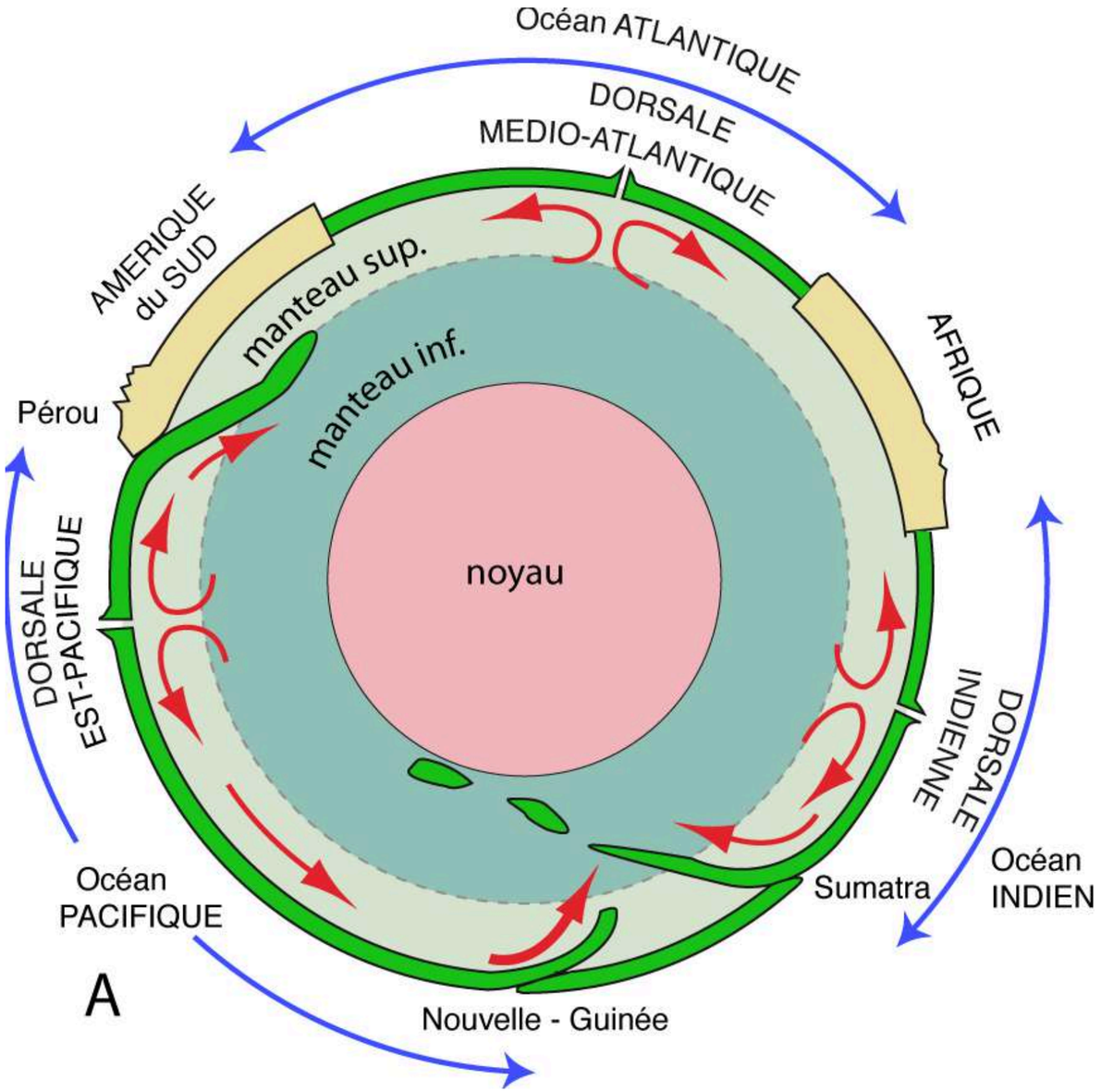
Yves Lagabrielle

Directeur de Recherche
CNRS émérite

Exhumer le manteau terrestre au fond des océans?

Trente années de travaux terre/mer
pour confirmer ce concept surprenant !

Affleurement de roches du manteau
Banc de Gorringe, 1981, soucoupe CYANA
Au large du Portugal
Profondeur : – 1000 m



Dans la dynamique de la lithosphère terrestre, le manteau demeure (presque) toujours sous la croûte

La Tectonique des plaques, élaborée dans les années 1960-1970, ne prévoit pas que le manteau parvienne à l’affleurement à la surface de la Terre, sauf dans deux contextes :

1. Les failles transformantes (limites de plaques coulissantes)

2. L’obduction de la lithosphère océanique sur un continent (limites de plaques convergentes)

Donc certainement pas en limite de plaques divergentes

Il fut laborieux de démontrer qu’en réalité le manteau terrestre est largement plus mobile que ne le prévoyaient les modèles géodynamiques issus de la Tectonique des Plaques.

