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Workshop "Volcanic Margins"

November 10th - 12th, 1997 in Potsdam, Germany

Impressum:

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Potsdam, November 1998

The GeoForschungsZentrum was privileged to host the **Volcanic Margins Workshop** in Potsdam from November 10 to 12, 1997. The workshop was conceived as a meeting of the ILP Project-Team IV-2 "The Ocean -Continent Lithosphere Boundary" to address recent research results and to help define future research directions. It was organized by Manik Talwani, ILP Project chairman, Millard F. (Mike) Coffin, Robert A. Duncan, Jörg Erzinger and Karl Hinz. I believe the organizing committee and participants will agree that it was a productive and enjoyable meeting.

Despite the November weather in Germany, some 60 invited scientists from 15 countries attended the workshop. The scientific contributions in this volume reflect the breadth and depth of new results and ideas exchanged at the meeting and show that the topic of **Volcanic Margins** is a very active area of cross-disciplinary research in many countries. With this participation, I believe we achieved our main goal of bringing together the "critical mass" of international geoscientists needed to take stock of current progress and identify outstanding goals for future research. This is the subject of the white paper presented in this volume.

The Organizing Committee is very much obliged to the sponsoring institutions for their financial assistance which made the workshop possible. We would like to specifically mention the GeoForschungsZentrum Potsdam (GFZ), the German Federal Institute for Geosciences and Natural Resources Hannover (BGR), the Joint Oceanographic Institutions (JOI/USSAC) and the International Lithosphere Program (ILP). Last but not least we wish to thank Ms. Sabine Bonack and several of our students in Potsdam for their invaluable help behind the scenes.

Potsdam, November 1998

Jörg Erzinger

Sectretary-General, ICL/ILP

ILP Workshop "Volcanic Margins"

November 10th - 12th 1997 at the GeoForschungsZentrum Potsdam

W H I T E   P A P E R

This white paper discusses the importance of volcanic rifted margins particularly as emerging from new data presented at the workshop. New questions have been raised. We focus on aspects of this phenomenon that merit community effort and resources.

1. INTRODUCTION AND PRESENT STATE OF KNOWLEDGE

Volcanic Rifted Margins (VRMs) appear to constitute the vast majority of passive continental margins. According to some estimates, as much as 70% of the Atlantic margins are volcanic. Similar ratios might be expected for other (less surveyed) margins. Thus the initial opening of oceans is a volcanic phenomena of tremendous significance.

VRMs are part of a spectrum of Large Igneous Provinces that include continental flood basalts, and ocean plateaus, that seem to differ mainly due to the composition and thickness of the lithosphere on which they are created, and the thermal state of the mantle from which magmas are produced. For VRMs associated with surfacing mantle plumes, the initial rapid eruption of magmas characteristic of continental flood basalts and ocean plateaus extends into the steady-state magmatism of early ocean basin formation in VRMs.

Volumes of erupted and intruded material associated with VRMs are enormous. Igneous material associated with Seaward Dipping Reflectors (SDRs) and the underlying material derived from mantle melting may amount to 4 million cubic km off the US and Canadian East Coasts. Similar material off the South American margin may be three times as large.

The combination of high-precision ^{40}Ar-^{39}Ar incremental heating age determinations and detailed magneto-stratigraphy in lava sections has provided powerful constraints on the timing and duration of volcanic activity.

VRMs appear to have formed very rapidly (perhaps in time intervals no longer than 1 or 2 million years). Considering the large volumes of igneous material that was generated during this time, it follows that the emplacement of VRMs is manifested by particularly intense and brief periods of material and energy flux from the Earth's interior to surface.

Thus, we are led to the inference of two fundamentally differing styles of Earth dynamics: One is uniformitarian, manifested by steady state sea floor spreading and complementary subduction occurring continuously at time scales often of tens of millions of years. The other is catastrophic, occurring only for a very brief period of time (a few million years at most) and at widely spaced intervals in the geologic record. Obviously, to understand Earth dynamics we need to pay as much attention to the catastrophic events as we do to the much more commonly studied continuous phenomena of sea floor spreading and subduction.

These catastrophic events, besides reorganizing plate motions, have had profound effects on the Earth's environment. Some of the environmental changes are associated with the effects on the atmosphere caused by the large amounts of intense subaerial volcanism associated with SDRs, as well as with changes in the marine sedimentary record. The relationship of these events with mass extinctions, global anoxia and other major changes in ocean chemistry (isotopic and trace metal) bears examination.

As the search for fossil fuels moves into deeper waters the examination of VRMs becomes very important. Oil and gas deposits are associated with failed rifts (e.g., the North Sea). Are they also associated with successful rifts? Are rifts and synrift deposits present at drillable depths under the feather edge of volcanics, imaged as SDRs? Are SDRs overlain by a normal succession of salt and carbonates? What is the thermal effect of SDRs on the maturity of hydrocarbons? Prospecting for oil and gas in the deep water areas of VRMs is very expensive. Understanding the structure, stratigraphy and evolution of VRMs is of the utmost importance for the exploration of hydrocarbons.

The composition and distribution of SDRs provides constraints on mantle rheology and melt segregation.

How mantle plumes might be related to SDRs and to the evolution of VRMs provides tantalizing clues to the nature and influence of plumes and, in fact, on convection in the mantle. For instance, what is the relationship between SDRs below almost the entire Eastern Continental margin of South America (extending perhaps 6000 km) with a South Atlantic plume?

2. LITHOSPHERE ARCHITECTURE AND THE UNDERLYING ASTHENOSPHERE

Any studies of a volcanic rifted margin will rely heavily on knowledge of the margin's fundamental lithospheric architecture. By architecture, we mean the thickness, composition, mineralogy, thermal state, and rheology of the lithosphere in three dimensions along and across a rifted margin. In addition to knowledge of the lithosphere, equivalent information on the state of the asthenosphere is crucial to understanding the processes expressed at VRMs.

2.1 Science Questions

We identified a number of critical scientific questions that must be addressed in VRM studies, including:

- What is the effect of lithospheric structure and deformation history on the development of VRMs? There is a spectrum of passive rifted margins that exhibit varying magmatic volumes, from plume-enhanced, to "normal" VRM, to amagmatic margins. How can these be understood in terms of variable thermal histories and lithospheric filters?
- How does the thickness, strength, and composition of lithosphere impose important controls on the distribution, composition, and extent of melting in VRMs?

- What is the relationship between the timing of magmatism and extension, and how does it vary among VRMs?
- How does asthenospheric temperature evolve through time in a rifting margin, and how does it control magmatic volume and consequently, lithospheric thickness? What is the relationship between mantle thermal structure and lithospheric architecture, before and after rifting? What are the important controlling factors?
- Are the lithospheric mantle and asthenosphere compositionally heterogeneous, and if so, how does this affect the composition and volume of VRM magmatism? What are the relative contributions to magmatism in VRMs from the lithosphere and the sublithospheric mantle?
- Can we characterize melt production, segregation, and emplacement in time and space on a rifting margin?
- What is the interplay between magmatism and rheology (and hence deformation style) during continental breakup?
- What causes uplift of continental areas adjacent to VRMs, and why don't these uplifted margins subside as the thermal regime decays? What is the relative importance of flexural uplift, underplating, thermal processes, and mantle dynamics to uplift patterns?
- What is the ultimate fate of VRM crust: does it become part of continental crust, or does it return to the mantle via subduction or delamination?
- What are the geochemical variations in eruptive volcanic products and mantle xenoliths, both in space and time, and how do they correlate with pre-rift tectonic theories?
- What are the environmental responses to LIP volcanism in a range of tectonic settings, including VRMs? Subaerial and submarine eruptions may have quite different effects. Should this be examined through acquisition of carbonate sedimentary sequences at varying water depths, in "near-field" and "far-field" locations with respect to LIPs/VRMs?

2.2 Broader questions include:

- What criteria should be used to identify VRMs in the continental geological record?
- Are VRMs incorporated in the continental crust, or do they provide important loci for future initiation of subduction along passive margins? As protoliths in the continental crust, what is their eventual fate?
- Is there a connection between major periods of subduction and start-up plumes, as suggested by numerical models of whole-mantle convection?

2.3 What do we need to measure better?

The scientific goals posed above point to a number of targets for focused study on volcanic rifted margins. Many of these targets manifest crucial margin processes, ignorance of which currently limits scientific progress. In particular, we need improved, quantitative understanding of:

- Volume of magmatic material along and across rifted margins.
- Distribution of remnant continental crust in the continent-ocean transition zone.
- Geometry of extrusives and intrusives.
- Geometry of mantle lithosphere - both pre-existing continental lithospheric mantle and the developing refractory mantle - in space and time on a rifting margin.

- Sub-SDR structure and composition - calibration of seismic facies with geological origin (composition, emplacement environment).
- Lithology, variability, and distribution of the 7.x km/s layer.
- Asthenospheric temperature distribution pre-, syn-, and post-breakup.
- Vertical motion history, especially early in rift/drift development.
- Plate kinematic history (rifting/spreading rate and obliquity), and its controls on margin magmatism and deformation.
- Microseismicity, strain distribution, and neotectonics of rifting margins.
- Deformation through time (lithospheric thinning profile, strain partitioning).
- Symmetry of magmatic and deformation processes.
- Coupled Ar-Ar and fission track studies, Pb, He, Re-Os isotope studies of erupted products.

2.4 Methods, tools, and approaches

The scientific targets delineated above in turn suggest new approaches to studying volcanic rifted margins. We need to proceed on three fronts: the continued use of fundamental approaches (e.g., drilling and geological sampling), the development of new techniques tailored to the challenges presented by margin architecture (e.g., improved deep seismic imaging tools), and the enlistment of techniques that have had limited, or no, application to rifting margins (e.g., mantle tomography). Maximum progress will be achieved by the concerted application to margin targets of a wide battery of approaches crossing disciplinary boundaries.

2.5 Required Techniques

Geophysical techniques should include the following:

- Better-resolved, deeper velocity and impedance images. Achieving this in the challenging margin environment will require new or improved technologies, including bottom cables, vertical cables, bottom shots, many OBH/S instruments, better seismic sources, and longer, multiple streamers. Application of these technologies will in turn require development of integrated and specialized processing and modeling techniques.
- Drilling. This includes both continental and oceanic drilling and associated downhole measurement capabilities.
- Seismic tomography. Three-dimensional images of Vp, Vs, Qp, and Qs, especially in the mantle of developing rift systems and the crust of ancient ones, are required.
- Magnetic data. Improved knowledge of the magnetization of rifted margin crust, both in a high-resolution sense and a gap-filling sense, is needed.
- Satellite-based measurements of neotectonic motions (e.g., GPS). Measurements of present-day surface strain will constitute important constraints on interpreting crustal structure and deformation patterns.
- In addition to these, a number of other measures will add to our understanding of volcanic margins. These include high resolution swath mapping, passive monitoring of seismicity, paleomagnetic measurements, paleoseismic measurements, fission-track and geomorphological studies, in-situ stress measurements and thermal history studies.

3. MODELS AND MODELING

Participants of the workshop advocated a role for modeling studies in which modeling serves as a means of conducting proxy experiments that can be used to identify the parameters controlling the large scale structure and stratigraphic architecture of rifted continental margins and the quantity and duration of associated magmatism, the loci and mode of magma emplacement, and magma compositions and petrologic evolution. A major goal of such modeling studies is to assess the sensitivity of these various margin attributes to variations in the controlling parameters. Of fundamental importance is the ability/need of modeling studies to address in an integrated manner the thermal, mechanical, and chemical processes occurring in the lithosphere and deep mantle during rifting. This should be achieved through a multidisciplinary approach that incorporates field studies and laboratory experimentation into the modeling process. The linkages between processes and observations hold the key to further advancement of our understanding of volcanic margins.

Two modeling philosophies are recognized:

- Families of models may be developed to elucidate the fundamental physical and chemical processes that govern the evolution of volcanic rifted margins.
- Iterative modeling can be used as an interpretive tool to test and refine hypotheses derived from field studies.

3.1 Current issues for modeling studies

Workshop participants identified a number of specific current issues concerning volcanic rifted margins that can be addressed with modeling studies in the near future. These issues are divided into 4 focus areas.

Interactions between the lithosphere and deep mantle

- Identify causes and space-time patterns of uplift and subsidence on VRM's
- Characterize the interplay between plate motion and mantle convection

The role of lateral and vertical rheologic heterogeneities

- Identify the rate and cause of strain localization during rifting and its impact on lithosphere architecture, mantle upwelling, and melt emplacement.
- Characterize the dynamic interaction between pre-existing and evolving heterogeneities, breakup, and melt migration.
- Quantify the role of inherited tectonic fabric on rift formation and evolution.
- Quantify the dynamic evolution of mantle heterogeneities of both thermal and compositional origin and how they influence the mantle flow system.
- Characterize the dynamic evolution of crustal fault systems. What controls the dominant dip direction (seaward vs. landward dipping faults)? How are fault systems connected at depth? What is the correlation between fault zones and pre-existing shear zones in rift basement?

Melt Systematics

- Integrate predictions of gross whole-rock major and trace element compositions and isotope geochemistry into geodynamic models based on modeled pressure and temperature and mixing scenarios.
- Fully integrate thermodynamics of fractional fusion processes into geodynamic models to assess melt production history and petrologic evolution.

Relationship of rifting and magmatism to the thermal evolution of syn- and post-rift sedimentary sequences

- Improve hydrocarbon maturation models.
- Incorporate role of magmatic underplating on the thermal and burial histories of sedimentary sequences.
- Quantify thermally driven fluid migration and the role of heat convection in the sedimentary column.
- Quantify the relationship between basin stratigraphy, sequence boundaries, and thermally induced uplift in space and time.

3.2 Technological and scientific needs

Articulation of the issues listed above enabled workshop participants to identify advances in the state of the art of geodynamic modeling as well as in technology, basic science, and interdisciplinary communications that will facilitate modeling of volcanic rifted margins. These include:

The state of the art of geodynamic modeling

- Nonlinear pressure and temperature dependent rheologies in both the lithosphere and deeper mantle have been shown to have a dramatic influence on the mantle convection planform, plume dynamics, melt production, interaction between the lithosphere and mantle convection system, and lithosphere dynamics. State of the art geodynamic models must include these complex rheologies.
- Dynamic modeling of fault nucleation, interconnectivity, and slip history is central to understanding deformation on the lithosphere scale during the early stages of rifting and on the basin scale during the drift stage.
- Development of single dynamic models that consider the coupled lithosphere/deep mantle system are required in order to fully assess the feedback between extension, mantle convection, plume evolution, and thermomechanical erosion.
- Full integration of melt systematics and petrologic models into dynamic modeling, including development of refractory residues, production of non-basaltic melts, melt migration models, and geochemical models will facilitate interpretation of petrologic data to infer mantle dynamics.

3.3 Basic science

- Quantification of solidus and liquidus temperatures for various candidate source rock compositions and refractory residues under the appropriate range of pressure and temperature conditions and volatile contents.

- Quantification of rheologic and other physical properties of crustal and mantle rocks, with particular emphasis on conditions near and above the solidus, brittle and semibrittle deformation, refractory residues, and the role of phase changes.

3.4 Technology

- Increased availability of high speed computing platforms with large memory architectures.
- Development of new rapid, flexible, and user friendly 3-D visualization techniques.
- Interdisciplinary communications
- Enhanced awareness of developments in applied mathematics concerning new mathematical models for nonlinear fluid dynamics at high pressure and temperature that include phase transformations and their thermodynamic consequences, and improved methods for dealing with multi-phase flow and multiple rheologies.
- Enhanced interaction with applied mathematics and computer science disciplines to develop new numerical methods or incorporate existing methods into geodynamic models that must by necessity deal with deformation processes that occur over a wide range of time scales.

These goals may be achieved through collaborative research and cross-disciplinary workshops.

