinite decollement within the upper mantle. However, there is no convincing evidence that S cuts up towards the west to the flank of the Peridotite Ridge as has been proposed by some.

RCM2 : WEpo02 : PO Ocean-Continent Transition off SW Iberia, Images from a Deep Multichannel Seismic Profile

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The aim of this contribution is to describe the structure of the ocean-continent transition (OCT) at a non-volcanic rifted continental margin. Here we present a deep multi-channel seismic reflection profile acquired across the Horseshoe Abyssal Plain (offshore SW Portugal) in 1992 and re-processed at Geomar in 1999, by means of the pre-stack depth migration algorithm, to enhance the presence of several steepen and straight-line landward-dipping reflectors.

This seismic profile provides a good image of the basement across the likely location of the ocean-continent transition in the Southwestern Iberian continental margin. There are two major hypotheses so far proposed for the origin of the thin crust within the OCT: such crustal type could have originated by either exhumation of upper mantle material during rifting of continents or by slow seafloor spreading. There are some examples, constrained by ODP drilling, showing the widespread occurrence of serpentinitized peridotites within the OCT in the Northwestern Iberian margin. Geological features here found resemble the same morphology of the OCT supposed to be present in our seismic profile.

A broad zone of highly contrasting basements highs containing major landward-dipping reflectors and minor seaward-dipping reflectors suggests the presence of peridotite ridges related to the last rifting stage of the margin. Three of the landward-dipping reflectors are located along the flanks of basement highs and from the top of the basement they reach a depth of more than 11 s TWT. We interpret these high reflections as landward detachments, in the

sense of shear surfaces, formed during the exhumation of the upper mantle which drives to the emplacement of the peridotite ridge within the OCT.

West of the presumed peridotite ridges the basement relief becomes less irregular, but a large number of landward-dipping reflectors is still visible in the deep basement compared to a very limited number of oceanward-dipping reflections. We suggest that this crustal structure could represent a wide zone of serpentinized peridotites or alternatively oceanic crust, characterized by the presence of atypical landward-dipping reflectors.

RCM2 : WEpo03 : PO Crustal Structure across the Continent-Ocean Transition on the Newfoundland Nonvolcanic Rifted Margin at SCREECH Transect 2

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The Newfoundland-Iberia conjugate rifted margin pair provides an excellent area to study the evolution of nonvolcanic rifted margins. We present initial reflection/refraction seismic results from one of three major crustal transects acquired during the SCREECH survey, a joint U.S.-Canada-Denmark study of the Newfoundland rifted margin. Transect 2, the central transect of the survey, occupies a position conjugate to a heavily studied segment of the Iberia margin, which includes drilling on ODP Legs 149 and 173. Transect 2 extends from continental crust at the western margin of Flemish Pass basin southeast across rifted continental crust, 'transitional' crust of unknown origin, and about 60 km onto known oceanic crust seaward of magnetic anomaly M0. High-quality reflection and refraction data were acquired, including 60-fold seismic reflection data acquired on the R/V Ewing's 6000-m, 480-channel streamer, and wide-angle data acquired on 25 ocean-bottom seismic instruments deployed from the R/V Oceanus. Basement structure across the transect shows three major domains: (1) a zone of continental crust characterized by block-faulted basement and common lower-crustal and Moho reflections, (2) a 90-km-wide zone of enigmatic origin showing smooth, featureless basement beneath the 'U' reflector, and (3) a wide zone straddling M0 showing strong basement relief (> 1.5 km) and frequent intracrustal reflections that dip more often landward than seaward; this zone is similar in appearance to the serpentine ridges drilled on the Iberia margin. A strong landward-dipping reflector at near-Moho depths separates zones 1 and 2; similar reflections elsewhere in the region have previously been interpreted as marking the continent-ocean boundary. Preliminary velocity analysis shows that a 3-km-thick crust of average velocity ~5.5 km/s beneath the U reflector, underlain by a boundary across which velocity increases sharply to 8.0 km/s. The smooth basement and velocity of this crust are consistent with its being upper continental crust, though at this stage we cannot rule out oceanic crust or serpentinite.