L’objet de cet exposé est de montrer la complexité des interactions nécessaires pour mettre en évidence ce concept d’exhumation du manteau, **notamment en contexte de divergence des Plaques.**

Un exemple de démarche scientifique sur le long terme mobilisant de nombreuses disciplines et de nombreux chercheurs

PLAN

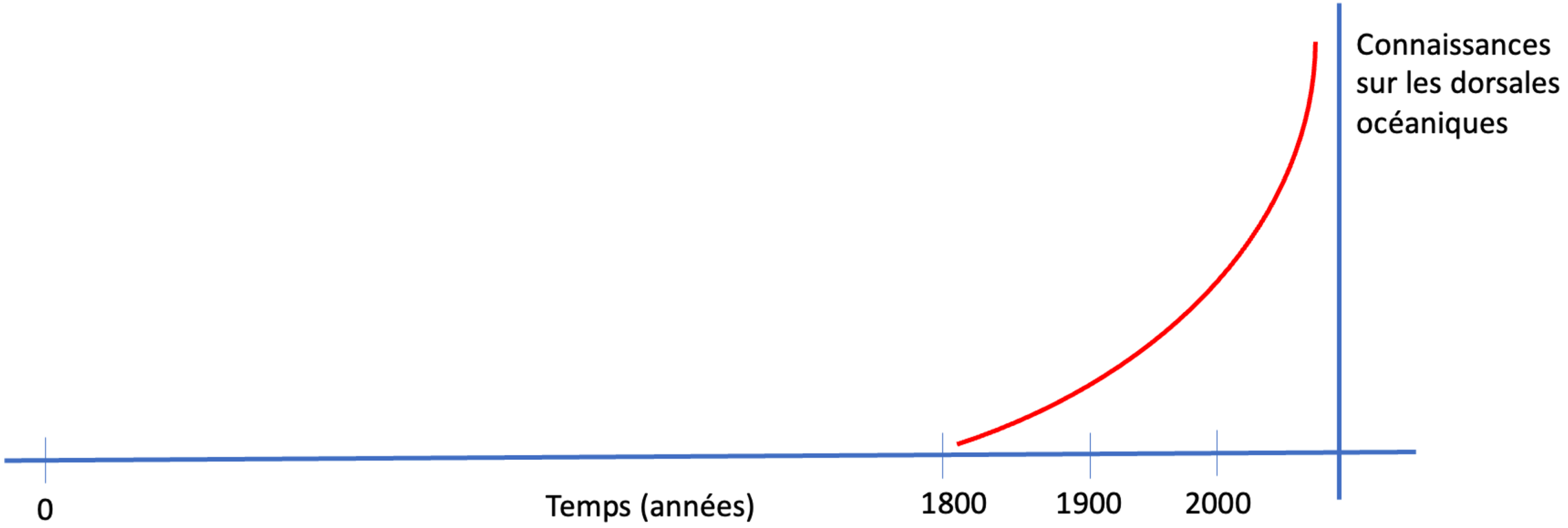
PARTIE 1 : les dorsales (historique)

PARTIE 2 : les ophiolites alpines « anormales »

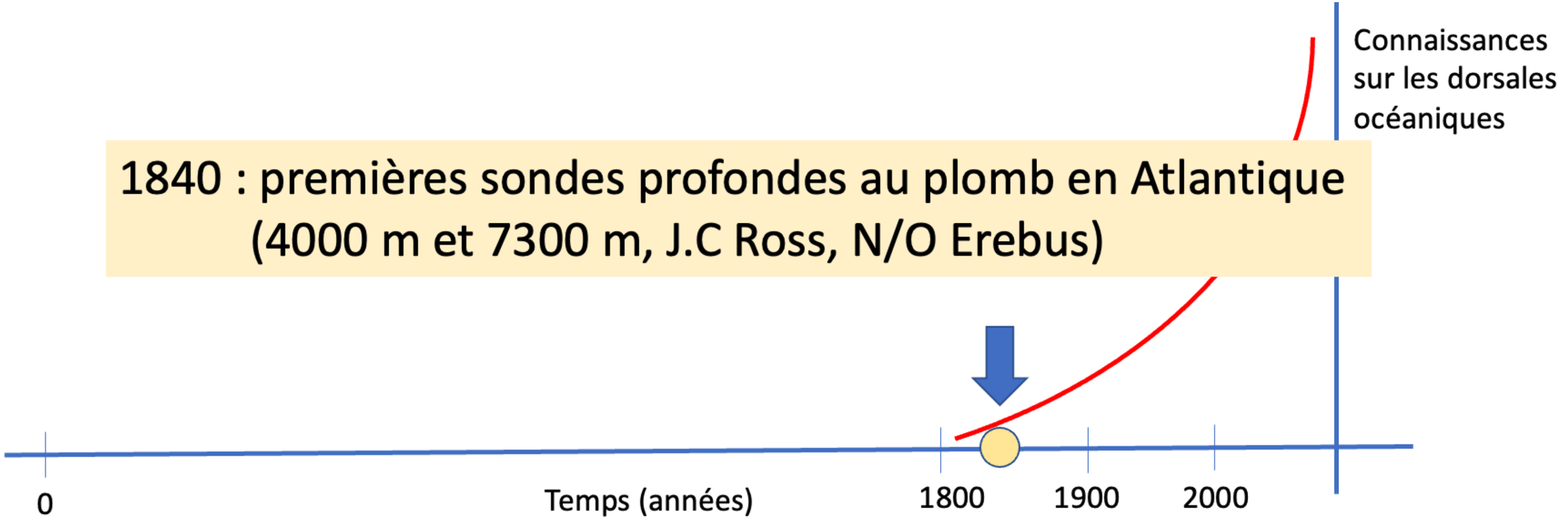
PARTIE 3 : une révolution tectonique majeure