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P R O G R A M

November 10 (Monday)

8:00 Registration
9:15 Opening remarks (Jörg Erzinger and Manik Talwani)

9:30 **Session 1: Keynote talks (**Chair: Manik Talwani)

K. Hinz: "Formation of Atlantic Volcanic Margins and Episodes of Intensive Production of Oceanic Crust in the Atlantic"

R. Duncan: "Timescales for Volcanism and Rifting at Continental Margin LIPs"

M. Coffin: "Models for the Emplacement of Large Igneous Provinces: A Review"

D. Bernoulli: "Rifting and Early Evolution of Ancient Ocean Basins: The Record of the Mesozoic Tethys and of the Iberian Margin"

12:00 Discussion

13:45 **Session 2: Volcanic Margins - Geophysical Observations**
Oral presentations (Chair: Olav Eldholm)

S. Holbrook and H. C. Larsen: "Variation in Magmatism in Time and Space on the East Greenland Rifted Margin"

S. Planke: "Seismic Volcanostratigraphy of Large-Volume Basaltic Constructions on Rifted Margins"

V. Abreu: "Geologic Evolution of Conjugate Volcanic Passive Margins: Pelotas Basin"

C. Cramez: "Aspects of hydrocarbon exploration"

16:00 Poster session

20:00 US MARGINS Program/ODP session, co-chaired by M. Coffin and S. Planke
Meeting of the ILP Project team "Ocean - Continent Lithosphere Boundary"
Individual discussion group sessions

November 11 (Tuesday)

8:45 R. Emmermann (Head of the GeoForschungsZentrum)
"About the GeoForschungsZentrum (GFZ) and the International Continental Drilling Program (ICDP)"

9:45 **Session 3: Interplay Between Magmatism and Tectonics**
Oral presentations (Chair: Jörg Erzinger)

A. Saunders: "Contribution of the Iceland Plume to Palaeogene Rifting and Volcanism in the North Atlantic"

J. Marsh: "Karoo and Etendeka Flood Basalt Provinces, Southern Africa, and Tectonic Development of Their Adjacent Continental Margins"

C. Lesher: "The Tertiary North Atlantic Large Igneous Province: Too much melt or too little?"

M. Menzies: "Evolution of the Southern Red Sea Volcanic Margin, western Yemen: Absolute and Relative Dating Techniques"

C. Hawkesworth: "Continental Flood Basalts Associated With Continental Break-up"

13:45 Poster session

16:00 **Session 4: Models and Modeling for Generation and Emplacement of Volcanic Margins**
Oral presentations (Chair: Mike Coffin)

P. Symonds and S. Planke: "The Western Australian Margin: Implications for Models of Volcanic Margin Formation"

C. Ebinger: "Cenozoic Magmatism in Africa: One Plume Goes a Long Way"

D. Harry: "Extension and Volcanism: Insights from Dynamic Modeling Studies"

C. Keen: "Effects of Small-Scale Convection in Igneous Crust Production at Rifted Continental Margins"

18:00 Posters (session continues on Wednesday)
19:15 Transfer to restaurant for business dinner

November 12 (Wednesday)

8:45 **Session 4: Models and Modeling for Generation and Emplacement of Volcanic Margins**

Discussion and posters continued from Tuesday

10:45 General discussion on developing an action plan for research and establishing a future ILP Project

14:00 Synthesis, drafting of workshop report (all interested participants, convenors, and session chairs)

18:00 **MEETING ADJOURNS**

ILP Workshop "Volcanic Margins"

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S C I E N T I F I C   C O N T R I B U T I O N S

Seismic imaging and construction of the extrusive breakup complex on the Møre volcanic margin

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The Paleocene/Eocene continental breakup of N Europe and Greenland was associated with transient, massive volcanism emplacing voluminous sequences of basaltic extrusives. Seismic data are frequently of poor quality in these volcanic terrains due to wave scattering, ringing and strong converted waves. We have carried out test processing on seismic data from the Inner Flows region to improve the sub- and intra-basalt imaging. Ray-traceing and finite-difference synthetic seismic data were used to determine processing parameters and optimize a processing sequence. A processing scheme using both frequency-wavenumber (F-K) and parabolic Radon-transform filtering, combined with a strong inner and outer mute, was chosen. Stacking velocities from semblance plots and constant-velocity stacks were picked iteratively, using a starting model constructed from observational and petrophysical considerations. The results show an improved seismic section with a clear base of the 0.7-1.5 km thick Inner Flows, and a deeper faulted terrain with rotated fault blocks not observed in the original data.

A regional grid of seismic profiles across the Møre margin displays characteristic volcanic seismic facies units. These include: Landward Flows, Stratified and Chaotic Outer Highs, Inner and Outer Seaward Dipping Reflector Sequences (SDRS), Lava Delta, Feeder Dikes, Inner Flows, Volcanic Basin, Laccolith, and Intrusive Complex. Seismic volcanostratigraphy analysis resulted in a schematic five-stage evolutionary model. *Stage 1 (Paleocene, ~62-58 Ma):* Volcanics emplaced as sills and hydroclastites formed by magma-water (or wet-sediment) interaction in a broad sedimentary basin. The unit may include andesitic/dacitic lavas as drilled by ODP Holes 642E and 917A. *Stage 2 (Late Paleocene, ~58-56.5 Ma):* Subsidence, erosion and decreased volcanism associated with formation of the unconformity between the Lava Delta and Volcanic Basin units and regional subsidence along the North Atlantic Volcanic Province. Initial formation of the volcaniclastic Inner Flows. *Stage 3 (Late Paleocene, ~56.5-55 Ma):* Explosive volcanism followed by effusive volcanism forming the Landward Flows, the Lava Delta and the Inner Flows units. The Landward Flows are subaerial flood basalts, being fragmented along the shoreline constructing the Lava Delta unit by progradation of coarse-grained hydroclastites and volcaniclastic sedimentary material. The aggradational Inner Flows unit is interpreted to consist of massive basalt, hydroclastites and volcaniclastic material derived from the Landward Flows and Lava Delta units. *Stage 4 (Early Eocene, ~55-54 Ma):* Effusive breakup volcanism and differential subsidence forming the wedge-shaped Inner SDRS by ponding of lavas within a rift valley. *Stage 5 (Early Eocene, ~54 Ma):* Explosive shallow marine volcanism in areas where the eruption centers subsided below sea level constructing the Chaotic Outer Highs. Large areas may have been covered by hydroclastic materials, e.g. as the Stratified Outer High. Evidence of a feeder dike system is observed as steep landward dipping reflectors below the Stratified and Chaotic Outer Highs.

Ethiopian flood basalts: a review of major features and some comments about their origin.

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If the small Columbia River province is exempted, the 30 Ma Ethiopian flood basalts are the youngest major example of this type of volcanism. Like other major flood basalt sequences, the entire sequence erupted in a very short period of time, in probably less than 1 million years (Hofmann et al., 1997). The dominant rock types are tholeiitic to transitional basalts, interlayered with subordinate felsic flows and tuffs. Recent studies by Pik et al. (1997) have demonstrated the presence of both low-Ti and high-Ti basalts. The former type, which has relatively low concentrations of all moderately to highly incompatible trace elements, is restricted to the northwestern plateau. The high-Ti basalts, of which there are two types distinguished by different trace-element and isotopic compositions, are more widely distributed. To explain the formation of these rocks, Pik et al. (1997) called on the partial melting of at least two types of mantle sources complicated by interaction with continental crust.

The post-plateau volcanic rocks erupted in slightly younger shield volcanoes at the top of the sequence, as mafic to felsic rocks directly associated with rifting in the Afar Depression, and as more widely dispersed centres of minor volcanic activity. With the exception of tholeiitic basalts in the Gulf of Tadjoura, all these rocks have a transitional to alkaline character, and the low-Ti types are missing (Deniel et al., 1994). Helium isotope studies of Marty et al. (1996) show that most of these rocks came from a deep-seated mantle plume source.

The eruption of the Ethiopian flood basalts coincides with the start of a period of continental rifting and plate reconstruction that continues to the present day in the continental and oceanic rifts of the Afar depression. Plate movements were slow (~2 cm/yr) and the distance between the volcanic plateau, which marks the site of initial plume melting, and the currently active hot spot in the Afar depression, is small. Many features of the Ethiopian province are consistent with models in which both flood volcanism and continental rifting are related to the arrival at the base of the lithosphere of a new mantle plume. Hofmann et al. (1997) developed a model intermediate between classic models of "active" and "passive" rifting, according to which the arrival of the plume head caused rifts to propagate from the Indian Ocean towards the Afar region after an original link to the Indian subduction zone became blocked by ongoing collision with India.

Although this model explains many of the tectonic relationships between the plume head, the active hot spot and oceanic and continental rifts, certain petrological and geochemical characteristics of the Ethiopian volcanic rocks pose problems. The situation can be contrasted with that in the North Atlantic Tertiary province, where continental rifting immediately preceded continental volcanism and resulted in the eruption of enormous volumes of basalt that are now preserved in the seaward-dipping reflector sequence. In Ethiopia, the rifting of Arabian and African plates followed ~10 Ma after the plateau volcanism and led to the formation of the Red Sea and Gulf of Aden. This rifting created oceanic crust only of normal thickness and there is no indication that enhanced mantle melting accompanied thinning of the lithosphere. The magmas which are presently erupting along the active rifts have transitional to alkaline geochemical characteristics with high concentrations of incompatible trace elements. Such magmas are best interpreted in terms of low degrees of partial melting of a mantle source that was not unusually hot. It appears, therefore, that the post-plateau volcanism was derived from a source distinct from that which gave rise to the flood volcanics. If a large-volume "plume head" ever existed, it appears to have been an ephemeral feature that disappeared within 10 Ma, before the onset of continental rifting in the Afar depression. The relationship between source of the plateau basalts and the currently active hot spot, whose presence is well documented by the He isotope data of Marty et al (1996), remains uncertain.

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Crustal structure of the passive volcanic margin of Namibia from on- and offshore seismic wide-angle investigations

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In December 1995, a seismic onshore/offshore experiment was carried out at the rifted continental margin of Namibia to investigate the transition from oceanic to continental crust related to Late Jurassic - Early Cretaceous continental rifting and opening of the South Atlantic Ocean. Continental rifting was accompanied by regional uplift, extension and magmatism, post-rift subsidence and sedimentation. The presence of the Tristan mantle plume and reactivation of Late Proterozoic structures of the Damara / Ribeira Orogen influenced or controlled these processes. Rift-related magmatism formed the large South Atlantic Igneous Province, which includes voluminous extrusives offshore (SDRS), continental flood basalts and subvolcanic ring complexes. This study concentrates on the geophysical expression of magmatic activity in the rifted transitional crust and its continuation into the Damaraland Alkaline Province onshore.

The seismic survey consisted of offshore multichannel seismic reflection, ocean bottom hydrophone (OBH) and onshore wide-angle measurements along three profiles across the continental margin. In this contribution, we discuss the interpretation of OBH and land data along the two northern lines, which are separated by about 150 km. OBH's were deployed with a spacing of 40 to 70 km while 3-component stations on land had a spacing of 2.5 to 15 km. The seismic signals were generated offshore every 140 m. The data are of high quality and the main phases, e.g., Pg, PmP and Pn can be distinguished easily. The Pn phase can be observed up to distances of about 400 km.

Forward travel-time modelling and damped least-squares inversion of OBH and onshore wide-angle data were used to derive P-velocity models for the two profiles. The crust/mantle boundary rises from about 40 km beneath the continent to about 16 km at a position 400 km offshore. On both profiles we observe offshore sedimentary rocks with thicknesses of up to 4 to 5 km. Based on the seismic velocities and the Moho structure, we can classify (1) oceanic crust, (2) break-up related transitional crust and (3) continental crust. The oceanic crust is 7 to 8 km thick. Thickening of the oceanic crust at about 300 km offshore coincides roughly with magnetic anomaly M4, which is supposed to represent the oldest oceanic crust in this region (125 Ma). The ocean-continent transition is a gradual rather than a sharp boundary. We observe a high-velocity lower crustal body 200-300 km offshore. The velocities of 7.1 to 7.7 km/s are similar to observations at other volcanic margins and could correspond to intruded mafic material.

The onshore parts of lines 1 and 2 differ. The continental crust along line 1 is characterized by higher velocities in the lower crust and by greater Moho depths in comparision with line 2. Both features could be explained by magmatic underplating. In support of this, line 1 crosses two subvolcanic ring complexes, Cape Cross and Messum, which are characterized in the wide-angle data by deep reaching high velocity anomalies. These intrusions were emplaced just before the onset of seafloor spreading along the northern marginal fault of the Damaraland Uplift. Line 2 lacks any Mesozoic igneous rocks on surface, and its crustal structure may be more typical of undisturbed crust of the Damara Orogen.

To extract more information from the large data set collected onshore we tested techniques normally used only in processing CMP normal incidence data. Processing and stacking of the wide-angle data results in a detailed image of the Moho reflectivity. Predominant features are (1) reflective energy in the lower crust and (2) an upwelling of the Moho beneath the Cape Cross intrusion. As a next step these reflections will be migrated to obtain a correct image of the lower crust.

Rifting and early evolution of ancient ocean basins: the record of the Mesozoic Tethys and of the Galicia-Newfoundland margins

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Alpine-type collisional mountain belts appear to preferentially preserve the history of rifted, non-volcanic continental margins. These margins present conspicuous analogies to present-day undeformed margins as the Armorican or the Iberian/Newfoundland examples document. In such margins, the record of their early evolution is in most cases deeply buried below post-rift sediments, and it is only in a few places, along sediment-starved rifted margins like that of Galicia, where continental and oceanic basement and pre- and synrift sediments are within the reach of deep-sea drilling. In these places, seismic, magnetic and gravity surveys, combined with drilling allow to image the overall structure of continental margins, but observation of details is restricted to drill cores and outcrop sampling from submersibles. In contrast, mountain belts provide extensive outcrops of oceanic and continental basement, overlying sediments and associated fault rocks. In these areas, the ocean-continent boundary is often tectonically decoupled and the elements of the former margin are tectonically dismembered; however, under favourable conditions, the history of the margin can be reconstructed. This is the case in the South Pennine-Austroalpine boundary zone and adjacent areas of the central Alps in eastern Switzerland, where well-preserved, rift-related faults allow for the reconstruction of the passive margin and the ocean-continent transition zone. Unlike other segments of the Tethys ocean, this former ocean-continent boundary was not subducted to great depth, but always remained near the surface of the orogen. In this contribution, we shall compare the evolution of this margin with that of the undeformed Galicia-Newfoundland counterpart. The South Pennine-Austroalpine margin and ocean basin was kinematically linked to the evolution of the central Atlantic opening in the Jurassic, whereas rifting and initiation of spreading between Iberia and Newfoundland occurred during the Cretaceous; however, the evolution of both systems is remarkably similar.

In the Galicia-Newfoundland transect and across the Alpine Tethys, rifting initiated in the future proximal margin areas (Briançonnais/central Austroalpine-South Alpine, Jeanne d'Arc basin/Galicia Interior-Lusitanian basin, see Fig. 1a), about 40 My before break-up. Extension was mainly accommodated by normal faults, delineating half-grabens. In the Southern Alps, field data show that the faults were listric and can, in some cases, be followed down to a depth of 12 to 15 km. Middle to lower crustal levels may have behaved ductilely, which is suggested by the soling out of listric faults at mid-crustal levels. In the lower crust and mantle lithosphere, extension appears to be accommodated by anastomozing shear zones. Mantle uplift during this initial phase of rifting is documented in the Alpine section by cooling ages obtained from mantle and crustal rocks which are contemporaneous with basin formation.

About 30 My after the onset of rifting, the site of rifting shifted laterally and eventually led to the submarine exposure of mantle rocks. Extension was concentrated in the area of the future distal margin. The asymmetry of the margin architecture (Fig. 1b) at the time of break-up and of the isostatic evolution of the margins allows to define the Briançonnais and Newfoundland margins as upper-plate margins characterized by uplift, deep-reaching normal faults, and moderate block tilting, and the South-Alpine/Austroalpine and Galicia margins as lower plate margins, characterized by low-angle detachment faults at a shallow crustal level, the widespread occurrence of tilted blocks, and the emplacement of extensional allochthons onto exhumed and serpentinized mantle rocks.