RCM2 : WEpo04 : PO Detailed Structure of the Complex Continent-Ocean Transition Northeast of Newfoundland

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The rifted continental margin northeast of Newfoundland is characterized by a wide zone of thinned and extended continental crust, the Orphan basin. The continental crust here is as little as 10 km thick, but shows no evidence of volcanism or magmatic underplating. Seaward of Orphan knoll, a small continental fragment, basement drops sharply, marking the termination of continental crust and the start of the continent-ocean transition. A detailed seismic refraction study of this transition zone was carried out using airgun source and ocean bottom receivers. Several intersecting profiles were shot, both along and across strike. Beneath the known continental crust, a well defined mantle velocity is present, but to seaward, the velocity structure appears to be complex, and is dominated by lower crustal velocities in

the range 6.8-7.2 km/s, which are interpreted as serpentinized peridotite, as on other nonvolcanic margins. The variable velocity structure is believed to be due to variations in the degree of serpentinisation. The serpentinisation appears to be strongest immediately seaward of the termination of continental crust, and in this region there is a basement high, which is interpreted as a peridotite ridge, as seen on the Iberia and Galicia margins.

Here, as elsewhere, it is not possible to determine by seismic methods alone whether and to what extent exhumed mantle is present. However, there is some evidence that at least a thin igneous layer may be present. First, there is a well defined discontinuity, seaward of the immediate transition, between the upper 2 km of lower-velocity crust and the underlying 7.2 km/s material. Second, well defined magnetic anomalies are present near the transition, suggesting the presence of significant igneous crust, in contrast to the weak magnetic signature of the transition zones at, for example, the Iberia, Newfoundland, and Labrador Sea margins.

RCM2 : WEpo05 : PO A Comparison of Seismic Reflection Profiles Across the Newfoundland Basin and Southern Iberia Abyssal Plain Conjugate Margins

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We present a 580-km-long multi-channel seismic reflection (MCS) profile, NFB-3, across the Grand Banks-Newfoundland Basin ocean-continental transition (OCT), acquired in summer 2000 as part of the SCREECH (Study of Continental Rifting and Extension on the Eastern Canadian Shelf) program. This profile covers the complete sequence of a fully evolved non-volcanic margin, from full thickness continental crust NW of Jean d'Arc Basin, thinned continental crust beneath the E. Grand Banks, the OCT in the Newfoundland Basin, to known oceanic crust near the Newfoundland seamounts. Our objective is to compare these structures with observations on transect IAM-9 across the Southern Iberia Abyssal Plain, which lies in roughly conjugate position.

On the Newfoundland profile NFB-3, the zone of thinned continental crust, which comprises a series of large tilted fault blocks bounded by seaward dipping listric faults, extends ~70 km from the shelf edge. The OCT further seaward is characterized by basement with muted topography ~150 km wide. Normal oceanic crust starts where basement becomes elevated seaward, associated with the high amplitude magnetic J-anomaly ridge. These general observations are similar to those of IAM-9 on the Iberia margin, where tilted fault blocks are observed up to 60 km from shelf edge and a zone of muted basement ~120 km wide is interpreted as exhumed and serpentinized mantle. However, these two profiles are different in detail within these zones. The observed province of complex ridges landward of the J-anomaly on IAM-9 is absent on NFB-3. A strong basement capping sedimentary reflector ('U-unconformity') is observed over the entire OCT on NFB-3 but not on IAM-9. This reflector terminates towards the seaward boundary of the OCT with oceanic crust. On NFB-3, the seaward half of the OCT is a distinctive region with a continuous sub-horizontal mid-crustal reflector but an absence of clear basement reflection beneath 'U'. Sub-horizontal reflectors are absent on IAM-9 but the basement is well defined within the OCT. On the landward half of the OCT along NFB-3, basement morphology is better defined as a series of highs and may potentially be a seaward continuation of extremely thin continental crust. A large, shallow fault block, associated with a local gravity high, is observed beneath the continental slope. This fault block creates a deep basin beneath the slope, whereas slope basins with comparable size are not observed on IAM-9. Based on the above observations, we conclude that

although these conjugates seem to be symmetrical in gross scale, differences within structural zones, especially the OCT, imply that processes by which these zones were created may be very different across the conjugates.