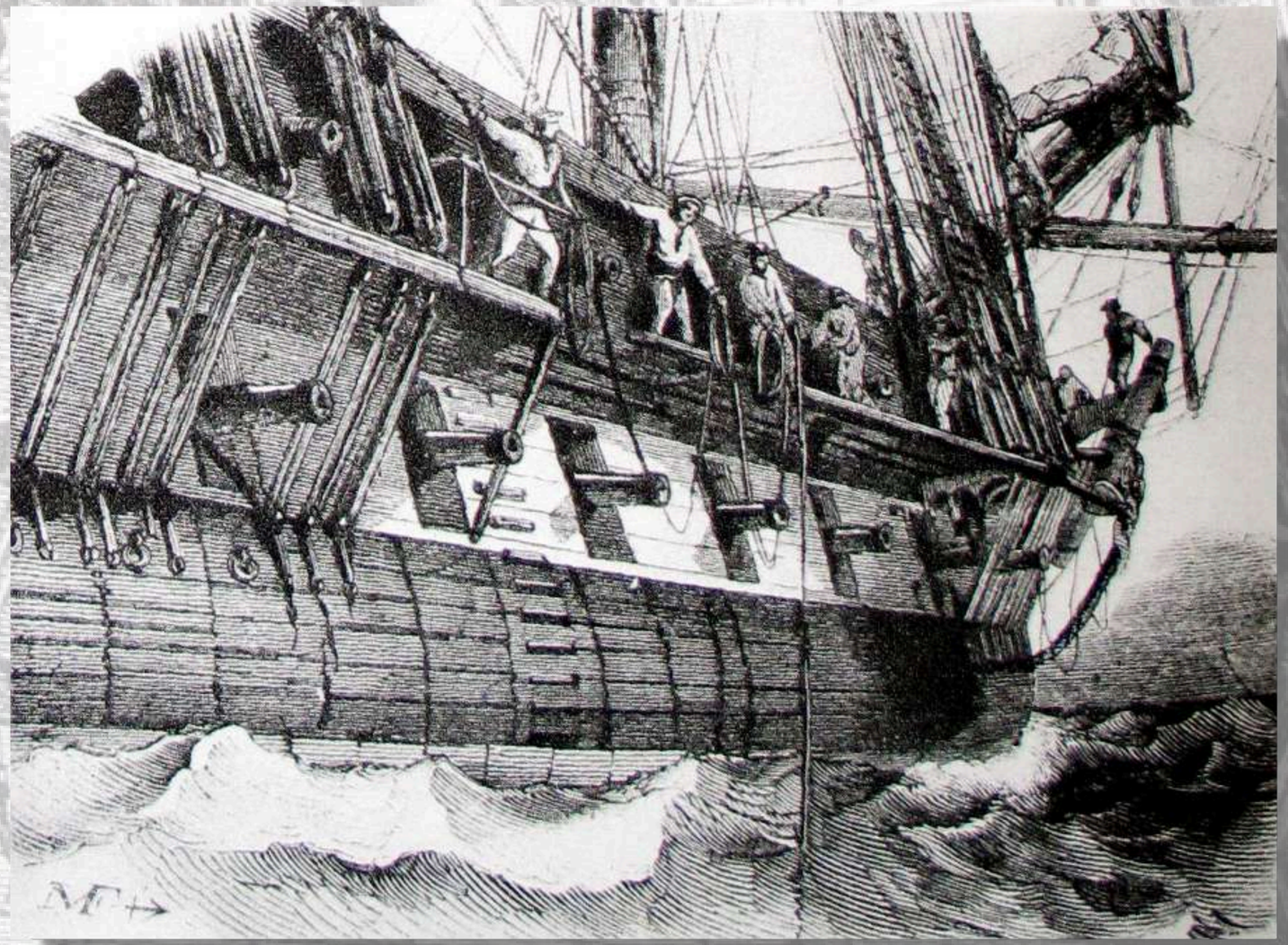
PARTIE 1

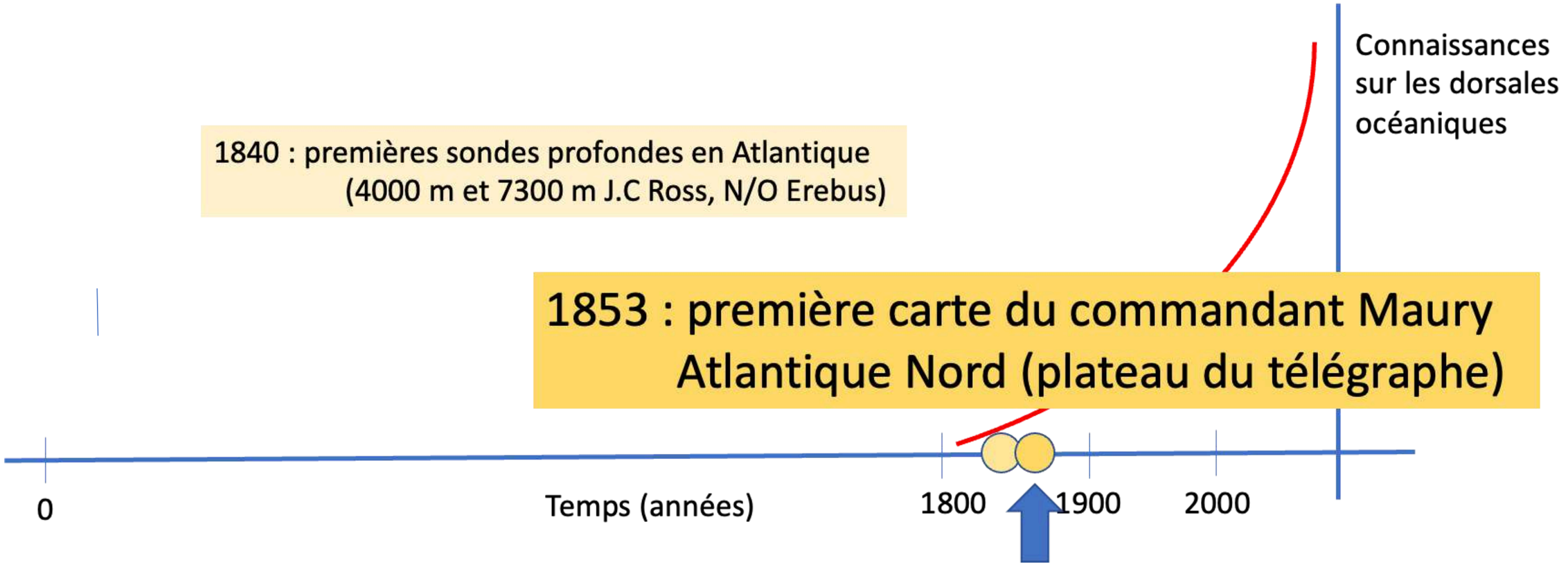
Une fantastique histoire de Science : la découverte des dorsales océaniques

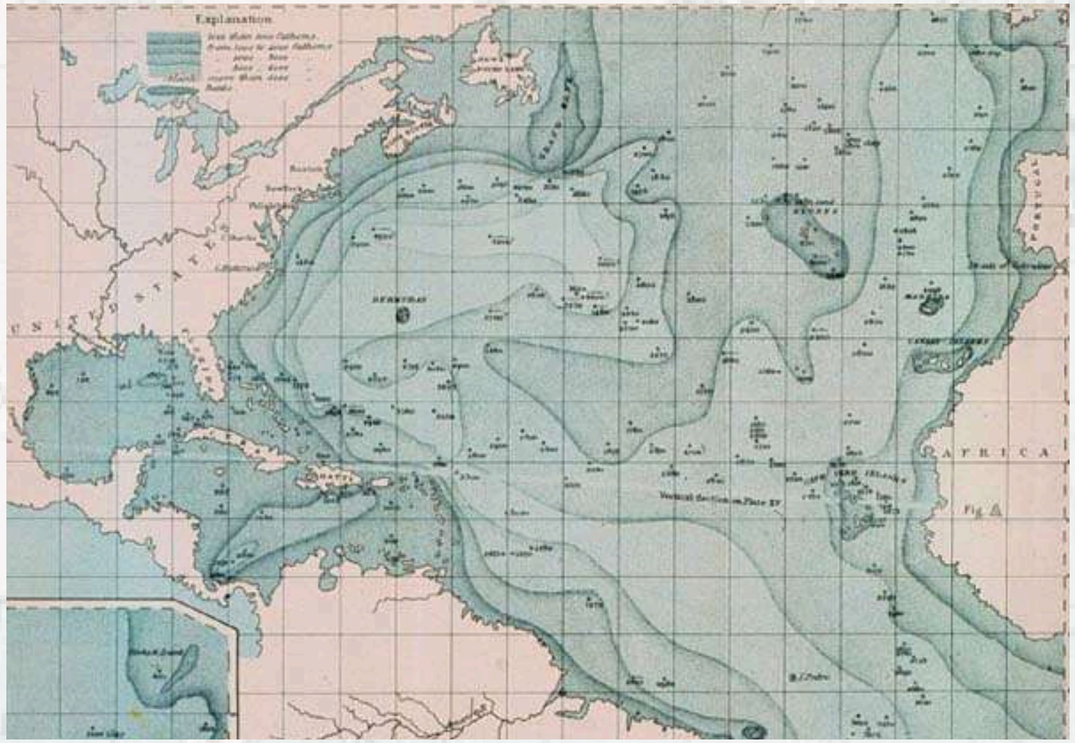

Connaissances sur les dorsales océaniques
0
Temps (années)
1800
1900
2000

1840 : premières sondes profondes au plomb en Atlantique
(4000 m et 7300 m, J.C Ross, N/O Erebus)