The change in style of deformation from symmetric and distributed over broad areas of the future margins, to asymmetric and localized during late rifting may reflect a change in rheology of the lithosphere. We assume that during an initial stage of rifting, the rheology of the lithosphere was defined by a weak and ductile lower crust, bounded by stronger brittle crust above and brittle to ductile upper mantle below. At a lithospheric scale, deformation may have been accommodated by pure shear at this stage. Uplift and cooling of upper mantle and lower crust led to strengthening of the previously extended lithosphere with subsequent shifting of the site of rifting to the previously only weakly extended area of the future distal margin. Because of cooling of the lower crust, upper crust and mantle were no longer mechanically decoupled, favouring fault planes cutting across and unroofing the upper mantle at the ocean floor. At this stage, large-scale deformation resembles simple shear. In both transects, the Iberian Atlantic and the Alpine Tethys, there was no volcanic activity contemporaneous with rifting. In the Alps, MOR-basalts typically overlay and are younger than the exhumed, serpentinized mantle rocks and the associated tectono-sedimentary breccias. A mid-ocean ridge may have formed subsequently, however, its potential remnants were strongly dismembered during subduction and partial exhumation. The similar spatial and temporal evolution of the margins of the Alpine Tethys and the Iberian Atlantic, although different in age, suggest that the same mechanisms of rifting were active. These mechanisms appear to be distinctly different from those characterizing "volcanic margins".

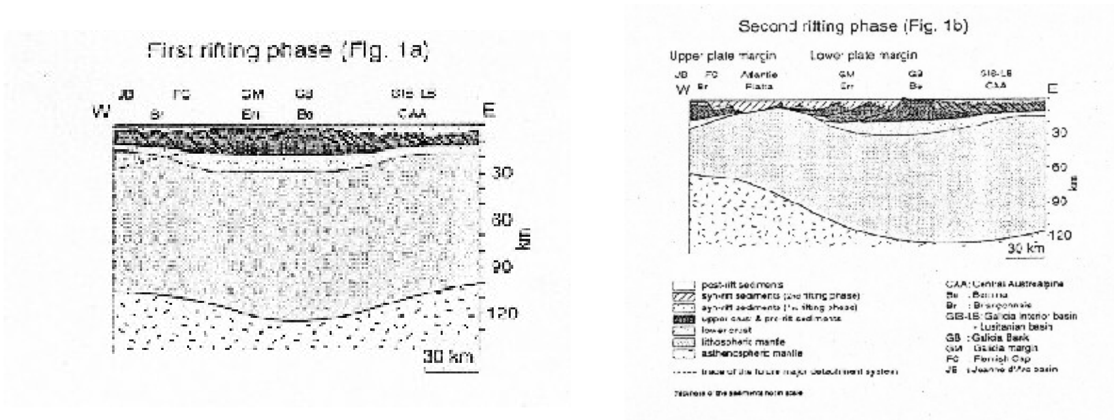

Figure 1. Kinematic model of rifting in the Iberian Atlantic and the western Tethys

Effects of small-scale convection in igneous crust production at rifted continental margins

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Observations of large igneous crustal thickness at rifted volcanic margins has led to suggestions that small scale convection in the upper mantle may be in part responsible for increasing the delivery of magma to the over-lying lithosphere. We have quantitatively assessed this concept by numerical modelling of the viscous flow caused by divergent plate motions.

The model consists of a viscous, temperature and pressure dependent, non-linear fluid whose behaviour is found by solving the Navier Stokes equations for incompressible flow in two dimensions using a finite element formulation. The upper part of the model is constrained to simulate a rifting lithosphere; horizontal plate velocities are specified as boundary conditions. Lithospheric thinning evolves to form a rifted margin and eventually to form oceanic crust. The melt volumes are calculated assuming decompression melting of dry mantle peridotite. An extensive range of model parameter values have been explored, which include plate velocity, wide versus narrow rifts, asthenospheric temperature, scaling viscosity, and the exponent, n, in the viscosity versus strain rate relationship.

Significant time-dependent small scale convection is generated at the lower model viscosities (and/or higher temperatures). These models may provide the required thick igneous crust observed at volcanic margins. However, they also give excessive variations in the thicknesses of igneous crust within the ocean basin and are therefore unacceptable. Sharper narrower rifts enhance convection and increase the melt produced against the margins. However we have been unable to produce both the very thick igneous crust observed at volcanic margins and a uniform thickness of oceanic crust with the above simple model parameters. The results suggest that if small scale convection is an important mechanism in volcanic margin formation, some other factor, not included in the model, must be active in producing and confining convective upwelling at the margin.

One additional factor which we have explored is that the mantle may be initially hydrated, which lowers its viscosity and allows large volumes of melt to b delivered at the margin. However, the water is eventually removed, leaving a dry mantle source with an increased viscosity during the formation of oceanic lithosphere. The increase in visocosity stabilises the flow and provides a uniform oceanic crustal thickness. Laboratory measurements suggest that a hundred-fold increase in viscosity occurs as the mantle is dewatered. This factor, coupled to the models for flow described above, allow the main features of volcanic rifted margins to be simulated.

The erosional history of Northeast Atlantic passive margins and constraints on the influence of a passing plume

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Models explaining continental break-up in the Northeast Atlantic resulting from the impact of the initiating Iceland plume on the base of the lithosphere successfully predict voluminous volcanism and rapid, temporary uplift of the Northwest European region in the latest Palaeocene, but fail to account for a regional 2-3 m.y. volcanic hiatus between ~58-55. New apatite fission-track analyses from Northwest Scotland indicate that a maximum of 2.5 km of erosion could have occurred since the Late Cretaceous, similar to values for southeast Greenland and north of Scoresby Sund. The erosion may have been facilitated by magmatic underplating during break-up.

This pattern contrasts with the Kangerdlugssuaq region of East Greenland, which has experienced 4-6 km of erosion since 45 Ma. Furthermore, the presence of lower-mid Eocene marine sediments overlying the lavas on the Blosseville Coast indicates that magmatic underplating on the Greenland coast adjacent to the Iceland-Greenland Ridge substantially post-dated flood volcanism and break-up, behaviour not predicted by simple plume-rift models. We propose that the initial regional mantle thermal anomaly emplaced at ~63 Ma was a blob of hot, but chemically normal, upper mantle causing uplift and volcanism before dissipating without causing continental break-up. This anomaly would have been relatively isolated and not fed with fresh material by a tail from below as in a long-lived plume. The relative approach of a pre-existing Iceland plume, stationary within the hotspot reference frame, can then be invoked to explain the later (~55 Ma), more plume-like volcanism and final break-up. The predicted crossing of the Greenland coast by the plume in the mid-late Eocene would account for the observed post-rift magmatic underplating and dynamic support on the Greenland but not the European side of the basin.

Models for the emplacement of large igneous provinces: a review

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Large igneous provinces (LIPs), voluminous emplacements of predominantly mafic extrusive and intrusive rock, are produced when mantle-derived melt reaches the upper crust, and manifest a mode of mantle circulation not accounted for in the existing plate tectonics paradigm. LIPs, which include continental flood basalts, volcanic passive margins, and oceanic plateaus, are globally significant: after basalt and associated intrusive rock formed at spreading centers, LIPs are the most voluminous accumulations of mafic material on the Earth's surface. Many LIPs result from long-lived magmatic sources in the mantle, sources which initially transfer great volumes ($<10^5$ to $>10^7$ km^3) of mafic rock into the crust over short intervals ($\sim10^6$ yr), but which later transfer material at lesser rates, albeit over long intervals ($\sim10^7$ to 10^8 yr). Over Proterozoic and Phanerozoic time, however, the fluxes of heat and magma from the mantle that LIPs represent are not distributed evenly-their episodicity punctuates the relatively steady state production of crust at seafloor spreading centers.

Plumes represent the most plausible mechanism for generating large quantities of melt by decompression of upwelling, thermally anomalous mantle. Plumes today account for 5-10% of the mass and energy flux from the mantle to the crust, but in the geologic past (e.g., parts of the Early Cretaceous) plumes may have accounted for ~50% of this flux. This variation in crustal production over the past 150 myr is more episodic and of greater magnitude than that documented for seafloor spreading. Laboratory experiments, and forward and inverse geodynamic and geochemical modeling have been undertaken to elucidate plume behavior. Specific plume models which induce a broad region of hot, enriched mantle beneath the lithosphere have been advanced to explain emplacement of LIPs. Relief on the base of the lithosphere acts to channel plume material laterally and pond it in places. The surface expressions of interpreted plumes, namely hot spots and LIPs, provide primary information in understanding mantle structure and dynamics.

One plume model, primarily based on results of laboratory experiments, invokes a mode of mantle convection independent of the dominant plate scale mode. The former initiates LIP-forming, upwelling, buoyant plumes which detach from the weak, heterogeneous, thermal boundary layer D" at the base of the mantle. Such plumes have a large, hot head over a narrow stem. When the deep plume impinges on the mechanical boundary layer at the base of the lithosphere, conductive heating and thinning of the lithosphere induce large-scale melting. The model suggests 'active' rifting, i.e., stress and strain are transferred from the plume to lithospheric plates. Uplift precedes and accompanies volcanism; prior lithospheric thinning is not required, but rifting may postdate the main volcanic event. The 'active' plume model also suggests occasional coupling among core, mantle, and crustal processes. A variation of this model suggests that conductive heating of lithospheric peridotite above a mantle plume produces melt instead of melting occurring within the plume itself.

Another plume model, developed from hotspot and volcanic margin crustal structure and petrologic/geochemical modeling, proposes adiabatic upwelling and decompressional melting of hot asthenosphere as a result of extending lithosphere. The plume-driven thermal mushroom causes dynamic uplift which accelerates the rate of extension and thereby the amount of melting. Thus magmatism is not driven by the plume but is a response to lithospheric extension and thinning: maximum melting occurs during crustal breakup. This model has both 'active' and 'passive' elements-both a plume and lithospheric thinning are required-and has been used to explain continental flood basalts and volcanic margins. A similar effect may be achieved if hot asthenosphere is trapped by relict lithospheric relief, or 'thin spots', from previous tectonism.

Alternative, non-plume models suggest that LIPs form only at the boundary between thick and thin lithosphere, which focuses both strain in the lithosphere and upwelling convection. In contrast to plume models, the non-uniform boundary condition of the lithospheric plates induces small-scale convection. In the case of conjugate volcanic margins, which extend over large distances along an incipient divergent plate boundary and are characterized by transient volcanism, convective circulation occurs within a narrow conduit of hot upwelling asthenosphere bounded by cold, old lithosphere. This results in the emplacement of thick oceanic crust during earliest seafloor spreading, and the convective circulation abates as seafloor spreading continues.

LIPs and plate tectonics are most closely associated when continents break up in temporal and spatial association with flood basalts; prominent examples, in order of decreasing age, include the Karoo, Paraná/Etendeka, Madagascar, Deccan, and North Atlantic Volcanic Province. Flood volcanism is absent in other instances of continental breakup, however, and the evidence to date is equivocal as to whether plumes weaken the crust, favoring breakup in their vicinity, or whether crustal thinning accompanying continental breakup merely allows underlying anomalously hot or wet mantle to ascend and decompress, producing flood basalts. We lack an integrated mantle circulation model that successfully explains both present-day plate motions and hotspot activity, and modeling of past circulation is still more elusive. What controls when and where LIPs are emplaced, how plumes at any scale interact with primary plate tectonic mantle convection, and why some hot spots persist for $\geq$100 my remain open questions.

Variations in crustal thickness and upper crustal structure with time at the SE Greenland volcanic rifted margin out to Chron 21 times

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Four new deep crustal seismic transects (combined wide-angle and vertical incidence data) across the East Greenland volcanic rifted margin from the Iceland Greenland Ridge in the north to Kap Farewell in the south provide an image of the spatial variation in margin structure and early Tertiary igneous (oceanic) crust as a function of distance from the Iceland hotspot track (Iceland-Greenland Ridge, IGR) as well as variations in crustal thickness and upper crustal structure with time. The oldest igneous crust (56-54 Ma) show the presence of a thick seaward-dipping reflector sequence (SDRS) with a smooth basement surface all along the 1000 km of margin covered. In line with the observation by Larsen and Jakobsdóttir (1988) the SDRS widens onto progressively younger crust northward towards the IGR, which show SDRS all across to Iceland. The outer (oceanward), diachronous boundary of the SDRS wedge is marked by sudden disappearence of the SDRS pattern below an irregular, hummocky or moundlike basement reflector. This basement topography is replaced seawards by a smooth basement surface, in places accompanied by a second, less well developed and shallower set of seaward-dipping reflectors. An apparently synchronous termination of this second wedge/smooth basement at magnetic chron 21 reverse time (48-49 Ma) is observed, and younger igneous crust is generally seismically opaque and show a strongly hummocky reflection pattern. Based on ODP Leg 152 drilling (Larsen et al., 1994) we interprete the main SDRS wedge as subaerially formed Icelandic type igneous crust, the mounded/hummocky interval seaward of ther main wedge as representing rapid subsidence of the spreading ridge to approximately 1000 m below sea level. We interprete the younger SDRS wedge/smooth basement to represent continued high lava productivity emanating from a submarine fissure swarm with limited or no rift topography. The latter may have been established around magnetic chron 21 time. The igneous crust systematically thins seaward along the three southern transects, and subsidence of the proto-Reykjanes Ridge below sea level takes place at a crustal thickness of ca. 14 km, but is not associated with any significant crustal changes. The rapid subsidence of the spreading ridge inferred suggests a plume dynamical mechanism rather than cooling effect which may cause the general seaward thinning of the crust.

Timescales for volcanism and rifting at LIPs

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Recent studies of several prominent LIPs have documented a multi-phase volcanic and tectonic history. The timing and duration of volcanic phases provide the means for distinguishing competing models for plume-lithosphere interaction, and important dynamic parameters such as melt production rates. We review and present new data for LIPs in a spectrum of tectonic settings: the North Atlantic, the Karoo, and the Caribbean. The first two are partly or dominantly continental volcanic rifted margin provinces, while the third is an oceanic plateau with well-developed extensional features. An important aspect of these studies, compared with earlier work, has been the application of high precision ^{40}Ar-^{39}Ar incremental heating methods to determine the crystallization ages of basalts and feldspars separated from phyric basalts. These experiments typically allow time resolution on the order of 1% or less of the measured age.

North Atlantic: Basaltic and dacitic lava flows, tuffs and related intrusive rocks were emplaced simultaneously across a ~2000-km diameter, roughly circular region centered on Greenland, beginning about 61 Ma. Initial volcanism was directed through pre-existing "thin spots" in the Archean to Paleozoic continental lithosphere in West and East Greenland, the British Isles and the Faeroe Islands, but clearly preceded successful continental rifting in the North Atlantic by about 5 m.y.

The sequence and timing of magmatic and tectonic events at the SE Greenland margin, recently integrated from ocean drilling and onland studies, were: (1) a subaerial, continental succession of lavas (>600 m) derived from melts that formed below a thick lithosphere and assimilated crustal material on their way to the surface (61-60 Ma); (2) a subaerial, oceanic succession of lavas (>5 km) whose compositions reflect rapidly thinning lithosphere and disappearance of continental contamination up-section (56-54 Ma); and (3) a submarine, oceanic succession of lavas of normal oceanic crust (53 Ma and younger). An unconformity and thin sedimentary horizon separates the highly evolved, waning stage of the continental succession from a picritic series of lavas beginning the oceanic succession (3-5 m.y. hiatus). The oceanic succession forms the seaward-dipping reflector sequence, a 5-7 km thick wedge of basalts seismically imaged along the entire East Greenland margin and its European conjugate -- this is by far the most voluminous phase of volcanic activity within the province, reflecting the highest melt production rates.

These observations are most consistent with impact of a rapidly ascending and spreading plume head at ~61 Ma, melting of mainly trapped ambient asthenosphere due to frictional heating close to the base of the lithosphere, with resulting volcanism through "thin spots", followed by final continental breakup and large-volume melting of the plume head itself through upwelling and decompression, followed by steady-state (normal) sea-floor spreading.

Karoo: An initial volcanic phase of predominantly basaltic composition (with minor picrites and nephelinites) is widely distributed across southern Africa (Namibia, Botswana, South Africa). Erosion has exposed an underlying plexus of dykes and sills of comparable volume. There is little evidence for significant extension at this time. A volumetrically subordinate, principally felsic phase followed, focused in the eastern, extending margin of South Africa and Mozambique. Radiometric ages from all localities fall in a narrow range of 184 to 178 Ma, with the vast majority of early phase lavas erupted at 183 - 177 ± 1 Ma. Sea-floor spreading between Africa and Antarctica began ~15 m.y. after, so it seems that volcanism and tectonism are not closely tied, except that plume impact may have contributed to the fragmentation of Gondwana. Compositionally correlative igneous rocks in Antarctica (Kirwan basalts; Ferrar sills, Kirkpatrick lavas and Dufek layered complex) are exactly contemporaneous with the Karoo province, and must be considered as part of the same, short-lived magmatic event. The distribution of igneous rocks is not radially symmetric as in the North Atlantic, but may reflect a lithospheric-asthenospheric control on plume material flow.

