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Abstract

Research into the formation of passive rifted margins is incontestably undergoing a paradigm shift. The discovery of exhumed continental mantle and hyperextended crust devoid of significant normal faulting directly overlain by shallow marine sediments is proving fundamental in defining the controls and processes that thin continental lithosphere. However, the development of these new concepts critically depends on the access to pertinent geological and geophysical data sets, which remains a key problem. At present, little is known about the depositional environments, sedimentary facies, the kinematics and age of structures, or the subsidence and thermal history of pre-to syn-rift sediments of many distal margins.

Mapping of rift structures and depositional systems in the Alps has helped to identify lithologies and structures similar to those drilled along the Iberia-Newfoundland margins or those supposedly comprising the pre-salt sag basins of the South Atlantic. The most prominent structures observed in the Alps are top-basement detachment faults. These structures can be traced from relatively unextended continental crust across the ocean-continent transition towards embryonic oceanic crust and are overlain by extensional allochthons, tectono-sedimentary breccias overlain by syn- and post-rift sediments and further oceanwards, MOR-basalts. Crucial observations include: 1) detachment faults formed either late in the extension process or after the crust was already thinned to less than 10 km; 2) shallow depositional environments despite major crustal thinning; and 3) even though there is a lack of volcanic activity, magmatic infiltration has occurred in the underlying mantle while the crust was thinning. These crucial observations have major implications for the thermal evolution and thus survivability of syn-to post-rift petroleum systems in hyperextended margins.
Mapping structures of ancient exposed hyperextended margins in the Alps: A key to understand the evolution of ultra-deep water passive rifted margins

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In collaboration with
L. Lavier, O. Müntener, N. Kusznir, Ch. Johnson
and many others
Major new discoveries in magma-poor margins in the last two decades

Refraction seismic data from the West-African margin: Ifremer /TOTAL
Contrucci et al. 2004

- Mantle exhumation and magma starvation in ocean continent transitions
- Hyper-extended crust with little seismic evidence for normal faulting associated with sag-basins
- Top-basement detachment faults in ocean-continent transitions
Where are the margins that show these features?

Refraction seismic data from the West-African margin: Ifremer /TOTAL
Contrucci et al. 2004

Magma-poor margins with evidence for hyper-extended crust and/or mantle exhumation based on high-quality refraction/reflection seismic data, drilling and/or dredging
The Alpine system in W-Europe

Present-day

Paleogeographic evolution

Late Cretaceous

Late Jurassic

From Manatschal and Bernoulli 1999
Alpine Tethys margins: Historical retrospect

“From oceans to orogens”
Eduard Suess 1831-1914

“Oceans in orogens”
Gustav Steinmann

“Tectonique embryonnaire”
Emile Argand 1916

“the close association of serpentinites, diabase, and radiolarite is characteristic for the axial part of the “geosyncline” and the deep ocean floor”

from Antlitz der Erde (after Sengör 1996)

after Bernoulli et al. 2003
Remnants of the Alpine Tethys margins in the Alps
the result of more than one century of geology

Briançonnais Platta/Err S-Alps

paleo-geography (end of Jurassic)

present-day

EUROPEAN MARGIN | ALPINE TETHYS | ADRIATIC MARGIN

Brian./Tasna Chenaillet Platta/Err

Manatschal and Müntener 2008

Lemoine et al. 1986

Modified after Bertotti et al 1993

Lemoine et al. 1986

Canavesse Gozzano High Lombardian Basins

Modified after Bertotti et al 1993

27-10-2008 AAPG Cape Town
Reconstruction of the Alpine Tethys margins in the Alps

**EUROPEAN MARGIN**

Brian./Tasna Chenaillet

**ALPINE TETHYS**

Platta/Err

**ADRIATIC MARGIN**

Manatschal and Müntener 2008

Lemoine et al. 1986

Modified after Bertotti et al. 1993

Lemoine et al. 1986

S-Alps

Mohn et al. in prep

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Proximal rifted margins

Le Massif du Taillefer
From Thierry Dumont, Grenoble

Preservation of rift-related
Early Jurassic fault blocks
Proximal rifted margins

**Il Motto**
*Eberli 1988*

Early Jurassic high-angle normal fault preserving the relationships between pre-, syn- and post-tectonic sediments