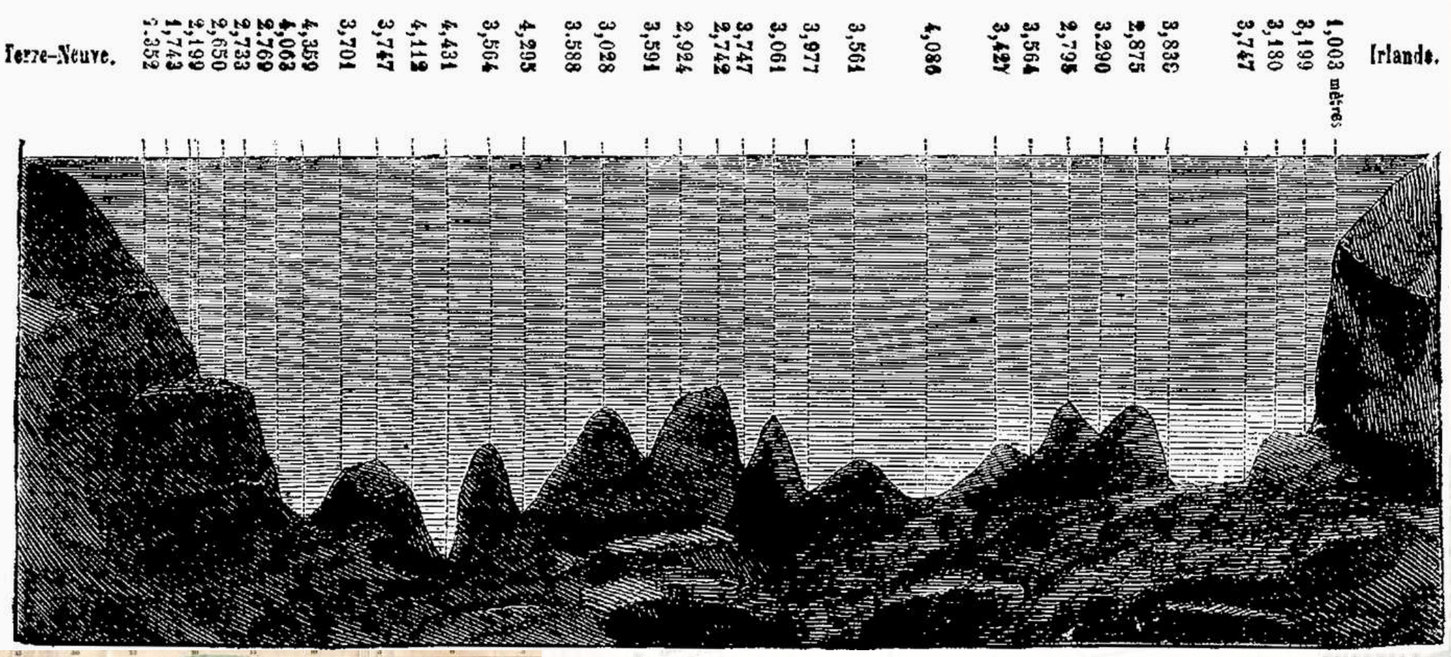

Connaissances sur les dorsales océaniques
1840 : premières sondes profondes en Atlantique
(4000 m et 7300 m J.C Ross, N/O Erebus)
1853 : première carte du commandant Maury
Atlantique Nord (plateau du télégraphe)
0
Temps (années)
1800
1900
2000



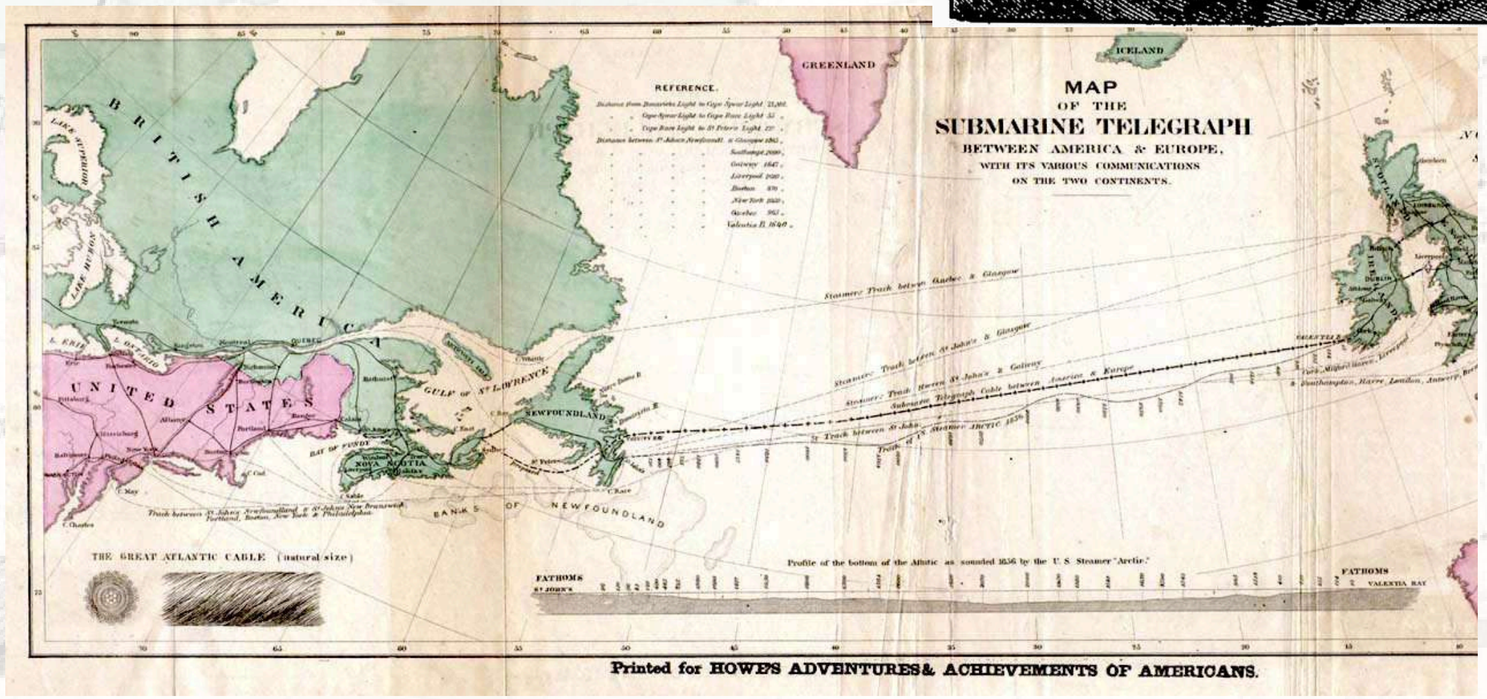
Une des premières cartes bathymétrique de l’Atlantique nord montrant un relief médian

Le commandant M. Maury directeur de l’Observatoire des États-Unis.