Caribbean: This province is an oceanic plateau, some 2-3 times normal ocean crust thickness, built entirely of submarine lava flows, hyaloclastites, and sills. The dominant composition is tholeiitic basalt, but ultramafic (picrites, komatiites) to alkali basalt compsitions are found. Thick series of sub-surface seismic reflectors are seen dipping away from the thickest parts of the plateau. This structure was apparently produced totally within oceanic lithosphere, without the usual continental rifted margin. Two widely distributed volcanic phases have been identified. The first at 88-90 Ma appears to be the main body of the plateau, produced by variable degrees of melting and homogenization of plume and asthenospheric mantle. The second at ~76 Ma is associated with extended, thinned parts of the plateau and is more uniformly depleted and MORB-like. A third volcanic phase of small-volume, parasitic central volcanoes of unknown age and composition appears to be structurally controlled. Multi-phase volcanism and extension are common features of other oceanic LIPs. The size and timescale of ocean plateau construction is comparable to that of volcanic rifted margins.

Cenozoic magmatism in Africa: one plume goes a long way

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Mantle plumes through time have permanently modified continental and oceanic lithosphere, yet little is known of the interactions between plumes and a laterally variable lithospheric lid. We aim to examine the interactions between a large mantle plume and topographic relief at the base of the continental lithosphere, comparing model and observations from the northern African plate, which is relatively stationary in a hotspot reference frame.

Northern and central Africa are characterised by extensive volcanism since ~45 Ma, manifest in the form of broad plateaux and narrower swells capped by eruptive volcanic centres (e.g., Darfur, Hoggar). The most voluminous magmatism occurs within the 1000 km- and 1300 km-wide Ethiopian and East African plateaux, respectively, which are transected by parts of the Oligocene-Recent Red Sea, Gulf of Aden, and East African rift systems. Several of the smaller swells lie on or near lithosphere thinned during Cretaceous-Paleogene rifting episodes. Burke (1996) suggests that the volcanism and uplift stems from up to 40 small plumes impinging on a sluggish plate. Our objective is to model only one large plume beneath the Ethiopian plateau, taking into account lateral flow and ponding of plume material in pre-existing zones of lithospheric thinning.

These thin zones are Mesozoic-Paleogene rift basins, and the passive margins of East Africa, which guide the flow of hot, buoyant plume material as far as the Cameroon volcanic line, ~2000 km west, and the Comoros Islands, ~1800 km SW, of the plume's centre.

From these numerical models of lithosphere-plume interactions, we find that one large plume beneath the Ethiopian plateau can explain the distribution and timing of magmatism throughout East Africa, Arabia, and the Indian Ocean margin of Africa, as well as volcanism at Hoggar, Darfur, and Adamawa. Cenozoic reactivation/inversion of pre-plume sedimentary basins in Africa may be caused by ponding of plume material in pre-existing lithospheric thin zones.

Indian continental margin and Deccan Large Igneous Province

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Massive, transient late syn-rift-to-breakup volcanism during the separation of the Seychelles microcontinent from India emplaced the Deccan continental flood basalts and their equivalents on the Seychelles-Mascarene Plateau and on the conjugate continental margins; i.e. the Deccan Large Igneous Province. Regionally, the tectono-magmatic evolution of the conjugate margins is poorly delineated due to absence of high-quality deep seismic profiles. Nonetheless, we estimate an original extrusive area of at least 1.8 x 10^6 km^2, and a extrusive volume of >1.8 x 10^6 km^3. We suggest a plate tectonic history comprising: 1) continental separation prior to A31 time in the NW Arabian Sea linked to the Mascarene Basin by a transform west of the Seychelles Plateau. 2) Development of the Seychelles microplate by fan-shaped spreading in the Mascarene Basin, and continental extension followed by fan-shaped spreading between India and the Seychelles during A29-27 time. 3) Cessation of fan-shaped spreading in the Mascarene Basin just after A27 time, and normal sea floor spreading along the India-Seychelles plate boundary. 4) Margin subsidence, modified south of Goa by the persistent, time-transgressive effects along the plume trail. Thus, the margin is divided into three regional provinces by the prolongation of regional transforms which formed the east and west boundaries of the Seychelles microplate during breakup and early sea floor spreading. In some aspects, the conjugate margins are different from many Atlantic volcanic margins, for example regional wedges of seaward dipping reflectors along the continent-ocean transition have not yet been reported. We ascribe this to the emplacement of the most voluminous lavas during chron 29r, i.e in a late syn-rift setting. The enigmatic Laxmi Ridge is a complex marginal high comprised of both continental and oceanic crust, probably created during breakup but may have experienced later magmatic and/or tectonic deformation.

Relation of alkaline volcanism and active tectonism within the evolution of the Isparta Angle, SW Turkey

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The Isparta Angle (IA) is formed along the boundary of the African and Eurasian plates by NE- and NW - striking faults north of the Antalya Gulf in SW Turkey. The NE - striking strike-slip Burdur fault bounds the IA to the west and is probably the continuation of the Pliny system of the Hellenic arc; the NW - striking Aksehir fault bounds it to the east. Platform-type, parautochthonous Mesozoic carbonate sequences such as Beydaglari and Anamas - Akseki occur in the western and eastern parts of the IA, respectively, whereas allochthonous ophiolite nappes include the Antalya, Beysehir-Hoyran, and Lycian nappes.

The IA and adjacent regions are divided into three areas - The Teke, the Antalya and the Akseki fragments - by NE-, NW- and N- striking active strike-slip faults with normal components. IA region volcanics are alkaline and hyperalkaline in character (potassic, ultrapotassic) and locally occur as subvolcanic stocks and dikes. They can be traced between the Afyon and Isparta regions. These volcanics consist mainly of latitic and trachytic lavas, leucitic and lamproitic dikes, and pyroclastic constituents. Alkaline volcanic centers are located on the west side of and parallel to the N-S trend of the Egirdir-Kovada (EK) graben. The volcanics range in age from 15 to 4 Ma and get younger from north to south; their arrangement along the N-trending EK depression indicates the development of this volcanic activity contemporaneous with active tectonics during the Miocene to early Pliocene. The volcanic centers are on the synthetic fault elements of the EK intracontinental rifting (or half -graben) in connection with the northward movement of the African plate.

Deep crustal structure and rheology of the Gascoyne volcanic margin, Western Australia

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The Western Australian margin was formed during Valanginian continental breakup between Australia and Greater India, and was associated with transient breakup volcanism. The Gascoyne margin segment, including the Exmouth Plateau, is characterized by extrusives (e.g., Seaward Dipping Reflector Sequences, SDRS), intrusives, and magmatic underplating. Flood basalts commonly cover rift structures along volcanic margins, e.g. along most of the NE Atlantic margins, making seismic imaging of deeper crustal structures difficult. Locally, very little flood basalts cover the rift system on the Gascoyne Margin enabling mapping of extensional structures and deep crustal features seaward to the continent oceanic boundary (COB). This margin is thus well-suited for studying continental breakup processes.

Interpretation of deep seismic reflection data (16 s twt) across the Gascoyne Margin reveals six distinct seismic facies units related to the tectono-magmatic breakup history. On the outer Exmouth Plateau four main units are identified: (1) extensively block-faulted upper crust; (2) a middle-crustal unit of discontinuous, undulatory reflectors; (3) a reflection-free deep crustal unit; and (4) a lower-crustal band of low-frequency, high-amplitude reflectors. Two additional units are found near the COB: (5) SDRS; and (6) landward-dipping reflectors in the lower crust below the SDRS.

The SDRS and thick oceanic crust (3 s twt or ~10 km) in the Gascoyne Abyssal Plain indicate high melt production, corroborated by seismic and borehole evidence of Early Cretaceous sill-intrusions in the landward basins. The SDRS are partly isostatically supported by rotated continental fault blocks in the lower crust. This interpretation is based on the observation of landward-dipping reflectors below the SDRS. The lower-crustal high-reflectivity band located near the top of the high-velocity unit (P-wave velocity of >7 km/s) is related to magmatic underplating. The underplated material is added to the crust, isostatically compensating the outer margin. There is a spatial correlation between the underplated area, upper-crustal block faulting, and shallow intrusives. The undulatory middle-crustal reflector unit is only identified in the same region, and is interpreted as a ductile deformed zone in which the upper-crustal faults terminate. The inner part of the margin consists of a deep basin showing little upper-crustal faulting and no evidence of middle crustal ductile deformation or underplating.

The mode of crustal deformation is strongly dependent on pressure and temperature. To examine the transient rheological effects of the emplacement of high-temperature mafic melts at the base of the crust we have constructed one-dimensional crustal strength profiles for various time steps based on the crustal structure of the Gascoyne margin. It is assumed that the heat transfer is conductive and that deformation is by non-uniform pure shear. The modeling shows that an upper crustal brittle layer of 10-km thickness is reduced to 6-km during a 5 m.y. period when 2-5 km thick hot mafic material is underplated. When underplating occurs during the late rift stages it may thus modify the style of upper crustal faulting. Furthermore, the deep part of the existing brittle faults may move into the ductile domain leading to destruction of their crustal fabric. The modeling results correlate well with the seismic facies interpretation. We propose that the seismic structure of the outer Exmouth Plateau can largely be explained in terms of the transient rheological structure associated with magmatic underplating, with: 1) thinning of the upper crustal brittle deformation zone; 2) middle crustal semi-ductile deformation erasing previous brittle fabric; 3) lower crustal ductile deformation destroying any previous layered crustal fabric; and 4) the top of the underplate represents a distinct lithological boundary clearly imaged in the reflection data.

Namibia volcanic margin and the South Atlantic large igneous province

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The Early Cretaceous South Atlantic continental breakup and initial sea floor spreading were accompanied by large-scale, transient volcanism emplacing the Parana-Etendeka continental flood basalts and voluminous extrusive constructions on the conjugate margins south of Torres Arch-Abutment Plateau. These constructions include prominent wedges of seaward dipping reflectors off Namibia, southern Brazil, Uruguay and Argentina. On the Namibia margin we interpret four main tectono-magmatic crustal units: 1) oceanic crust; 2) thickened oceanic crust with 5-7 km thick seaward dipping wedges; 3) 75-150 km wide breakup related rift zone partly covered by the dipping wedges; and 4) thicker continental crust, partly deformed by Paleozoic extension, east of the Early Cretaceous rift. Unit 3 also contains breakup related intrusives and units 2-3 are underlain by a probable high-density lower crustal body. The common origin and similarity of the Parana-Etendeka continental flood basalts suggests that there is continuity between these two provinces and thus, these basalts are present offshore in the breakup related rift zone. Similar settings also characterize other South Atlantic margin segments. We infer an up to 300 km wide and 2400 km long rift zone representing lithospheric extension leading to breakup and formation of the South Atlantic volcanic margins.

Extension and volcanism: insights from dynamic modeling studies

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Numerical simulations of continental rifting illustrate the complex relationship between extensional tectonics and the rate, duration, and location of associated magmatism. Many aspects of magmatism at rifted continental margins are found to be counter intuitive. For example, finite element models of extension in a rheologically heterogeneous lithosphere produce a whole-crust simple shear style of rifting that is commonly associated with limited syn-extensional volcanism. However, the models demonstrate that thinning in the underlying lithospheric mantle can be quite pronounced, resulting in substantial amounts of magmatism without requiring unusually high mantle temperatures. One consequence of this style of extension is the development of potentially large lateral pressure gradients in the lower crust. Ascending magma may be deflected by these pressure gradients, resulting in intrusive and extrusive centers that are significantly offset from the zone of melt generation in the mantle. This offers one possible explanation for the presence of large igneous provinces on rifted continental margins that are not centered around the rift axis, such as the Parana province of South America.

Of equal interest are the circumstances required for non-volcanic continental rifting. Previous modeling studies have shown that if the base of the lithosphere maintains a constant heat flux during extension then magma generation by decompression melting in the asthenosphere is unlikely. We have developed a broader range of models that show that limited magmatism can also be produced with a constant temperature or adiabatic basal boundary condition if the extension rate is relatively high. In this case, thinning of the lithospheric mantle is highly localized and progresses rapidly once the asthenosphere has ascended to shallow enough depths to produce melt. As a result, melt generation does not begin until 2-5 m.y. prior to the onset of seafloor spreading, even if the mantle potential temperature is large. Since constant heat flux boundary conditions are more likely at low extension rates (allowing for cooling of the lithosphere) and constant or adiabatic boundary conditions are more likely at high extension rates, it appears that optimal conditions for generation of large amounts of magma during extension occur at moderate extension rates. Under these conditions, the total volume of melt generated is controlled primarily by the mantle potential temperature, as has been previously recognized. Finally, the models demonstrate that the often overlooked lithospheric mantle can play a significant role in melt production during the early stages of continental extension. Early syn-extensional melting is widely recognized in continental extensional provinces such as the Basin and Range province of western North America, but it is difficult to account for with conventional decompression melting models because melting within the asthenosphere will not begin until a relatively large amount of extension has occurred, even at high mantle potential temperatures. This is also true of the lithospheric mantle if it follows a dry peridotite melting relationship. However, melt metasomatised lithospheric mantle may contain significant amounts of basaltic composition material.

If the lithosphere is initially about 100-150 km thick, this mantle will begin to melt immediately after the onset of extension, and can produce relatively large amounts of magma during the early stages of extension. As extension progresses the lithospheric mantle passes into the basalt sub-solidus field, and melting ceases. This occurs at about the same time as the asthenospheric mantle passes into the peridotite supersolidus field, leading to a progression in magma sources from early rift lithospheric mantle to late rift asthenospheric mantle.

Continental Flood Basalts associated with continental break-up

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The interplay between magmatism and tectonics is complex, and it is particularly difficult to infer ancient tectonic settings from the compositions of igneous rocks. For example, not all OIB-like rocks are related to mantle plumes, and the calc alkaline rocks generated under extension in the Basin and Range can be very similar in both major and trace element compositions to those generated in compressional regimes above recent subduction zones. Continental flood basalts (CFB) exhibit a significant range in compositions, and perhaps in average eruption rates, and it is increasingly argued that they may be generated by different processes in different settings. Differences in their average eruption rates imply that they also affected the environment differently.

The Deccan and the Parana-Etendeka CFB are taken as contrasting examples among the well studied Mesozoic CFB. The former include rocks which have major, trace element and radiogenic isotope ratios strikingly similar to those erupted on the associated hot spot trace in the oceans. Their high average eruption rates, and the similarities of their fractionation-corrected major element compositions to those predicted from melting of fertile peridotite with potential temperatures of ~1530°C, are consistent with melt generation within the mantle plume. In contrast, most of the Parana-Etendeka CFB have major, trace element and isotope compositions not commonly observed in oceanic basalts, and these have consistently been attributed to source regions in the continental mantle lithosphere. It is inferred that different mechanisms may have been operating in their formation.

A feature of magmatism in the Parana-Etendeka CFB is that it appears to have had a strong tectonic control in that it was associated with two dominant dyke swarms, one trending NW-SE and the other approximately coast parallel. The former have compositions similar to the high Ti/Y lavas of the northern Parana, whereas the coast parallel (N-S) dykes have compositions similar to the low-Ti/Y lavas of the southern Parana. Most of these CFB have compositions consistent with derivation from within the mantle lithosphere, and the published Ar-Ar ages range from 138-125 Ma, but with a marked peak at 133-129 Ma. Melt generation rates increase from ~ 0.05 km^3yr^{-1}on the NW-SE trending dykes to ~0.2 km^3yr^{-1} on the coast parallel dykes with time, as do the amounts of extension. A simple model has been developed to examine the amounts and rates of melt generated from the continental lithosphere (at the hydrous solidus) and asthenosphere under finite duration extension over anomalously hot mantle. Emplacement of a mantle plume with Tp = 1450°C beneath a 150 km thick continental lithosphere, was followed 5 my later by the onset of extension. Two competing factors control the thermal evolution of the lithosphere; heating due to the anomalously hot underlying mantle and cooling as a consequence of extension. Initially, melt is derived exclusively from within the mantle lithosphere (viz. the Parana CFB) until b = ~1.4, whereupon melting in the mantle lithosphere ceases abruptly. On further extension, no melt is generated until b = ~2.8 and then it is all from the asthenosphere (dry peridotite) as a consequence of decompression. The increasing rate of extension rapidly leads to full ocean spreading over anomalously hot mantle, producing the thickened oceanic crust of the Rio Grande Rise and the Walvis Ridge. A feature of such models is that there is a small but detectable period in which no melt is generated after the end of melt generation in the lithosphere and before the onset of melting in the underlying asthenosphere.