![Diagram showing Proximal rifted margins with labels for pre"rift", syn"rift", post"rift", high-angle normal fault, and locations of European margin, Adriatic margin, proximal, and distal zones.](image_url)
Necking zone (Briançonnais domain/H-Block)

Briançonnais near Briançon
(SE France)

Sub Briançonnais (≤ 20 km)
(Médianes plastiques)

Briançonnais (≤ 25 km)
(Médianes rigides)

Necking zone (Briançonnais domain/H-Block)

Briançonnais domain
Lemoine et al. 1986, Borel 1995
distal domain showing uplift during final rifting and rapid subsidence after continental breakup

proximal margin neck distal ZECM oceanic ZECM distal neck proximal margin

Valais/Versoeyen Briançonnais

European margin Adriatic margin

Mohn et al. in prep

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Necking zone (Bernina domain)

Val dal Fain/Bernina domain
(SW-Switzerland)

Bernina domain
Mohn et al. in prep

Exhumation of basement along top-basement detachment faults and onlapping of syn- to post-rift sediments

proximal margin neck distal ZECM oceanic ZECM distal neck Bernina proximal margin

European margin Adriatic margin

Mohn et al. in prep

Syn-rift sediments onlapping onto basement or defored pre-rift
Necking zone & distal margin (Malenco/Margna)

Val Malenco (Italian/Swiss border)

P-T-t path of a Permian crust-mantle boundary

Mohn et al. In prep

Malenco/Margna domain
Müntener et al. 2000

Exhumation and P-T-t constraints from a Permian crust mantle boundary

proximal margin neck distal ZECM oceanic ZECM distal neck proximal margin

Err/Bernina

European margin Adriatic margin

Mohn et al. In prep
Low-angle detachment faults overlain by extensional allochthons
The Tasna OCT (SE Switzerland)

Tasna Ocean Continent Transition (OCT)

Florineth and Froitzheim 1994, Manatschal et al. 2007

wedge of continental crust and mantle exhumation

Mohn et al. in prep

European margin

Adriatic margin

SSW

NNE

Swiss Alps

continentward side

oceanward side

UTD

LTD

Alpine thrust fault

proximal margin

neck

distal

ZECM

oceanic

ZECM

distal

neck

proximal margin

Ocean Continent Transition (OCT)
Embryonic oceanic crust (Chenaillet)

Manatschal & Müntener 2008

Tasna OCT

embryonic oceanic crust

Chenaillet

Platta/Err OCT

subcontinental mantle

basalts

allochthons

detachment

Manatschal & Müntener 2008

Mohn et al. in prep

European margin

Adriatic margin
Magmatic processes in the OCT

Melt infiltration/reaction in plg. peridotite

Gabbros in serpentinize mantle

Pillow basalts overlying exhumed mantle

Tasna OCT

embryonic oceanic crust

Chenaiiliet

Platta/Err OCT

subcontinental mantle

basalts

allochthons

detachment

subcontinental mantle

European margin

Adriatic margin

Mohn et al. in prep
Mantle characteristics in the OCT (from O. Müntener)

The key observation:
Infiltrated mantle is exhumed by brittle detachment system

Consequence:
Infiltration had to occur already before final mantle exhumation to the seafloor; i.e. infiltration had to occur during thinning phase.
**Stratigraphic record and isostatic evolution of the margins**

**Distal margin (Briançonnais)**
- erosional unconformity
- syn-tectonic
- pre-tectonic

**Proximal margin (Il Motto)**
- post-tectonic
- high-angle fault

From Thierry Dumont

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**Stratigraphic record and isostatic evolution of the margins**