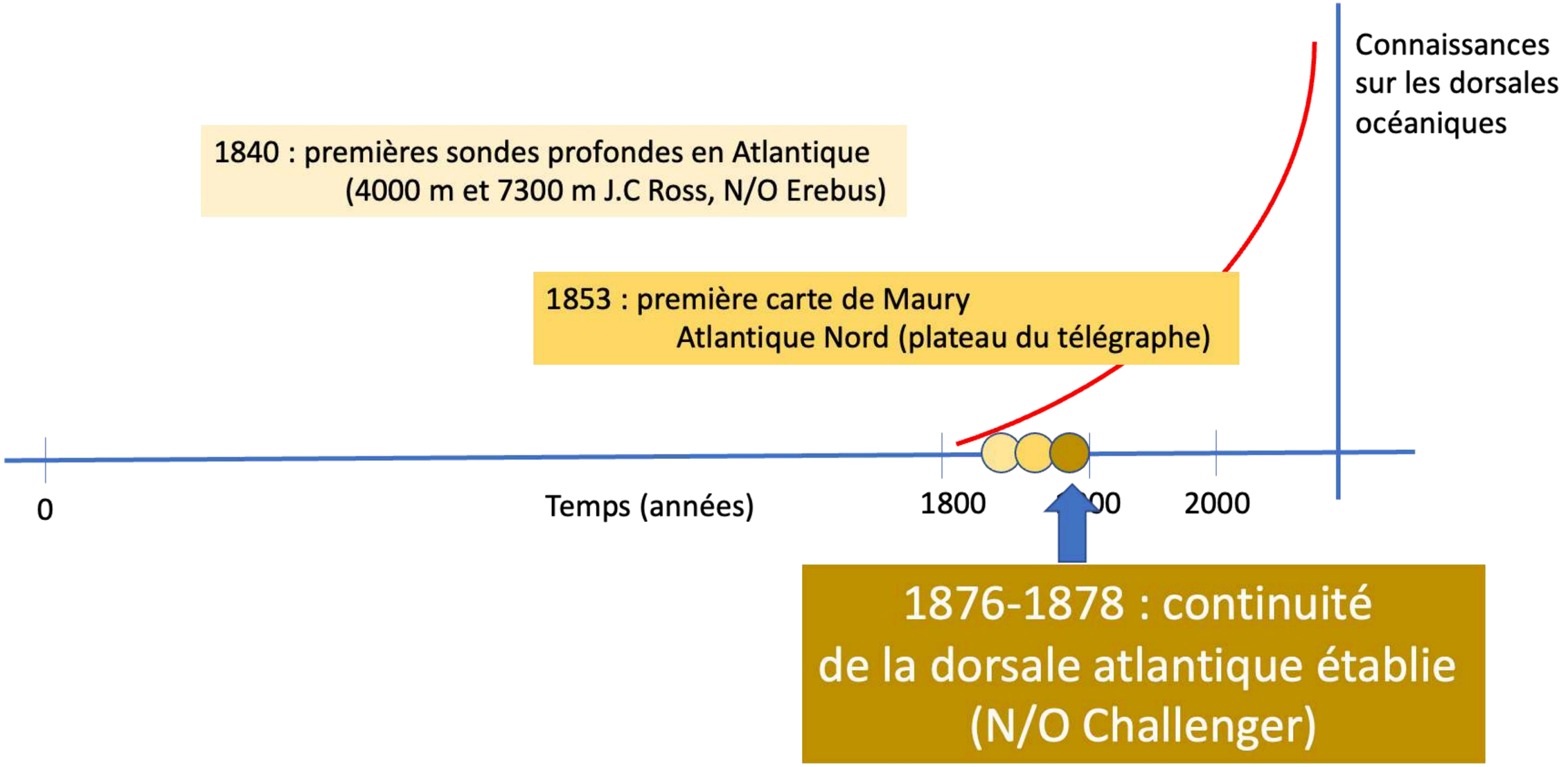
Pose du premier câble transatlantique (3000 km après le succès de la pose du câble Douvres-Calais en 1851 (33 km). env.)