Isochronous changes in the images of the Cretaceous-aged oceanic crust of the Angola Basin / South Atlantic

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The compilation and analysis of abundant MCS reflection profiles in the Angola, Cape, Brazil and Argentine Basins as well as of widely extended so-called flow-line traverses south of these regions revealed clearly structured variations of the Cretaceous-aged oceanic crust regarding its reflectivity pattern, its shape of the basement surface and its crustal thickness. On the basis of these particular features we defined four crustal categories for the area under study:

Crustal category A comprises the prominent wedges of seaward dipping reflector sequences (SDRS) beneath the continental margins of the South Atlantic (see also Reichert et al. and Schreckenberger et al., this volume).

Crustal category B has a small-scale irregular basement relief, and the upper and middle crust is seismically almost transparent. Coherent reflectivity is low in lower crustal levels.

Crustal category C has a strongly reflective and irregular basement relief with offsets in the range of 100-300 m. The shallow crust contains some subhorizontal reflection elements, and the middle crust is seismically almost transparent. The lower crust and possibly the uppermost mantle is represented by a reflective sequence, 1-1.5 s TWT thick, of reflections dipping approximately 20°-30° towards the spreading axis.

Crustal category D is characterized by a flat to smooth basement surface and a sequence of seaward-dipping reflectors beneath. This upper-crustal sequence resembles the SDRS of volcanic margins (our category A), but its thickness is much smaller (0.3-0.8 s TWT). Typically, the lower crust exhibits high-amplitude reflectivity without a preferred pattern. This sequence is up to 1.5 s TWT thick. Its upper boundary against the mostly transparent middle crust has a variable relief. Downward termination of the reflectivity pattern is rather abrupt between 9 and 10 s TWT in the Angola and Brazil Basins.

Correlation of the categories yielded a ridge-axis parallel zonation evidencing isochronous proper-ties of the respective zones. Crustal category A represents the sub-aerial emplacement of extensive lava flows during the early rift stage that presumably occurred concomitantly with the emplacement of the Paranà and Etendeka continental flood basalts. Crustal categories B on the one hand and C and D on the other represent contrary types forming an alternately isochronous series that extends a couple of thousand kilometers in ridge-parallel direction.

In our view, the strong zonation of oceanic crust properties is in contrast to the different current hypotheses for the formation of the volcanic continental margins since radially symmetric hot plumes or hot spots are presumed likewise. On the contrary, the elongated widely extending (up to 3200 km) and alternating zonation suggests that we are dealing with episodic events or hot phases of the mantle generating different crustal types during the respective stage of crustal accretion. Tentatively, we refer to the Lherzolite ophiolite type (HOT) regarding crustal category B and to the Harzburgite ophiolite type (HOT) regarding crustal categories C and D; the latter showing increased crustal thickness and high lower-crustal reflectivity being in good agreement with the required HOT properties and the presence of layered gabbros in deeper crustal levels.

The proposed model is supported by the results of seismic wide-angle/refraction studies at three selected locations in the Angola Basin. Location AB-1 shows a crustal thickness of 6-7 km (including 1.5-2 km of sedimentary cover) while the lower crust with velocities >7 km/s is 2-3 km thick. This correlates well with crustal category B. On the contrary, locations AB-2 and AB-3 show crustal thicknesses of 8-9 km including about 1km of sediment on top while the lower crust attains thicknesses between 4.5 and 6 km. In our interpretation this coincides with crustal categories C (AB-3) and D (AB-2) where the more detailed classification is deduced from the MCS data.

East Greenland Margin - SIGMA Transect III

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The influence of the Iceland hotspot on the formation of the South-East Greenland margin was investigated by four seismic wide-angle and near -vertical margin crossing transects carried out from the R/V Ewing in 1996. Transect III is situated 630 km from the hotspot track and coincides with drill sites visited on ODP legs 152 and 163. Along this transect we recorded near-vertical reflection data, wideangle data on 17 marine locations and 6 land locations as well as gravity and magnetic data. The velocity structure of the crust on the landward end of the transect shows a continental crust, and the seaward end is close to normal oceanic crust. The continent-ocean transition (COT) takes place over approx. 50 km and is defined by the replacement of continental style velocity structure by a thick crust with mafic-igneous velocities, reaching 7.4 km/s at the base of the crust, coinciding with the interpretation by Larsen et al (in press ODP sci. res. 152). The COT is followed by a thick, mafic igneous crust, a thick subaerially extruded Seaward Dipping Reflector Sequence (SDRS), and with a high velocity lower crust, which merges into normal oceanic crustal velocity structure. The reflection seismic data show a development in formation of the extruded part of the crust from the proven subaerially extruded (Larsen and Saunders, in press ODP sci.res 152) major SDRS at and immediately after the COT, through a rough area, interpreted as a change to submarine extrusion, back to a smooth top basement with a second and smaller set of SDRS. Similarities of basement reflection pattern with the main SDRS wedge indicate an abundant magma supply producing flows able to flow significant distances. One interpretation could be that the ridge re-emerged above sealevel, to form a subaerially extruded SDRS similar to the main wedge, but the thinning crust and initial subsidence estimates based on gravity modelling favour a model where the ridge submerged sufficiently deeply (> 1000 m; T. Gregg, pers. comm) to allow sufficiently long flows. The gravity modelling must include a mantle cooling with time in order to match the observed gravity.

The deep crustal structure of the continental margin off Van Mijenfjord, West Spitsbergen: Preliminary results

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While the North Atlantic including the Greenland Sea began to open approximately 50 Myr ago, there was no direct connection between the North Atlantic mid-ocean ridge system with the one in the Central Arctic. It took more than 30 Myr, before a deep water entrance into the Central Arctic was installed and a mid-ocean ridge system developed in the Fram Strait. Features like the Knipovich Ridge, the Molloy Fracture Zone, the Molloy Deep, the Spitsbergen Fracture Zone and the Lena Trough were created through the propagation of the North Atlantic mid-ocean rift system towards the north. Intensive bathymetric and geophysical investigations in the past (Sundvor & Austegard, 1990; Eicken, 1994; Crane & Solheim, 1995) have mapped this complex geology in the Fram Strait south of 80°N. The opening of the Fram Strait was accompanied by a southward drift of Svalbard relative to North Greenland. Remnants of this large strike slip movement of Svalbard can be found onshore and offshore its western margin. During this orogeny, a narrow thrust and foldbelt developed along the west coast of the island. Prominent geological elements are the Hornsund Fault Zone (HFZ) and the Tertiary orogeny belt of Svalbard. Close to this prominent fault zones a spreading axis, the Knipovich Ridge, is located at, or just beyond the continental slope. The active ridge is only 100 km west of the proposed continent-ocean transition (COT) as proposed by Myhre and Eldholm (1987). Later, seismic experiments and gravity modelling confirmed the interpretation of the Hornsund Fault Zone as COT along the margin (Austegard & Sundvor, 1991). In the area of the COT off Hornsund a positive anomaly of more than 100 mgal controls the modelling of this area as the seismic reflection data show only poor signals in the transition zone. The existing geophysical data give no indication of underplated high velocity material in the lower crust within the transition zone which are suggested by geodynamic models for continental margins close to a hot spot (here, the Yermak hot spot).

In September 1997, therefore, the Alfred Wegener Institute for Polar Research (AWI) acquired new high resolution seismic refraction data in the area of the Van Mijenfjord to investigate the location and structure of the COT along the western Spitsbergen margin. Based on the available geophysical information it was suggested that the COT is located close to present coastline allowing its mapping with densely spaced seismic recording stations (in total 15) within the Van Mijenfjord. In addition, ocean bottom hydrophones (OBH) were deployed up to 70 km off the fjord. The REFTEK stations onshore were equipped with up to 9 geophone chains (36 geophones). Three large volume airguns (2x60 l, 1x32 l) were used as seismic source from RV Polarstern.

While we found seismic velocities of 3.5 to 4.4 km/s for sediments in the Van Mijenfjord, west of HFZ lower seismic velocities (2-3 km/s) are present. The seismic data quality is very poor on all 20 recording stations, when signals passed the HFZ. This may indicate, that a very complex geology is scattering the energy to a large amount. The Pg phase can be observed up to the onset of the mantle phase at 100 km. Velocities up to 6.5 km/s can be identified directly from this phase. Yet, no higher refraction velocities could be observed. A smooth velocity gradient down to the Moho ending up with 6.9 to 7.0 km/s explains the PmP arrivals very well. Close to the onset of the Pn Phase the travel time branches are very complex and difficult to interpret.

The preliminary model of the wide angle data show that the crust is thinning from 35 km in the inner part of the fjord to 15-18 km west of the HFZ. This is in good agreement with the gravity modelling (Austegard & Sundvor, 1991). Weak reflections just below the PmP Phase indicate that the lower crust is segmented close to the crust-mantle transition. Signals later than the PmP phase are not modelled yet, but may indicate strong faulting down to the Moho within the Tertiary orogeny belt. No clear evidence for the presence of underplated, high velocity material in the lower crust has been found in the area investigated. Signals from oceanic crust are recorded just west of the HFZ.

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Fast plumes and the separation of timescales in mantle convection

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In flood basalt provinces copious amounts of material have been brought to the surface within an extremely brief period of time, on the order of a few Myr. A small, fast moving plume appears to be a more viable mechanism from observational constraints than postulating a gigantic plume head with a diameter equal to or larger than the thickness of the upper mantle. In order to reconcile the idea of a fast moving plume with the observed plate velocities, it is necessary to have a mechanism for inducing a sharp separation of timescales in the flow. Thermal convection with a non-Newtonian temperature- and depth-dependent rheology can self-consistently produce extremely fast plumes rising at speeds around a few to tens of meters per year in an otherwise slowly (cm/yr) convecting mantle. This mechanism is capable of bringing very hot material from the transition zone to the near surface, where considerable melting would take place. In a high-resolution (2 km resolution) simulation we find that plumes in a Newtonian mantle are an order of magnitude slower than their non-Newtonian counterparts, and that the detailed thermal structure of the non-Newtonian plume head is much more complex. Hot thermal anomalies near the surface are up to 20% warmer in the non-Newtonian case.

The Tertiary North Atlantic Large Igneous Province: Too much melt or too little?

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Models for crustal accretion at the rifted margins of the Tertiary North Atlantic large igneous province (NALIP) should account for available constraints on mantle melt productivity offered by petrology, geochemistry, geochronology and geophysics. Petrology and geochemistry indicate that during continental breakup and initiation of seafloor spreading at 61-56 Ma the mean extent of mantle melting increased from 5 to 20%, largely in response to thinning of the lithosphere. Comparison of results of forward modeling of polybaric melting with the magnitude of rare earth element fractionation in primary mantle melts from sites both proximal and distal to the Faeroe-Iceland-Greenland ridge suggests melt generation at temperatures <100º C above ambient mantle. The highest extents of melting correspond to the emplacement of the seaward-dipping reflector sequences (SDRS) along the continental margins, and are comparable to those inferred for normal ocean ridge settings. Geochronology and geophysics constrain the rate of melt production during formation of the SDRS to be 8-13 x 10^{-4} km^3 y^{-1} per km rift length. These crustal production rates are roughly an order of magnitude greater than for normal oceanic crust. In a case study of the Southeast Greenland volcanic rifted margin, trace element systematics constrain the mean extent of melting to be 15% for basalts of the SDRS (Fram et al., in press, ODP Leg 152 SR vol.). Larsen and Saunders (in press, ODP Leg 152 SR vol.) estimate a maximum half spreading rate of ~4.4 cm y^{-1} during emplacement of the SDRS. Even for such a high spreading rate only 25% of the crustal volume is accounted for by passive upwelling. The remaining 75% is attributed to the presence of active flow. We estimate that the excess mantle flux necessary to account for the 20 km thick basaltic crust formed by modest extents of partial melting between 56-52 Ma requires a flow rate of >12 cm y^{-1}. We speculate that three factors may have facilitated a transient period of active upwelling along the rifted margins of the North Atlantic: 1) the Tertiary source mantle was compositionally, in addition to thermally, buoyant; 2) the presence of metasomatic fluids or partial melt lead to increased non-Newtonian behavior of the upwelling mantle;

and 3) the early development of lithospheric thin spots and a steep continent-ocean transition focused mantle upwelling. The apparent contradiction between the petrology/geochemistry, indicating modest degrees of mantle melting, and geochronology/geophysics, requiring high rates of melt production, are not adequately accounted for in current incubating and starting plume models. A revision of the paradigm for the formation of volcanic rifted margins needs to incorporate explicitly the influences of active upwelling, variable source composition, and lithosphere structure, in addition to anomalous temperature, on the dynamics of mantle flow and melt generation beneath rifting continents.

Crustal structure and evolution of the East Antarctic volcanic margin

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The Earth's crust of the East Antarctic margin located in the eastern Weddell Sea (EWS) and Laser Sea (LS) contains a thick (more than 5 km) sequence of oceanward dipping reflectors typical of worldwide volcanic margins and so interpreted as consisting of extrusive rocks (Hinz et l, 1981). This sequence known as Explora Wedge has been best studied in the EWS where a considerable amount of geophysical data have been collected by many countries. It is clearly recognized here by the high-amplitude (up to 300 nT) long-wavelength magnetic anomaly including well correlated linear anomaly components, the number of which is ranged from 2-3 on the Coats Land (CL) margin up to 7 on the western Dronning Maud Land (WDML) margin. The components adjacent to the continent tend to diverge landward and are correlated over WDML with an inshore set of pronounced linear magnetic and gravity anomalies developed out of Explora Wedge within the normal (according to seismic refraction data) continental crust and interpreted confidently as the mafic intrusive bodies. Based on observed correlation and modeling of anomalies it is suggested that there is a common suite of intrusions (dykes) extending from the mainland to the offshore area and implying a similar nature of country rocks. If this is the case, the major part of Explora Wedge is underlain by the stretched continental crust favoring the "Late Rift" model for the formation of this sequence. In this interpretation the continent-ocean boundary is located beyond the offshore-inshore system of coaxial anomalies i.e. oceanward of the upper continental slope of the EWS.

In pre-breakup Gondwana reconstruction Explora Wedge is placed radially within the 2000 km in diameter mantle plume head proposed by White and McKenzie (1989) beneath the central part of Southern supercontinent on the base of distribution of Early to Middle Jurassic flood basalts in the Karoo province (SE Africa) and WDML. The geophysical and geological data from the EWS region show decrease in the volume of emplaced igneous material and magnitude of crustal uplift (including oceanic crust) from WDML and its margin toward the south-west. The Explora Wedge being as much as 100-120 km wide on the WDML margin pinches out gradually off CL whereas total thickness of the igneously contaminated crust, involving the volcanic sequence, in these regions is reduced from 16-18 km to 10-12 km, respectively. Moreover the crust of the outer part of WDML is supposed to be heavily underplated and intruded by the mantle derived rocks that is evidenced by modeling of extensive, high-amplitude (about 150 mGl) gravity anomaly, unique to this area, and by increment of seismic velocities in the lower crust up to 7.2 - 7.4 m/s. The crustal uplift is best distinguished in the structure of acoustic basement (tops of Explora Wedge and oceanic layer 2) in the EWS which probably retained the record of Mesozoic thermal buoyancy. The surface of the acoustic basement progressively descends from 4-6 km on the WDML margin to 5 - 8 km on the CL margin. All revealed phenomena are well consistent with the inferred thermal characteristics of the White and McKenzie's plume, being hotter in the central part (beneath the WDML, for the region considered) and cooler on the periphery (beneath the CL), and provide an additional proof that plume processes were responsible for formation of the volcanic margin and igneously contaminated crust.