RCM2 : WEpo06 : PO Depth-Dependent Lithosphere Stretching, Mantle Exhumation and the "Upper Plate" Paradox at Rifted Continental Margins

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Extension estimates determined from upper crustal faulting, whole crustal thinning and post-rift thermal subsidence show that depth-dependent stretching of the continental lithosphere is a consistent observation for the outer ~100 km of rifted margins. Upper-crustal extension is significantly lower than estimates of whole crustal extension or whole-lithosphere thinning. Depth-dependent stretching cannot be explained by sub-seismic resolution faulting, aseismic extension, second generation faulting or lithosphere simple shear. Paradoxically all rifted margins appear to be "upper plate" in terms of detachment models (Driscoll and Karner, 1998). Both analytical and finite-element models of early sea-floor spreading generate depth-dependent stretching of rifted continental margin lithosphere. Depth dependent stretching models also predict that continental mantle is pulled out from beneath the continental crust during early sea-floor spreading, exposing continental mantle at the surface. Exhumation of continental mantle at rifted margins is independently supported by wide-angle seismology, direct sampling, geochemical analysis, magnetic anomalies, and orogenically exhumed rifted margins. We propose that depth dependent stretching and mantle exhumation at rifted margins are inevitable consequences of early sea-floor spreading rather than pre-breakup rifting, and occur symmetrically on both conjugate margins so explaining the "upper plate" detachment paradox.

RCM2 : WEpo07 : PO Loss of Lower Crust and the Nature of the Continent-Ocean Transition, the South China Margin

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The South China Sea and associated passive continental margins (South China Shelf, Palawan/Dangerous Grounds and Nan Con Som Basin) form a classic example of break-up within a juvenile continental arc crust environment. One-dimensional backstripping of wells under the South China Shelf shows that crustal extension exceeded that in the mantle lithosphere prior to break-up. In contrast the intra-continental Beibu Gulf Basin, isolated from the continent-ocean boundary, had a more uniform style of deformation. Crust and mantle extension varied in phase, suggesting depth-dependent extension rather than a lithospheric-scale detachment. Estimates of total crustal extension derived in this way are similar to those measured by seismic refraction methods (Nissen et al., 1995), indicating that isostatic compensation is close to being local (i.e., $T_e < 5$ km). In addition, extension under South China Shelf continued for at least ~2 m.y. after the onset of seafloor spreading, an observation that also suggests a weak continental lithosphere. Two-dimensional flexural modeling was used to study crustal extension along interpreted multi-channel seismic profiles across the South China Shelf east of Hainan Island and on the conjugate Palawan margin. The lower crust is estimated to have extended more than the upper crust and mantle lithosphere during break-up, an effect that become more pronounced towards the continent-ocean transition (COT; Clift et al., in press). This material must have travelled in a basinward direction, where it is predicted to be incorporated into the oldest oceanic crust. The COT and the central Pearl River Mouth Basin, within the South China Shelf, are marked by localized submarine volcanism despite the degree of extension being modest (cf. Bown and White, 1995). This observation suggests the lithosphere was not in thermal equilibrium prior to extension. Elevated mantle temperatures are not considered likely because of the lack of seaward dipping volcanic sequences and the presence of deep water sediments in the rift axis (ODP Site 1148) at the point of break-up. The

RCM2

The Formation of the Continent-Ocean Boundary Zone

timing of major extension is broadly mid-late Eocene (~45-30 Ma), but is impossible to correlate in detail with poorly dated strike-slip deformation in the Red River Fault Zone.