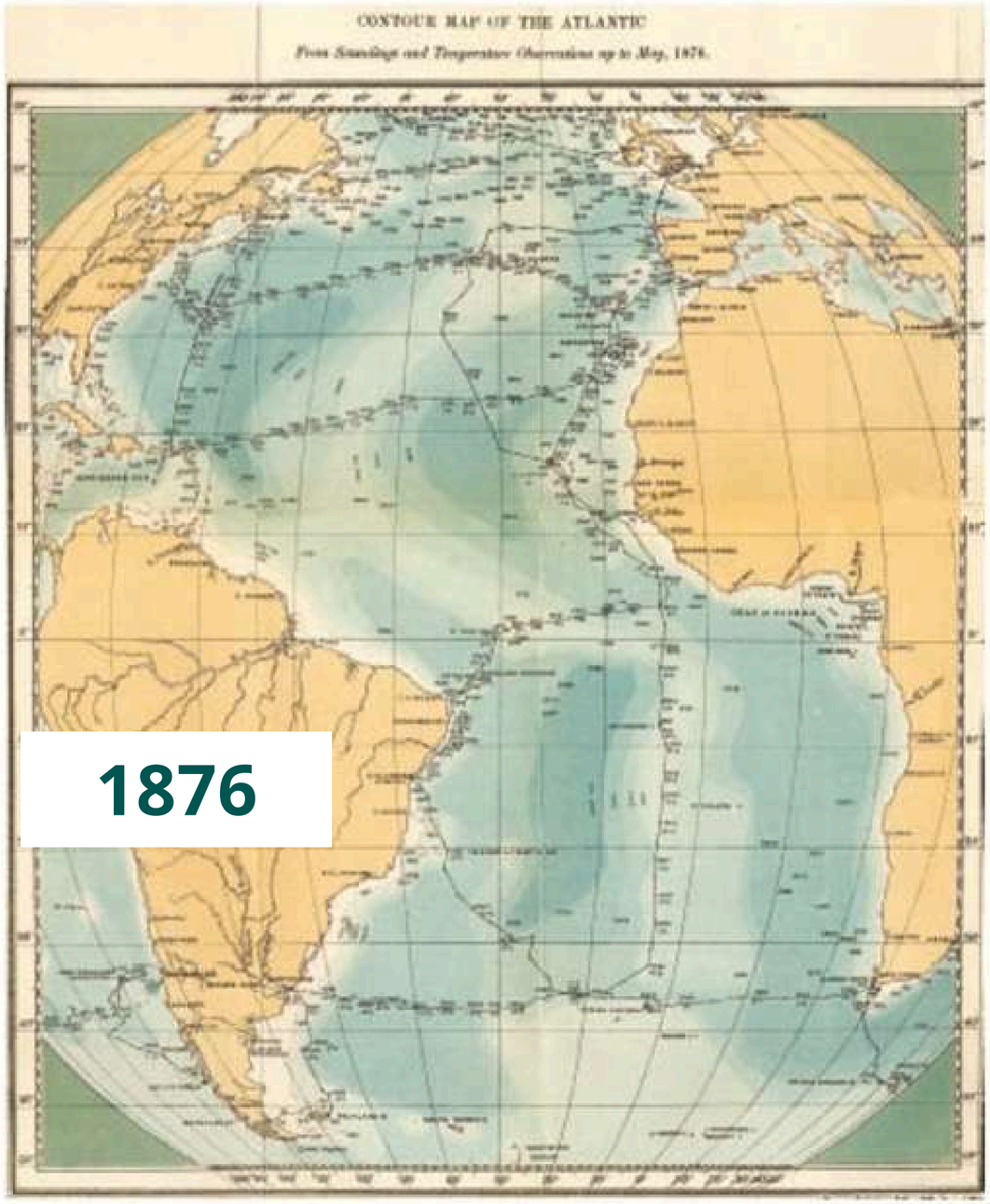


Profondeurs de l'océan Atlantique de l'Irlande à Terre-Neuve, d'après les sondages du lieutenant Daymam, N/O Cyclope,1857.
(Premiers micro-carottages du fond)