In addition to aforesaid there is an evidence of vigorous igneous activity during early phase of sea-floor spreading between south-east Africa and East Antarctica which has led to formation of many volcanic plateaus, ridges and other edifices (Mozambique Ridge and Agulhas Plateau on the African margin and Maud Rise, Polarstern Bank and possibly Andenas structure on the Antarctic margin) and can be also considered as a result of plume (hotspot) influence. However some facts (i.g. the prominent Orion magnetic anomaly in the southern Weddell Sea placed beyond the proposed plume head province and interpreted as one more igneous complex) testify that magmatic history of the Central Gonwanaland margin was more complicated than is predicted by plume model.

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A simple advection model of initial volcanic margin subsidence

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Many volcanic rifted margins are characterized by an initially rapid phase of voluminous igneous activity that lasts less than 5 m.y. Observations along the U.S. east coast and east Greenland margins suggest that this igneous production is accompanied by rapid subsidence of the volcanic center. That is, as extension proceeds, the elevation of the ridge axis falls. Analyses of basalt seismic stratigraphy along the U.S. margin suggest that the rift axis subsided by ~0.9 km within less than 3 m.y., and morphologic evidence from the east Greenland margin suggests that the volcanic center there subsided by ~1.0 km within 4-8 m.y.

This initial subsidence may be directly related to the volume and geometry of anomalous mantle present beneath the margin at breakup and during the early stages of spreading.

Subsidence of the active volcanic center precludes vertical conductive cooling as the primary subsidence mechanism. Instead, it is likely that this subsidence is related to a "tapping off" of anomalously hot mantle material, as magmatic production wanes over this interval. Here we present simple models of advective cooling beneath the ridge axis which may explain the observed subsidence. Mass balance calculations show that ~1.0 km of uplift is produced by a 100-km-thick column of mantle that is ~250 C hotter than normal. We show that lateral advection of hot mantle during extension, accompanied by vertical advection of heat through melt extraction, can efficiently remove this thickness of hot material, and thus explain the subsidence observations, if the initial volume of hot material is small and finite.

It is important to note that much of the initial subsidence along volcanic margins occurs subaerially and has in fact been inferred from transitions in extrusive morphology associated with subaearial versus submarine volcanism. The sedimentary column thus does not record the earliest phase of volcanic margin subsidence, but instead records the predominantly conductive cooling phase that proceeds once most of the mantle thermal anomaly has been removed. The techniques of subsidence analysis that have been developed and applied in sedimentary basins - drilling, dating, elevation estimation - need to be systematically applied to the basalt sequences of volcanic margins to better quantify the initial phase of volcanic margin subsidence. Such systematic studies will provide important constraints on the volume and distribution of anomalous material beneath the lithosphere during volcanic margin formation.

Karoo and Etendeka flood basalt provinces, southern Africa, and the tectonic development of their adjacent continental margins

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Southern Africa hosts remnants of two continental flood basalt provinces emplaced in association with fragmentation of Gondwana. The earliest is the 183 Ma Karoo Province whose relationship to continental breakup and sea floor spreading is complex. Geochemical stratigraphy, Ar-Ar dating and palaeomagnetism indicate that Karoo mafic igneous rocks throughout southern Africa were emplaced over a very short interval at 183 Ma. Volcanism commenced in the N. Lebombo-Mwenezi area, spread across the whole of southern Africa (Lesotho-Namibia-Botswana) before withdrawing to the Lebombo-Mwenezi-Save region with emplacement of rhyolites at 179-180 Ma. Kirwanveggen volcanism in Dronning Maud Land, Antarctica, was exactly contemporaneous and geochemically identical with that in the southern Lebombo.

Within the main Karoo basin volcanism occurred in association with orogenic unloading of the Gondwanide (Cape) fold belt and the possible start of microplate reorganization to the south. There is little evidence of significant extension within the main basin where the development of large dolerite sheet/sill complexes over significant dyke swarms suggests a neutral stress regime. However, along the Lebombo-Mwenezi-Save lineament, and to the east, there was significant lithospheric thinning by eastward extension with some strike-slip movement along the Mwenezi-Tuli line, all contemporaneous with volcanism. Evidence for prolonged significant eastward extension lies in the Lebombo structure and associated Rooi Rand dyke swarm, the thinned continental crust of the Moçambique Ridge, and the development of the Explora Wedge and Weddell Rift in Antarctica. We place Antarctica in a "loose fit" position against Africa with the Andene-Explora escarpment abutting the east face of the Moçambique ridge. Thus the Lebombo is not the simple pair of the Explora Wedge as suggested by some authors (e.g.Cox,1993). The earliest proven sea floor off south east Africa is at anomaly M22 (ca 150 Ma) although the gap between this anomaly and the continent-ocean boundary is considerable and Lawver et al.(1991) suggests that sea floor spreading might have commenced at 165-170 Ma, some 13 - 18 Ma later than Karoo volcanism. Magmas erupted along the Lebombo lineament did not flow west into the main Karoo basin but to the east. Thus, mafic rocks from the Lebombo-Mwenezi-Tuli-Save lineaments have different sources to those from the main Karoo basin, southern Botswana and Namibia, yet both retain strong lithospheric geochemical signatures. Possible plume-derived mafic rocks are (i) the initial and volumetrically insignificant Mashikiri nephelinites in the northern Lebombo-Mwenezi area, and (ii) the late-stage Rooi Rand dyke swarm which has OIB/MORB geochemical affinities.

The younger Etendeka Igneous Province is associated with the separation of southern Africa and South America. The main phase of Etendeka flood volcanism in northern Namibia occurred within a short interval at 132 Ma and was exactly contemporaneous with dyke intrusions in southern Namibia and in the vicinity of Cape Town. Between Cape Town and southern Angola, rift initiation and continental breakup propagated northwards in segments. There is clear evidence of extension, lithospheric thinning, rift faulting, and sedimentation in grabens in the Luderitz Basin commencing some 20 Ma prior to Etendeka volcanism and associated dyke intrusion. In the Walvis Basin, adjacent to the main remnants of Etendeka volcanic suite, there is evidence of extension but no significant sedimentation prior to volcanism. Sea Floor spreading commenced at about 135 Ma (anomaly M12) off Cape Town, at 127 Ma (anomaly M4) in the Luderitz Basin, and may have been later (ca 120 Ma) in the Walvis Basin. The Etendeka-Paraná subaerial volcanism is usually ascribed to the impact of the Tristan plume on the base of the continental lithosphere. The evidence from the SW African margin is that continental extension and rifting is not initiated by plume impact as there is no close temporal correlation between rift initiation and continental volcanism. The latter commences when the continental lithosphere over the plume is sufficiently extended. In the Etendeka, some of the earliest flood basalts (Tafelkop basalts) have isotopic characteristics which are correlated with the Tristan plume and basalt clasts in underlying coarse conglomerates have OIB geochemical signatures. However,the bulk of the Etendeka and Paraná mafic rocks have strong lithospheric geochemical signatures. Later volcanism returns to asthenospheric (Horingbaai dykes) and OIB-type sources (pre-Upper Barremian Kudu basalts). Despite the different ages and the difference in complexity of tectonic setting, the overall geochemical cycle - from plume to lithospheric to sub-lithospheric sources - in the magmatism of both the Karoo and Etendeka is similar. Although plumes are postulated to initiate magmatism in these provinces, lithospheric extension and rifting are initiated by plate boundary forces.

Evolution of the Red Sea volcanic margin, western Yemen : absolute and relative dating techniques

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Absolute dating has a fundamental role to play in understanding rift processes. The absolute age of volcanic rocks and crustal cooling provides a basis against which the relative age of other processes, in particular surface uplift, can be defined. These techniques have been applied in the study of the continental to oceanic crust transition often associated with the development of volcanic margins, e.g. southern margins of the Red Sea. While it is obvious that break-up was associated with faulting, volcanism, and mountain building, the temporal relationships between these processes (i.e., extension, magmatism, and surface uplift) need to be constrained with field and laboratory data.

Absolute dating

(a) Magmatism

$^{40}Ar/^{39}Ar$ dating of potassic minerals provides a powerful tool for unravelling the age of volcanic rocks. On the Yemen margin of the Red Sea, $^{40}Ar/^{39}Ar$ mineral dating indicates that volcanism began around 31 Ma. ago and that the youngest erosional remnant has an age of 19 Ma. High resolution

$^{40}Ar/^{39}Ar$ mineral dating indicates an important switch from basic to silicic volcanism at ca 29 Ma and a decrease in eruption rates toward the end of the Oligocene.

K-Ar dating: The $^{40}Ar/^{39}Ar$ database for the onset of volcanism (31-29 Ma) is in marked contrast to the K-Ar database for the same rock samples (66-14 Ma) and screened K-Ar data indicate that the earliest volcanism occurred at 20-32 Ma. However, even with careful consideration of secondary effects, for the same rock sample K-Ar data can differ from $^{40}Ar/^{39}Ar$ data by as much as 5-10 m.y. Development of shallow crustal magma chambers and associated hydrothermal systems may have been the source of much of the secondary processes that affected the K-Ar systematics. Consequently caution must be exercised when applying K-Ar dating techniques to basic volcanic rocks.

(b) Exhumation/cooling:

Apatite fission track dating of the Precambrian basement, beneath the sedimentary and volcanic cover, indicated that the volcanic margin was deeply exhumed in the Oligo-Miocene (i.e. < 25Ma). In addition track length data revealed that along the Red Sea margin exhumation was relatively rapid. This contrasts with the Gulf of Aden non-volcanic margin where crustal cooling was less rapid and occurred in the Oligocene. Field evidence of exhumation was found within the uppermost volcanic stratigraphy where $^{40}Ar/^{39}Ar$ dating was used to bracket the age of that erosional episode at 26-19Ma. This is consistent with the apatite fission track dates.

(c) Extension:

$^{40}Ar/^{39}Ar$ dating of the volcanic rocks in the hanging walls of domino fault blocks provided a maximum age for the timing of extension. Similarly apatite fission track dating of the basement rocks in the footwall of domino fault blocks dated the timing of crustal cooling, and, as such, provided an indication of the maximum age of extension. Both dating techniques reveal that on the Red Sea volcanic margin and on the Gulf of Aden non-volcanic margin, extension occurred <26Ma. and <35 Ma respectively. Integration of these results with the data from (a) and (b) indicates that late Oligocene magmatism pre-dated continental break-up by 5 m.y. and that Oligo-Miocene break-up and exhumation were contemporaneous.

Relative dating of surface uplift

The present-day existence of Palaeogene marine horizons *ca* 2 km. above sea level, confirms that surface uplift must have occurred, producing a 3-4 km high volcanic margin, and apatite FT analyses indicate that exhumation/denudation began in the Miocene. If surface uplift is a pre-requisite for erosional and/or tectonic denudation then one can must conclude that uplift was pre-Miocene. Therefore pre-Miocene geology may contain evidence for surface uplift. The pre-Miocene geology is composed of marine sedimentary rocks overlain by fluvial continental sedimentary rocks, thick palaeosols and sub-aerial lava flows (ca 2500 m). Although one could argue that the sedimentary rocks contain evidence of a change in baselevel on the order of tens of metres (i.e., shallow submarine to continental [fluvial] to continental [sub-aerial]) the evidence for uplift is somewhat controversial.

While one could argue that surface uplift was synchronous with the onset of volcanism there is no evidence that pre-volcanic surface uplift of several kilometers occurred prior to volcanic activity. This is at variance with some theoretical models.

Summary

Integration of all these field and laboratory data indicates that break-up of the Afro-Arabian continent and opening of the Red Sea occurred primarily in Oligo-Miocene times. While surface uplift and volcanism (>31 Ma) were essentially contemporaneous, they pre-dated break-up (extension) and exhumation (cooling) by *ca* 5 Ma.(<26Ma).

Contrasting margin style formation close to the former triple junction south of Greenland

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The southeast Greenland volcanic rifted margin and the supposedly non-volcanic rifted margin off southwest Greenland represent the two northern rift branches of the former triple junction south of Greenland. Reprocessed MCS data from and potential field modeling near the triple junction southwest of Greenland show three distinct crustal zones across the margin: (1) Crust (continental ?) with a smooth surface, (2) Oceanic basement with little and smooth relief, and (3) An intensively blockfaulted oceanic basement with blocks downrotated away from the spreading center.

We interpret the initiation of seafloor spreading to have been during chron 27R. 100 km of crust formerly interpreted as oceanic crust (Roest and Srivastava, 1989), are now interpreted as stretched continental crust (zone 1). An apparent absence of faulting, normally seen in stretched continental lithosphere could result from a cover of flow basalts. This is supported by the smooth surface, a general negative magnetization but lack of clear seafloor spreading anomalies. During chron 27R - 24R regular seafloor spreading with abundant magma supply produced a smooth basement (zone 2). A major reduction in magma supply took place during chron 24R, and spreading became partly accomodated by tectonic extension, producing the blockfaulting seen in the most seaward area (zone 3).

We link the opening of the southern Labrador sea to the impact of a plume head below the Greenland micro-plate during chron 27R, changing mantle conditions from normal to a high temperature, melt producing mantle. These conditions, with regular seafloor spreading, lasted till chron 24R, when breakup, rifting and eruption of vast amounts of lava east of Greenland drained the plume source, leaving the southeast Labrador Sea as a magma starved system. The contrasting margin styles seen east and west of Greenland close to the triple junction show that magma distribution on the base of the lithosphere after a plume impact is far from being uniform. Relief of the base of the lithosphere could be a critical factor for this distribution.

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Seismic volcanostratigraphy of large-volume basaltic constructions on rifted margins

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Large-volume basaltic melts are frequently formed in the mantle during continental rifting and breakup reflecting fundamental processes in the Earth's interior. These melts are emplaced at various crustal levels as intrusives or extrusives, being partly controlled by the existing crustal structure. Seismic characteristics of the basaltic constructions varies widely. The P-wave velocity range is from 1.5 to 7.5 km/s, where the low end represents tuffs and volcaniclastic sediments while the upper end represents deep crustal intrusives or magmatic underplating. Additionally, different constructions such as sill complexes, subaerial flood basalt piles, and hydroclastic buildups are commonly: 1) homogenous and isotropic, 2) anisotropic, and 3) heterogeneous, respectively, for typical wavelengths used in seismic reflection and wide-angle work. In fact, a basaltic volcanic system is in terms of seismic structure and constructional processes at least as complex as any clastic system.

We have developed the concept of seismic volcanostratigraphy, i.e. the study of the nature, history and emplacement of volcanic constructions based on seismic data, to analyze the complex nature of voluminous basaltic constructions on the NE Atlantic and Western Australia rifted margins. The method relies primarily on seismic facies analysis combined with studies of petrophysical, borehole, and outcrop data, with the various aspects being integrated by synthetic seismic modeling. The main seismic facies units related to extrusive breakup volcanism are Inner Flows, Landward Flows, Lava Delta, Inner Seaward Dipping Reflector Sequences (SDRS), Outer High, and Outer SDRS. On a given margin transect all units are seldom present, and one unit may occur several times. The volcanic morphology and seismic properties of these facies units are primarily related to presence of water during the eruption and emplacement stages and the local basin geometry. The initial volcanism appears to take place in a shallow marine or wet-sediment environment forming hydroclastites. Subsequent subaerial volcanism in a broad basin setting constructs a sheet-like body of flood basalt, developing into a tripartite 'Gilbert-type' coarse grained delta along the shoreline, with the Lava Delta as a hydroclastic foreset, and the Inner Flows as a heterogeneous volcaniclastic/hydroclastic/massive lava bottomset. The Inner SDRS is formed by infilling of a restricted rift-basin during subsequent continuing rifting, while the Outer High is a hydroclastite build-up formed when the spreading axis is submerged to shallow marine conditions. The explosive volcanism during this stage will lead to massive formation of tuffs that may be deposited over large areas. Finally, the Outer SDRS is formed in a deep sea environment during similar processes as the Inner SDRS by deep marine flood basalt volcanism.

The upper crustal magmatic intrusions can be recognized as high-amplitude, partly climbing events in seismic reflection data. Various terrains with different seismic facies characteristics are observed, and the two dominant types are: 1) smooth, strata-form events in unstructured basin settings, and 2) fragmented, locally steeply climbing reflectors in previously faulted regions. In addition, magmatic underplating is constructions of one or more tabular intrusive bodies emplaced near the base of the crust, typically being identified by P-wave velocities of 7.0-7.5 km/s and a high-amplitude, smooth top reflector. The magmatic underplate can cause a thermal weakening of the overlying crust, permanently changing the structural fabric of the crust. Rheological modeling and seismic facies analysis of deep seismic reflection data off Western Australia suggest that the characteristic seismic fabrics at mid- and deep-crustal levels are related to such a transient thermal weakening.