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RCM2 : WEpo08 : PO The Structure of Volcanic Passive Margins: Inferences from Analogue Modelling and Magmatic Flow Determination

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Volcanic passive margins (VPM) are characterized by (1) thick seaward dipping lava sequences, (2) plutonic complexes associated with dyke swarms parallel to the coast, and (3) zones of high seismic velocity in the lower crust likely attributable to magma underplating. A conceptual model of volcanic margin development has recently been proposed (Geoffroy, 2000). This model assumes that the tectonic development of VPM is controlled by soft-points constituted of diapir like instabilities of the asthenosphere. Punctual rheological heterogeneities defined by melting small-scale asthenospheric diapirs overlaid by magma storage zones at various level in the lithosphere and by large polygenetic volcanoes at topographic surface may strongly affect the localization and style of breakup. Geoffroy's (2000) model implies that (1) crustal strain is localised and propagates from polygenetic volcanoes (or their feeding crustal reservoirs), and (2) that the magmatic growth of VPM is controlled by lateral injection of dykes from these reservoirs. To testify point (1), we performed at lithospheric scale a set of 2D and 3D analogue modelling which focused on the mechanical effects of magma type rheological heterogeneities on lithosphere extension (Callot et al., under press, 2000). Four layer brittle-ductile models were constructed with sand and silicone putties. A break-up geometry comparable to volcanic margin COB geometry is obtained when the high-strength sub-Moho mantle is interrupted by a low viscosity body. There is a direct link between the spatial distribution of the punctual rheological heterogeneities and strain localization in the upper crust. The resultant strain field is comparable to the geometry of onshore volcanic margins. With regards to point (2) the location of the source of the extrusive magmatic products at VPM (flood basalts and seaward-dipping reflectors) is constrained by the determination of magma flow direction in dykes using Anisotropy of Magnetic Susceptibility. Forty Tertiary dykes have been sampled at four different localities along a 125 km long segment of the East Greenland margin. The present day erosional level is situated at ~6 km below the paleotopography (T.F.D. Nielsen, 1999, pers. com.). Magma flow is inferred from normal fabric dykes using the imbrication of magnetic foliation plane at dyke margins (Moreira et al., 1999). Analysis of minerals preferred orientation within thin-section allows to control the inferred flow direction. Our results show that the extrusive products were mostly fed by horizontal injection from apart high-level magma chambers, in a way similar to what is observed in Iceland. We thus confirm both at crustal and lithospheric scale the validity of the proposed model.

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RCM2 : WEpo09 : PO Continent-Ocean Boundary along the Norwegian Continental Margin

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The continental margin off Norway and the Barents Sea, 62-77°N, evolved after opening of the Norwegian-Greenland Sea during chron 24r, i.e. near the Paleocene-Eocene transition. The lithospheric breakup was accompanied by massive, regional magmatic activity. Thick lava sequences cover both the early Eocene oceanic crust and large parts of the adjacent continental crust. Structurally, the margin comprises rifted and sheared segments spatially related to a crustal segmentation governed by transfer zones developed during previous, Mesozoic rift episodes. By introducing the continent-ocean boundary (COB) as the change from oceanic to continental basement in the uppermost crust, and the continent-ocean transition (COT) as the region of crustal change considering the entire crust, we are able to map these features as well as document significant differences between the rifted and the large-offset sheared margin segments. From an integrated analysis of seismic and potential field data we infer: (1) a 10-30-km-wide COB along the volcanic rifted segments. The much wider COT encompasses both part of the thickened oceanic crust seaward of the COB and the strongly intruded and underplated, extended continental crust on the landward side. Although its width varies, the COT comprises a >100-km-wide zone across the prominent Møre and Vøring marginal highs. (2) A distinct, 5-10-km-wide COB along the Jan Mayen, Senja, and Hornsund sheared segments. The COB is particularly well-defined across the Senja Fracture Zone where breakup lavas are largely absent. This crustal setting is also characterized by a well-defined and narrow COT bounded at depth by a steeply dipping Moho between oceanic and continental crustal levels.