**Proximal margin**
- distal
- ZECM
- oceanic
- ZECM
- distal
- neck

**Distal margin**
- proximal margin
- neck
- distal
- ZECM
- oceanic
- ZECM
- distal
- neck

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**Geographic locations**
- Dauphiné
- Valais/ Versoven
- Briançonnais
- Chenaillet
- Platta
- Err
- Bernina
- Upper Austroalpine

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**Other locations**
- Ivrea
- Malenco/Margna
Rift-related structures observed along the margin

Platta (SE Switzerland)

Err (SE Switzerland)

Il Motto (SE Switzerland)

low-angle detachment fault
extensional allochthones
exhumation of continental and mantle rocks

high-angle normal fault
tilted blocks
exhumation limited to fault scarps

Proximal

Distal

Mohn et al. in prep

European margin

Adriatic margin

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Fault-sediment relationship

- **Err** (SE Switzerland): Syn-rift onlapping onto low-angle fault.
- **Bernina** (SE Switzerland): Pre-rift stretched along low-angle fault and sealed by syn to post-rift.
- **Il Motto** (SE Switzerland): Syn-rift terminating against high-angle fault.

Diagram:
- Distal margin:
  - European margin
  - Adriatic margin
- Proximal margin:
  - European margin
  - Adriatic margin

Mohn et al. in prep
Implications of exhumation of crust in the necking zone for the formation of a new siliciclastic source

“siliciclastic” syn-rift sediments

“calcareous” syn-rift sediments

creation of a new “siliciclastic” source due to exhumation

European margin

Adriatic margin

Mohn et al. in prep
How to reconcile all these observations in a tectonic model

- **Three mantle domains can be distinguished** *(inheritance, infiltration, extraction)*
- **Poly-phase tectonic evolution** *(how do brittle and ductile deformation interact?)*
- **Poly-phase magmatic evolution** *(what controls infiltration vs. diking)*
- **Complex sedimentary evolution** *(limits of stratigraphic correlations)*
- **Complex isostatic and thermal evolution** *(how important are mantle processes?)*

The implications for petroleum systems are obvious
Sequential overprinting of rift-modes

- **Temporal Evolution of Rifting**
  - **Mantle and Crustal Accretion**
    - Infiltration
    - Extraction
    - Inheritance
  - **Individualisation of Block H**
    - Infiltration
    - Inheritance
  - **Distributed Rifting**
    - Inheritance

- **Exhumation Phase**
  - “Simple shear”
  - Callovian/Bathomian (< 165 Ma)

- **Thinning Phase**
  - Toarcian to Callovian/Bathomian (~180-165 Ma)

- **Stretching Phase**
  - “Pure shear”
  - Latest Triassic to Toarcian
From observations to conceptual and numerical models

Conceptual geological model → Three dimensionnal evolution of continental break-up → Numerical modelling


Observations → iterative approach → modelling

Major questions that remain to be answered

• What are the processes that control extreme crustal thinning to less than 10 km?
• What is the transition from mantle exhumation to seafloor spreading?
Are there other good field analogues to study extreme crustal thinning and lithospheric breakup?

- S-North Atlantic

V-shaped basins preserve along strike the complete rift evolution

Profile ECORS-Golfe de Gascogne

Modified after Pinet et al. (1987)

Péron-Pinvidic and Manatschal (in prep)
The Bay of Biscay-Western Pyrenees
PhD Suzon Jammes
in collaboration with L. Lavier, Ch. Tiberi, Chris Johnson (ExxonMobil), TOTAL and Action Marges

How is extreme crustal thinning accommodated in a transtensional environment at the termination of an oceanic domain?

- What is the crustal structure ahead of a propagating ocean?
  Processes related to crustal thinning and mantle exhumation

- What is the paleogeographic evolution?
  Timing of partitioning between strike slip and extensional structures

- How are rift structures reactivated during compression?
  Importance of structural/lithological/thermal inheritance

Map showing the location of seismic sections and well data (from BRGM)
Selected References