The seismic volcanostratigraphic studies reveals extensive breakup-related volcanism along most of the NE Atlantic and Western Australia margins. The concept is also useful to highlight the interplay of tectonism and volcanism, e.g. oceanic plateaus like the Wallaby Plateau appears to be constructed from a mixture of volcanics and extended blocks of pre-breakup continental crust, and emplacement of sills is greatly affected by the upper crustal structure. Furthermore, these studies provide insight into seismic wave-propagation and geodynamic processes at volcanic margins.

Velocity structure at the Namibia volcanic margin - evidence for increased ancient mantle activity ?

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An amphibic off- and onshore seismic experiment was carried out across the Namibia volcanic margin comprising three traverses of 630km, 620km and 560km length, respectively. The marine seismic energy source was used for MCS reflection data acquisition and seismic wide-angle/refraction data recording by seven ocean bottom hydrophones (OBHs) and a set of 25 mobile seismic landstations.

The aim of this study is the investigation of the rift-related volcanic-magmatic processes accompanying the initial stage of the opening of the South Atlantic Ocean. On the African continent they are represented by the acid volcanics of the 'Damara Igneous Province' and by the Etendeka continental flood basalts (CFB). Beneath the outer shelf and the continental slope they form an extended belt of volcanic extrusions characterized by 'seaward dipping reflector sequences (SDRS)' (see also Hinz et al. and Schreckenberger et al., this volume).

The MCS data clearly show two distinct series of SDRS: one close to the coast and a second one in the west. The latter is less pronounced on the southernmost profile. In the north the sedimentary cover strongly diminishes toward the coast. Small syn-rift basins are suspected at some places concealed by ringing effects that are partly generated within the SDRS level. The oceanic crust in the west is about 8km thick and overlain by some 3.5km of sediments. About 200km west of the coast crustal thickness starts to increase toward the east. The Moho depth beneath the coast is 30km and increases to 40km inland.

Initial one-dimensional modeling of OBH data within the SDRS zone near the coast yields velocities of 4.2km/s on top of the SDRS at about 2km depth below seafloor (bsf) increasing to approximately 6.5km/s in 11km bsf. This zone is underlain by a unit with high apparent velocities of 7.1km/s indicating anomalous lower crust. In analogy to results from the volcanic margin off Virginia at the North-American East Coast (HOLBROOK et al., 1994) we infer that the high velocities beneath the SDRS off Namibia could represent MgO-enriched and mafic intrusives.

From all data collected so far along the Namibian volcanic margin and in the Angola Basin isochronous variations in the accretion of the oceanic crust are obvious. We therefore suspect that the high-velocity zone underneath the coastal series of SDRS probably forms a distinct element that differs from 'normal' oceanic and continental crust properties. Obviously, plume models are not suited to explain such structures. The evaluation of the entire data set will show whether the hypothesis of episodic non-plume mantle activity finds further support.

Crustal structure of the Greenland - Iceland Ridge

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The Greenland-Iceland Ridge is the western trace of the Iceland hot spot, conjugate to the Faeroe-Iceland Ridge to the east. As part of the SIGMA study of the southeast Greenland margin, a combined vertical incidence/wide-angle seismic profile was run along the ridge, with shots from a 140-L airgun array data recorded on fourteen seafloor receivers and five land stations. The results show a velocity structure for the ridge that clearly indicates a mafic igneous composition comparable to that of oceanic crust. Thin sediments overlie the basement layer, of velocity 4.5-5.5 km/s, which is significantly thicker than normal oceanic layer 2 and which is interpreted as a thick sequence of subaerially extruded volcanics. Clearly identifiable seaward dipping reflector sequences are seen on the reflection data. The main crustal layer, corresponding to oceanic layer 3, has a seismic velocity of about 6.5 km/s, which increases rapidly to 6.8 km/s and then more slowly, reaching 7.2-7.3 km/s at around 25 km depth. The lowermost crust shows distinct layering, with complex and variable layers of high velocity (7.6-7.8 km/s). These are thickest and best developed beneath the western part of the ridge, toward the Greenland margin, and are less well defined near Iceland. There is some indication of this deep layering in the reflection data. The total thickness of igneous crust also increases significantly toward Greenland, reaching 38 km in the western part of the profile compared to 32 km near Iceland. The unusually high-velocity lowermost crust is interpreted to be composed primarily of ultramafic cumulate layers, whose presence would be consistent with magmas formed by a high degree of melting. The structure close to Iceland is similar to that obtained by the FIRE experiment for northeast Iceland, and the increased thickness of igneous crust toward the Greenland margin may be ascribed to the combined effects of a plume impact sheet, as seen elsewhere along the Greenland margin , together with the localized plume stem magmatism.

Extension estimates and implication for vertical movements in the Fenris Graben-Gjallar Ridge region, Vøring continental margin

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Maastrichtian-Paleocene lithospheric extension in the Fenris Graben-Gjallar Ridge region in the western Vøring Basin has been calculated based on crustal thickness and subsidence analysis corrected for underplating, and on structural restoration. Stretching values b, from the ratio between present and restored section lengths, are calculated to ~1.5-1.6 across a 36 km wide fault zone just landward of the early Tertiary flood basalts. The subsidence analysis derived lithospheric extension, based on the tectonic subsidence obtained by backstripping, yields b values ranging from 1.3 in the western Rås Basin to 2.3 in the Fenris Graben-Gjallar Ridge region which is closer to the area of early Tertiary breakup. The crustal thickness derived extension, based on deep seismic reflection and refraction data, results in an average crustal stretching factor ~1.74 along a 117-km-long dip profile, and ~2.3 in the Fenris Graben-Gjallar Ridge region. The structural restoration has facilitated the division of pre- and syn-rift sediments across the extensional terrain, which is subsequently used to evaluate mode and mechanism for the lithospheric deformation. The structural restoration also shows that a middle crustal

dome complex, observed in the southern part of the study area, can be explained by extensional unroofing associated with formation of a metamorphic core complex. Comparison of uniform and two-layer differential stretching models indicates that the uniform extension model may account for the observed syn-rift subsidence, whereas the differential model introduces syn-rift uplift. Nonetheless, other mechanisms such as a mantle plume at the base of the lithosphere, magmatic underplating and rift flank uplift have affected the vertical motion, causing as much as 1.2 km of late syn-rift uplift. The uplift explains the observed erosion and the sub-aerial environment during late rifting and initial seafloor spreading ~50-70 km west of the study area. Excluding the breakup related igneous activity, the observed structural style of the volcanic Vøring margin resembles the "typical" non-volcanic Iberian margin both in the mode and distribution of extension as well as in the spatial correlation of regions affected by crustal and lithospheric thinning.

Crustal structure of the East Antarctic passive margin at 6°E

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Introduction

The break-up of Gondwana created passive continental margins along Africa, South America, India and Australia. The deeper structure of these margins, ranging in age from 180 Myr to 90 Myr, is mostly unknown. This is also valid for the conjugate East Antarctic margin between 30°W and 60°E. From early multichannel seismic investigations (Hinz and Krause, 1982) it is well known that volcanic seaward dipping reflectors (SDRs) are present along the Antarctic margin. Hinz and Krause (1982) suggested a Jurassic age for these units and named them Explora Wedge. They have been formed during the early break-up of Gondwana. So far the western termination of the wedge has been interpreted to be at 20°W, while its eastern continuation is less known. A recent multichannel survey (Hinz, 1996) identified SDRs as far as to Astrid Ridge.

From interpretation of aeromagnetic (Hunter et al. 1996) and marine gravity data (Jokat et al., 1996) it has been suggested that the SDRs underlie the continental margin to 30°W. The combination of the potential anomaly fields with the seismic data strongly supports the interpretation that the SDRs somehow mark the continent-ocean transition (COT) along the East Antarctic margin. To verify this interpretation an expedition was carried out by AWI/BGR in austral summer 1996 to perform a deep seismic sounding experiment across the proposed COT. Two seismic refraction lines were acquired at

6°E (line 96100 close to Astrid Rigde) and at 12°W off the Explora Escarpment. We used seven ocean bottom hydrophone systems (OBH) for recording the signals. The seismic source for profile 96100 was a 54 l Airgun Array operated from the Akademik Nemchinov. The shooting interval was 175 m, while the OBHs were almost 35 km apart. Here, the modelling results of line 96100 will be presented.

Results

In general, the profile can be divided into two parts. In the northern part we observe thickened oceanic crust. Here, the crustal thickness is about 11 km and the Moho depth is at approximately 15 km. In the southern part the seismic velocities suggest a transitional crust. Here, the Moho depth ranges between 14 and 25 km. The uppermost part of the transition zone is built up by SDRs, which can be identified in the seismic reflection and refraction data. The volcanic layers have a velocity of 4.2 to 5.2 km/s and are between 1.5 and 3 km thick. These units disappear approximately in the middle of the profile, where the transition to pure oceanic crust is suggested. At the base of the transtional crust a high velocity zone (up to 7.4 km/s) has been modeled. The exact geometry of the high velocity zone towards the south in not known, as ice conditions did not allow a southward extension of the line.

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Contribution of the Iceland Plume to Palaeogene Rifting and Volcanism in the N Atlantic

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Seaward-dipping reflector sequences found along the margins of the North Atlantic basin testify to the eruption of large volumes of magma during Palaeocene and Eocene times[1]. Sampling of these SDRS, which provide one of the diagnostic characteristics of volcanic rifted margins is, however, sporadic, restricted to the Vøring Plateau (ODP Leg 104)[2], Hatton Bank on the Rockall Plateau (DSDP Leg 81)[3], and the SE Greenland margin (ODP Legs 152 and 163)[4,5]. The lavas are predominantly basaltic, although picrites, dacites and rhyolites also occur.

Recent drilling on the SE Greenland margin[4,5] demonstrates that the SDRS were formed before, during and after crustal rifting and plate separation. The oldest SDRS recovered to date, in the Middle and Lower Series lavas at Site 917, have an emplacement age of approximately 61 Ma[6]. These lavas were coaeval with the activity recorded in West Greenland[7] and the earliest parts of the British Tertiary Igneous Province[8], implying a widespread thermal event at this time[9]. The early lavas from SE Greenland were erupted through continental crust, prior to the main episode of plate break-up[10]. The later, Upper Series lavas from Site 917 were erupted during plate break-up, and include several high-Mg, high-T lavas. Later magmas preserved at Sites 989 and 990 on the SE Greenland margin were also crustally contaminated, and it is not until Site 918, on the main sequence of SDRS, that uncontaminated basalts are found (ca. 54 Ma)[11].

If we assume, from the seafloor magnetic anomaly data, that plate separation occurred at Chron 24r time (56-53.5 Ma)[13], then the thermal anomaly responsible for the 61 Ma lavas at Site 917, West Greenland and the BTIP clearly predates break-up. This in turn strongly suggests that models of VRM formation that rely solely on enhanced mantle convection[14] are inadequate.

Several workers, including ourselves, have argued that the excess magmatism associated with the North Atlantic VRMs is related to the development of the Iceland plume. Picritic, high-MgO liquids preserved in West Greenland[15]. E Greenland[16], and the BTIP[17] are consistent with a high-T magmatic event, although the excess temperature associated with the plume is not accurately known; estimates vary from 100 to 300°C[15,17]. The widespread distribution of the earliest magmatism, at about 61 Ma, implies very rapid lateral emplacement of hot mantle source material, perhaps due to the impact of a plume head at the base of the lithosphere, or the vigorous reactivation of a pre-existing plume system[9,11]. Subsequent break-up of the lithosphere led to decompression melting, perhaps with a component of active convective melting, forming the huge volumes of lavas associated with the SDRS[12].

To demonstrate involvement of the Iceland plume we have used published and new elemental and isotopic data to attempt to 'fingerprint' the existing Iceland plume. The plume is compositionally heterogeneous[19], with a depleted component that overlaps with MORB in isotope space. However, all Icelandic basalts plot within a tightly defined array on a plot of Nb/Y versus Zr/Y; mid-ocean ridge basalts, with lower relative abundances of Nb, plot below the Iceland array[20]. Thus, light-rare earth element depleted basalts from the Iceland neovolcanic zones resemble MORB, but have distinctly higher Nb/Y. Using this simple chemical fingerprint, it is evident that SDRS from Sites 918, 989 and 990 on the SE Greenland margin, and some basalts from Site 642 on the Vøring plateau have Icelandic characteristics, whereas basalts from Hatton Bank, furthest from the ancestral plume axis[21], are more MORB like. *The plume was, and probably still is, compositionally zoned, with a MORB-like shell of mantle around a core of Icelandic mantle*[20].

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Crustal evolution of Central-East Greenland influences Tertiary magmatic underplating

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East Greenland is a well suited natural laboratory for studying crustal evolution. Its geological history from Archaean times to the Tertiary break-up of the North Atlantic is nicely documented in spectacular outcrops. The AWI has undertaken a geophysical study of East Greenland between 70° N and 76° N aiming at an understanding of the architecture and evolution of its continental lithosphere. Although the continental margin is not covered by these studies, the dataset allows to address questions regarding the lithospheric influence on magmatism.

The line of the initial break-up of the North Atlantic deviates far to the east around Central-East Greenland. Along the line, which connects the rift segments to the north and south and short-cuts this deviation, extensive volcanism took place onshore. It produced the massive pile of flood basalts of Geikie Plateau and heavily intruded the Mesozoic Jameson Land sedimentary basin (JLB). North of Kong Oscar Fjord (KOF), this volcanic event can be traced along the coast as far north as Shannon Island, but the volume of intrusives and extrusives is considerably less than south of KOF.

In this northern area, the existence of a magmatic underplate at the crust/mantle boundary could be shown by combining seismic refraction and aeromagnetic data. The underplate is characterised by seismic velocities of about 7.2 km/s and a reversed remanent magnetisation resulting in a pronounced negative magnetic anomaly. Later volcanism probably overprinted this magnetic anomaly, preventing estimates of the extent of the magmatic underplate towards the east and its possible connection to the continental margin. To the south, the anomaly ends in the area of the KOF. South of KOF, there is no geophysical evidence for magmatic underplating of the JLB, although the crustal thickness is comparable to north of KOF and extensive magmatism took place in JLB. Hence, the magmatic melts, which were produced along the entire line connecting the future rift segments, reached the surface south of KOF whereas north of KOF the largest part of the melts got trapped at the crust/mantle boundary.

I suggest that these regional differences in magmatism could result from different lithospheric setting. From the combined interpretation of seismic refraction and gravity data with surface geology a regional model for the crustal evolution since the Caledonian orogeny was derived. It indicates that after the Devonian extensional collapse the area north of KOF experienced lithospheric thinning in two stages which are separated in time and space and produced two distinct steps in the Moho. South of KOF, in contrast, the Moho rises continuously and culminates in about 22 km depth beneath the JLB. This suggests that lithospheric stretching in this area affected the same crustal package during the entire period. It is likely that this differential development resulted in a contrasting architecture of the crust to either side of the KOF, supporting the hypothesis of lithospheric influence on magmatism.

However, our dataset could not resolve the crustal structure north of KOF in as much detail as it is known from existent datasets of the JLB. Hence, the critical differences in crustal structure which determined the contrasting behaviour of the crust towards magmatism remain unclear.

Therefore, comparing in detail the crustal architecture of the underplated and non-underplated areas north and south of KOF would be a very promising target for future studies which aim at the influence of lithospheric setting on magmatism. In addition, examining the structure and eastward extent of the magmatic underplate and its possible connection to the continental margin eventually allows to transfer the results to the continental margin.

Magnetic modeling of seaward-dipping reflector sequences: examples from Atlantic volcanic margins

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Seaward-dipping reflector sequences (SDRS) are one of the most distinctive characteristics of volcanic margins. They were created during the formation of many passive continental margins and are visible in many reflection seismic sections, not only at Atlantic margins. DSDP/ODP drilling of SDRS showed that they are composed of a great number of thin basalt flows which were emplaced subaerially or under shallow-water conditions. Drilling results also show that the basalts have a high natural remanent magnetization (NRM). We used published NRM values from ODP Site 642E to calculate the mean (effective) magnetization for the basalts of the Voring Plateau volcanic section and concluded that the NRM lies in the range between 3.5 and 4.5 A/m. In order to rule out the possibility that the magnetic characteristics of the basalt flows from the bore-hole on the Voring Plateau are a specific property of that special location, we compared them with published magnetization intensities of extrusive oceanic basalts, Icelandic flows, and continental flood basalts. It could be confirmed that NRM intensities of 3 to 5 A/m are common values for extrusive basalts.