RCM2 : WEpo10 : PO The Role of Dyke Swarms in Forming the East Greenland Continent-Ocean Boundary

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A dense dyke swarm and crustal 'flexure' is exposed along a 250 km long zone of Greenland coast within and south of the Greenland-Iceland Ridge. Field relations show that by an large dykes intruded subvertically and over a significant period of time. Intrusion started before breakup at ~56 Ma and extended to at least 50 Ma. Assuming that on a statistical basis we can consider dykes to have intruded vertically and at right angle to the minimum compressive stress, we can use our field measurement of thousands of dyke orientations and dyke thicknesses to determine spatial variations in the following parameters: 1) Crustal rotation and extension; 2) Magmatic dilation and extension; 3) Paleo-stress field. Variation with time in these parameters can also be assessed based on the relative chronology of the dykes. The coastal zone studied is located close to the geophysically defined continent-ocean boundary (COB) and enable us to investigate details of this structure not resolvable by geophysics. The earliest 10% of the dykes were emplaced prior to breakup and slightly oblique to the margin in an echelon pattern of relatively thick dykes, with magma ascending subvertically from the base of a fairly thick crust. These earliest dykes were rotated 10-30° seaward prior to a large group (60%) of syn-breakup to early spreading dykes intruded. This group was emplaced more parallel to the line of breakup, but along slightly curved trajectories extending from major intrusive centers, which developed with time and segmented the margin. Lateral flow of magma from these centers is indicated by systematic thickness variations, just like the amount of tectonic extension and crustal dilation by dykes seems to increase towards these igneous centers. Very pronounced increase in crustal dilation by dykes is seen across the margin and locally reach >50% along the coast. Offshore extrapolation of this increasing magmatic dilation into a true sheeted dyke complex show good correlation with the geophysically defined COB, though slightly more proximal to the coast. Palinspastic reconstruction of the initial rift zone (i.e., removal of tectonic and magmatic extension) suggests that breakup was initiated along a 30 km-wide rift. It is likely that this

rift was initiated through normal faulting but also evident that dyke dilation soon took over as the primary mode of crustal extension. The role of dykes in forming COB's is thus manifold: (1) Magma-pressures reduce the differential stresses necessary to accommodate extension and thus facilitates further extension along the same line. (2) Focused volcanism within magmatic segments lead to lateral dyke propagation. (3) Transportation of magma to the surface exerts a top load that eventually deforms the margin into a characteristic 'flexure'. (4) An increased density of dykes ultimately lead to a gradual transition into completely oceanic crust, rather than a tectonically thinned COB that characterize non-volcanic rifted margins.

RCM2 : WEpo11 : PO Implications for Source Components in Faroe Islands Basalts and Sediments from Sr, Nd and Pb Isotopes and Zircon Xenocrysts

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Early Paleocene flood basalts and sediments on the Faroe Islands record the interplay between magmatic and sedimentary processes during initial opening of the North Atlantic Ocean. We report major and trace element geochemistry, including Sr, Nd and Pb isotope data, on basalts and intercalated tuffs and fluvial sediments. Analysed flows are all tholeiitic, with isotope signatures dominated by mainly two components: (1) enriched continental lithospheric mantle and (2) assimilated Lewisian type (2.8 Ga) basement. The upper lava series contain scattered flows with a more depleted signature similar to present day North Atlantic MORB, interpreted to reflect lithospheric rupture and the onset of continental drifting. Assimilation of basement rocks becomes more dominant towards the upper part of the lower and middle lava series, with highly contaminated dacitic rocks occurring as a conglomerate at the boundary between the lower lava series and the coalbearing sequence. Major element geochemistry (e.g. FeO-MgO systematics) on Faroe Island basalts suggest normal eruption temperatures, with now evidence of a thermal anomaly in the underlying mantle source region. Zircon xenocrysts separated from a middle series flow give dominantly 327 Ma U-Pb ages, similar to ages reported for the onset of volcanism in permo-carboniferous basins and rifts in the North Atlantic. This may suggest that fissure eruptions and initial breakup was focused along existing fault zones associated with permo-carboniferous basins. Isotope data on intrabasalt fluvial sediments indicate no input of clastic material from basement rocks. Extensive chemical weathering in a humid Paleocene climate is evident by consergined fluvial sands consisting of near 100% siderite.