Using the effective magnetization intensities inferred from ODP Site 642E we made magnetic models for the SDRS at the Voring Plateau margin that give an excellent fit to the observed magnetic anomalies. We conclude that two different polarity intervals (C25R and C24) are represented in the SDRS and that also the deeper layers of the thick volcanic sequence that have not yet been drilled must have preserved a high remanent magnetization.

We also show seismic data and magnetic models for the South Atlantic continental margin off Argentina where SDRS coincide with a magnetic anomaly called `anomaly G'. The magnetic models confirm that the SDRS are the source of anomaly G, though not everywhere where SDRS have been identified on seismic sections a distinct magnetic anomaly is observed. Although we are convinced that the SDRS off Argentina are the source of anomaly G, an explanation for its irregular shape has to be given: We suggest that the high reversal frequency in the early Cretaceous caused the emplacement of basalts with alternating NRM polarities thus reducing the effective magnetization of the sequence, though it can not be excluded that demagnetization processes or local accumulations of volcaniclastic sediments are the cause for low magnetization intensities. The suspected relationship between SDRS and magnetic anomalies was also found for the J-anomalies in the Central Atlantic.

We explain the observed association between SDRS and strong magnetic anomalies by subaerial basaltic volcanism that deposited long flows of flood basalts. Because single basalt flows cool quickly after their subaerial emplacement they acquire a strong and stable thermoremanent magnetization. The successive accumulation of flows resulted in the formation of the typical reflectors and of thick wedges of SDRS having NRM intensities comparable with that of the thin pillow basalt layer of 'normal' oceanic crust. Consequently, it is the thickening of the extrusive basaltic layer that causes the distinct magnetic anomalies over SDRS that we predict in our model.

Interplay between extension, plume-lithosphere interaction, magmatism and vertical motion on volcanic rifted margins

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Maastrichtian-Paleocene rifting and earliest Eocene continental breakup in the NE Atlantic was characterized by rift inversion and excess volcanism associated with the arrival of the Iceland Mantle Plume beneath the lithosphere from ~63 Ma. Our study has been aimed on understanding the temporal and spatial relationship between extension, plume-lithosphere interaction, magmatism, and the history of vertical motion. From the mid-Norwegian margin, a dense grid of seismic data make us conclude that initial rifting (75-63 Ma) was associated with central rift subsidence and sedimentation. The extension was locally occurring on low angle normal faults over isostatically up-warped lower crust, resembling metamorphic core complexes often observed in highly extended continental rifts and along non-volcanic passive margins. During the final stages of rifting (≥ 63-54 Ma) the rift zone was influenced by emplacement of large volumes of igneous rocks at crustal levels. These rocks are imaged on the seismic data as bodies of 7+ km/s layers at the base of the crust interpreted as magmatic underplating, as sills and dikes in the sedimentary units, and as thick extrusives across the outermost margin. Igneous rocks at crustal levels tend to rebuild the thickness of the extensionally thinned crust, and cause reduced subsidence, or relative uplift, of the underplated regions. This rebuilding will generally not cause surface uplift above a pre-rift reference level, and cannot alone explain the observed central rift erosion being responsible for the thick Late Paleocene deposits in the adjacent shallow basins. Uplift and erosion is, thus, addressed also by evaluating the regional effects of the Iceland Mantle Plume temperature anomaly. Along the Maastrichtian-Paleocene rift axis it is estimated that ~600 m plume related uplift aided central rift inversion resulting in formation of a wide Late Paleocene-earliest Eocene land area.

Geochronology of East Greenland and Faeroes flood basalts in relation to continental breakup and the opening of the North Atlantic

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The central position of the Tertiary flood basalts of East Greenland (EGFB) and Faeroes (FFB) within the North Atlantic Igneous Province (NAIP) makes them pivotal in understanding the interplay between plume impact, continental breakup and excess magmatism. Traditionally, the EGFB has been placed within magnetic chron 24r (ca. 56-53.5 Ma), contemporaneous with earliest seafloor spreading and the formation of the North Atlantic Margin seaward-dipping reflector sequences (SDRS). We report here results from an $^{40}Ar/^{39}Ar$ dating program which shows the parallel presence of a pre-breakup phase of magmatism in East Greenland and the Faeroes and also a major increase in productivity during the opening of the North Atlantic.

The EGFB comprises a lower series representing initial volcanism within sub-basins which is unconformably overlain by voluminous flood basalts. The FFB comprises a thick lower series, which is separated from an overlying middle and upper series by 10 m of coal-bearing claystones. The new age determinations show that the EGFB lower series is older than 24r and corresponds with the age of the lower series of the FFB. Following an apparent hiatus of about 1-2 m.y., volcanism recommenced in East Greenland around 56 Ma , with the eruption of a ~ 7 km thick sequence of plateau lavas in ~ 1 m.y.

Geochemical evidence indicates the presence of plume mantle beneath Greenland 5 m.y. before continental breakup. We conclude that the initial and closely coincident volcanism in East Greenland

and the Faeroes, as well as West Greenland, SE Greenland, and the British Isles was caused by the arrival and rapid dispersal of the Iceland plume head beneath the Greenland lithosphere in the Early Paleocene. Following a ~ 2 m.y. minimum or lull in magmatic activity, melt production rates as represented by the FFB and EGFB reached a maximum around 56-55 Ma. Even higher melt productivity is recorded within the East Greenland SDRS during the interval 56-53 Ma. The peak of magmatism during final breakup and early seafloor spreading testifies that the dominant control on melt production in the Early Tertiary NAIP was the rupture of the continental lithosphere, allowing increased amounts of melting of the Iceland mantle plume through decompression.

Gravity and magnetic anomalies along the continental margin between Dronning Maud Land and Coats Land, Antarctica

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Antarctica represents one of the key continents within the Gondwanaland supercontinent. The break-up of this supercontinent started about 180 million years ago in the Weddell Sea. The record of this break-up process provides critical information for the evolution of the Weddell Sea. Existing geodynamic models propose an initial break-up in the southern Weddell Sea associated with major outpouring of continental flood basalts. During this study a compilation of all existing gravity data in this area has been used for mapping the structural trend of the continental margin. In addition, airborne magnetic data have been used for a joint interpretation. The main structural features in the Weddell Sea related to Gondwana break-up can be identified on the gravity and magnetic maps of this region:

The buried Explora Wedge discovered on the continental margin off Dronning Maud Land consists of a thick (5 km) sequence of seaward dipping sub-acoustic basement reflectors (Hinz & Krause, 1982). This outpouring of extrusive lavas is presumed to be related to the early separation of Africa and Antarctica in the late Mid-Jurassic (Hinz & Krause, 1982). This inferred volcanic rocks produce a strong curvilinear positive magnetic anomaly which was named Explora Anomaly (Hunter et al., 1996). North of the Explora Wedge, the Explora Escarpment is defined by a pronounced bathymetric high of about 0.3 - 2 km elevation above the abyssal plain of the Weddell Sea associated with a basement high (Miller et al., 1990). A second basement high between 30°W and 40°W of about 0.6 - 2 km fully covered by sediments was detected by Kristoffersen & Haugland (1986) on seismic data. It has been regarded to be the prolongation of the Explora Escarpment and, for this reason, was named Andenes Escarpment (Kristoffersen & Haugland, 1986). This proposed linear feature has been interpreted in previous studies (Kristoffersen & Haugland 1986; Hinz & Kristoffersen 1987) to represent the plate boundary of East Antarctica. Hence, the discovery of the Polarstern Bank, a north-south striking chain of three seamounts (Miller et al.,1990; made the presence of a continent ocean boundary in this area unlikely. The Andenes Escarpment and the Explora Escarpment may be of different geological origin and therefore the ridge-like structure of the former Andenes Escarpment was renamed by Jokat et al. (1996) to Andenes Plateau. East of the Andenes Plateau a failed rift basin, the Weddell Rift was first proposed by Hinz & Kristoffersen (1987). From gravity and magnetic models they propose crustal thinning below the rift which may have resulted in the generation of oceanic crust in this area. The rift centre is flanked by transitional crust and wedges of Mid-Jurassic volcanic rocks (Kristoffersen & Hinz, 1991). The poster will present an overview of the potential field data and the knowledge of the continental margin in this area.

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The Western Australian margin: implications for models of volcanic margin formation

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Recent seismic reflection and OBS refraction data, combined with existing seismic and well data, has revealed the presence of an extensive magmatic province along the western Australian margin. The province is over 2000 km in length and up to 450 km in width. It contains well characterised volcanic features related to both volcanic rifted margin-type and plateau-type large igneous provinces (LIPs), and these are particularly voluminous in rift-transform corner settings. The magmatism is represented by thick volcanic sequences on the Wallaby Plateau; multiple seaward dipping reflector sequences (SDRS's) and hyaloclastic buildups along the Cuvier and Gascoyne margins; sill intrusions and magmatic underplating beneath the south-west Exmouth Plateau; flood basalts on the Rowley Terrace and Scott Plateau, and subaerial basalt flows penetrated in a number of wells in the adjacent Browse Basin; and Neocomian bentonitic claystone derived from ash falls around the margins of the Exmouth Plateau. All of these volcanic features are thought to be the result of voluminous magmatism around, or just following, the time of continental breakup - Late Jurassic (~155 Ma) in the Argo Abyssal Plain in the north, and Early Cretaceous (~135 Ma) in the Gascoyne, Cuvier and Perth Abyssal Plains to the south - although the exact age of the volcanism is rarely well constrained. The moderate level of breakup-related volcanism in this region, compared to areas such as the North Atlantic, has left wide zones of the margin extensional terrane uncovered by volcanics, and allows unique seismic imaging of many of the primary features related to fundamental rift and magmatic processes.

The temporal and spatial distribution of magmatic features along the western Australia margin provides important constraints on the applicability of the various models for LIP emplacement. Elevated asthenospheric temperatures have occurred throughout the region over at least a 20 million year period from 155-135 Ma. Whether the temperature was high for the full 20 million year period, or only during the two breakup events, is yet to be determined. The magmatic features generally occupy a broad belt running parallel to the areas of margin formed during both breakup episodes. The exception is the area adjacent to the southwest Argo Abyssal Plain, in the vicinity of ODP Site 765, where there is little evidence of volcanic features on the margin and the oceanic crust is a 'normal' 7 km thick. Further north, the margin is associated with extensive flood basalt sequences, sills, some SDRS's beneath the outer Scott Plateau, and a 10 km thick oceanic (basaltic) crust. This along-strike variability within the same breakup segment is unlikely to be related to different modes of LIP emplacement, but appears to reflect different pre-existing lithospheric compositions (cratonic v. orogenic) and extensional styles.

Both plume and non-plume models have been propose to explain the arrangement of volcanic features along the western Australian margin. The Wallaby Plateau-Zenith Seamount trend of the southern Cuvier margin is the most likely location for a hotspot trail related to a plume. However, there are a number of problems associated with such a model - there is no evidence of major adjacent onshore rift volcanism; Valanginian age breakup magmatism is wide spread and not just restricted to the Cuvier margin segment; and there is no present-day hotspot that tracks back through this area at the time of breakup. Models that seem to best explain the timing and distribution of the volcanic provinces and features are those that incorporate a broad, long-lasting zone of elevated asthenospheric temperatures, which may or may not be plume related, with the magmatism being initiated, and its timing and distribution being controlled by dynamic processes associated with rift, breakup and transform tectonism.

Seismic data over the 300 km wide Gascoyne margin volcanic province provides new insights into the tectono-magmatic processes involved in the formation of SDRS's. Multiple SDRS's are present varying from those in the east that contain long, continuous reflectors, and thus presumably longer basaltic flow lengths, to those composed of much shorter and more disrupted flows in the west. Many of the SDRS's appear to be bounded by relatively low-angle, listric, east-dipping normal faults. These structures have created the half-graben accommodation spaces into which the lavas flowed, and subsequently rotated the flows during continued fault movement. The faults are highlighted by reflectors which may image the fault plane, dykes injected along the fault zone, or both. Several of the faults exhibit late-stage, reverse reactivation. Large volcanic build-ups occur above several of the fault zones and blur the imaging of the underlying SDRS. The faults indicate that extension is an important aspect of volcanic margin formation, just as it is at many slow-spreading mid-ocean ridges. Such structures have also been observed in ophiolites, and early-stage oceanic crust. The interplay of build-ups, faults and SDRS's may indicate that the magmatic and extensional processes are intermittent, or perhaps switch around within the evolving volcanic province. A more detailed understanding of the relationship between magmatism and extension, including the probable temperature and rheological control on the geometry of the landward-dipping faults, should provide new insights into volcanic margin processes.

Large areas of the Wallaby Plateau and the outer Scott Plateau do not have the seismic character commonly ascribed to LIP volcanic basement, and may represent extended and magmatically modified continental crust. It is important to recognise such provinces, and to incorporate the concept into geodynamic models of volcanic margins, because they can significantly reduced the volume of magmatic products required to build LIPS and may imply lower asthenospheric temperatures than suggested by some modelling.

The western Australian margin is now covered by a considerable amount and variety of geophysical data, and may prove to be a key area in which to investigate the possibility of volcanic rifted margin formation in a non-plume setting.

Isotopic diversity in the Damaraland Alkaline Province, Namibia: variations in crustal and mantle reservoirs and processes of mixing

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The general conceptual model of continental rift magmatism includes the production of large volumes of basic mantle melts and the partial melting of continental crust, which leads to bimodal igneous associations. The Jurassic - Cretaceous magmatic province on the rifted continental margins of Brazil and Namibia is a typical example of this setting, and it includes both continental flood basalts (CFBs) and subvolcanic complexes and intrusives. Studies of the Paraná- Etendeka CFB province have established the influence of different mantle sources and the importance of crustal contamination. Nevertheless, the role of asthenospheric, plume- or subcontinental mantle in the genesis of the CFBs is still controversial as is the contribution of cratonic vs. mobile belt-type crust. In contrast to the flood basalts, the coeval subvolcanic complexes have a greater range in chemical and isotopic composition and their spatial relationship to the local crust and mantle is less ambiguous. Therefore they may offer a better chance to characterise the crustal and mantle interaction in this setting.

The Damaraland Alkaline Province in NW Namibia extends from the Atlantic coast to about 350 km inland and includes over twenty subvolcanic complexes which are coeval with the Paraná-Etendeka CFBs (ca. 135 - 125 Ma). Detailed petrogenetic studies have been published from only one of these (Milner & le Roex, 1996). Our study provides new Sr- and Nd- isotopic data from seven additional complexes which represent the full range of compositions present: carbonatites and nepheline syenites (*Kalkfeld, Ondurakorume, Etaneno*), gabbros and syenites (*Messum*), metaluminous and peralkaline rhyolites (*Paresis*), metaluminous granites (*Brandberg*) and peraluminous granites (*Erongo*). The carbonatites and Ne-syenites yield primitive mantle values for εNd (t = 130 Ma) and Sr_i of -1 to +1 and 0.704 to 0.705, repectively. A depleted mantle component in the Messum complex is indicated by elevated εNd values (up to +4 in gabbros). Felsic rocks from the complexes clearly show the influence of two crustal components. Very low εNd values of metaluminous rhyolites from the Paresis complex (-21 at Sr_i = 0.710) indicate *lower crustal* material (pre-Panafrican cratonic basement), whereas the Nd and Sr isotopic composition of the Erongo granite overlaps with that of *upper crustal* basement (Damara metasediments and granites).

The isotopic data from granitoids of the Brandberg complex define a trend intermediate between Bulk Earth and the upper crust. Open system processes were therefore clearly involved, but the Brandberg data deviate from the Paraná-Etendeka CFB trend, which has been established as an example of AFC "mixing" between primitive tholeiite and the upper crust. However, the Brandberg trend can be modelled using the same end member compositions but higher D_{Sr} values (plagioclase-dominated fractionation) and lower assimilation/crystallization rates.

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