RCM2 : WEpo12 : PO Evolution of the Walvis Basin Offshore NW- Namibia - Preliminary Results from FE- Modeling and Mass Balance Calculations

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Etheridge et al. (1989) modelled the Namibian continental margin as the upper plate of a pair of conjugated, asymmetric passive margins. Upper plate margins are characterized by long-lasting uplift and erosion as well as the development of a major escarpment separating a narrow coastal plain from the eroded remnants of the uplifted continental interior. There are several mechanisms contributing to marginal uplift but the isostatic response to contrasting rates of denudation between the gently inclined coastal plain and the interior plateau is the most suitable mechanism to create persistent uplift and erosion, even on the mature Namibian passive continental margin (e.g. Gilchrist & Summerfield, 1990).

A plain strain finite element modeling approach, scaled for the whole crust, is used to quantify continental extension, break-up in the early Cretaceous, and the evolution of the Namibian passive continental margin. Crustal deformation is calculated on the basis of rock rheology, the evolution of the crustal temperature field, and specific boundary conditions. Additionally, large-scale normal faults are incorporated into the model so that subsidence history and basin geometry can be related to the geometry and kinematics of the main basin-bounding faults. These faults may have already been active during the formation of earlier rift-systems of possible Karoo age (Permo-Carboniferous to Jurassic), forming pre-existing zones of weakness that influenced the resulting passive margin geometry (e.g. Stollhofen, 1999).

The crustal-scale finite element model is coupled with a basin-scale model for which it provides improved input parameters like basal heat flow and basement subsidence. The stratigraphic modeling package "STRATA" (Flemings & Grotzinger, 1996) is based on the diffusion equation and is used to describe sedimentation and maturity-development in the Walvis Basin. For a two-dimensional traverse across the Namibian continental margin a mass balance is presented which relates uplift and erosion onshore to sedimentation offshore. Additional model geometries and boundary conditions like uplift- and erosion-rates and sediment supply are inferred from published geological data.

The ultimate goal of the project is to present a 3-D-quantitative model of passive margin evolution for an exemplary segment in northwestern Namibia. Future work will include a detailed lithological correlation of sediments in the Walvis Basin with their equivalent remnants on the uplifted and eroded onshore-part of the Namibian passive margin. The deep seismic profile ECL-89-41 and cutting samples from the nearby 2012/ 13-1 well off northwestern Namibia, as well as new field data, will serve as a reference frame for this approach.

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RCM2 : WEpo13 : PO

New K-Ar Constraints on the Silicic Volcanism in Central Afar, its Implications in the Rifting Process

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The Afar depression is a triple junction characterised by thinned continental crust, where three rift systems merge (Red Sea, Gulf of Aden and East African Rift). About 100 new K-Ar ages (Cassignol/Gillot technique) and geochemical analyses on Plio-Pleistocene lavas allow us to detail the volcanic activity in Afar. Our data reveal a clear evolution through time in relation with rifting. For the last 3 Myr, intense fissural volcanic activity causing the emplacement of the trap-like 'stratoid series' was more and less continuous. It now covers most of the depression, except the presently active rift segments. Through time, from Stratoid Series volcanism to rift segments one, contribution of depleted mantle increase producing more and more tholeiitic magma. New ages enhanced the correlation between the rhyolitic volcanism and the Red Sea and Aden continental rift zones initiation: Silicic activity mainly occurred during two phases, 1.3 and 0.6 Myr ago before each stage of rift propagation inside Afar depression. Furthermore, at a ridge scale as at a small rift segment one, silicic lavas are systematically older than the basaltic ones. Evolved lavas were erupted at the axis of a future rift segment prior to the main extensive phase when basaltic fissural activity develops. This explains why elements of silicic centers are presently located on the both sides of active rift. They seem to be a necessarily precursor feature. After that, the extension increasing, magma was directly erupted from the source to surface as basaltic lava without differentiation process occurring. Differentiated volcanoes (and magma chambers associated) considered as zones of local weakness, would allow the development of fractures which generate then fissural magmatism. This mixed system of rifting, including volcanic and tectonic components can be compared to the continental break-up, including also active component (hot spot) and passive one (regional stress).