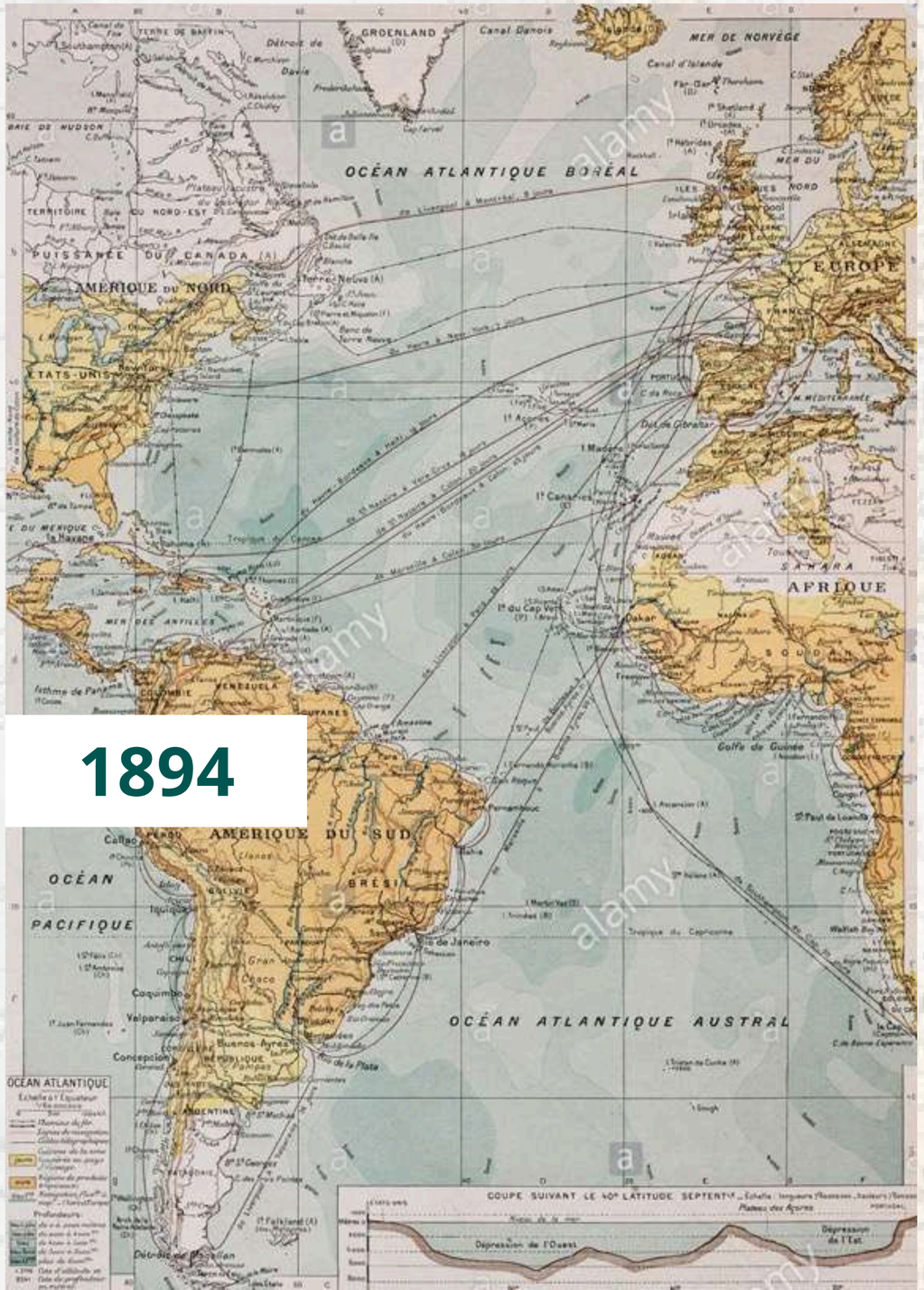


Carte et coupe bathymétrique de l'océan Atlantique nord, d'après les sondages du commandant Maury (1858).


Connaissances sur les dorsales océaniques
1840 : premières sondes profondes en Atlantique
(4000 m et 7300 m J.C Ross, N/O Erebus)
1853 : première carte de Maury
Atlantique Nord (plateau du télégraphe)
0
Temps (années)
1800
2000
1876-1878 : continuité de la dorsale atlantique établie (N/O Challenger)

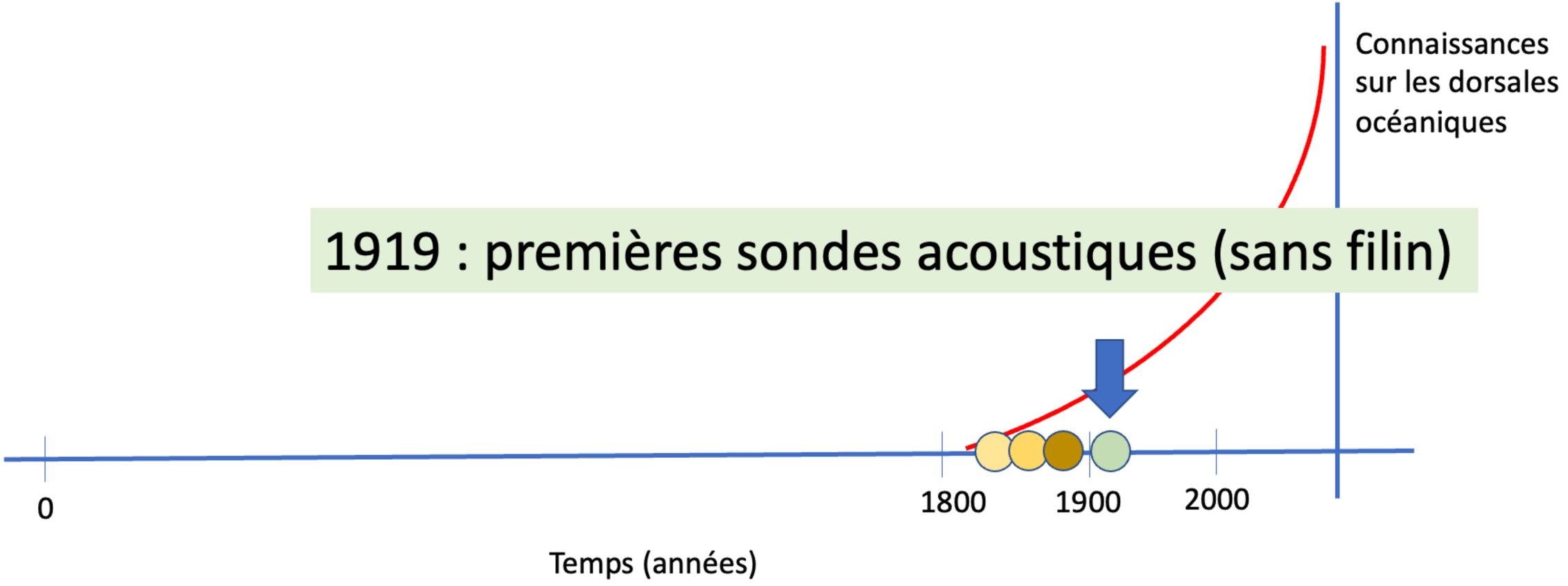


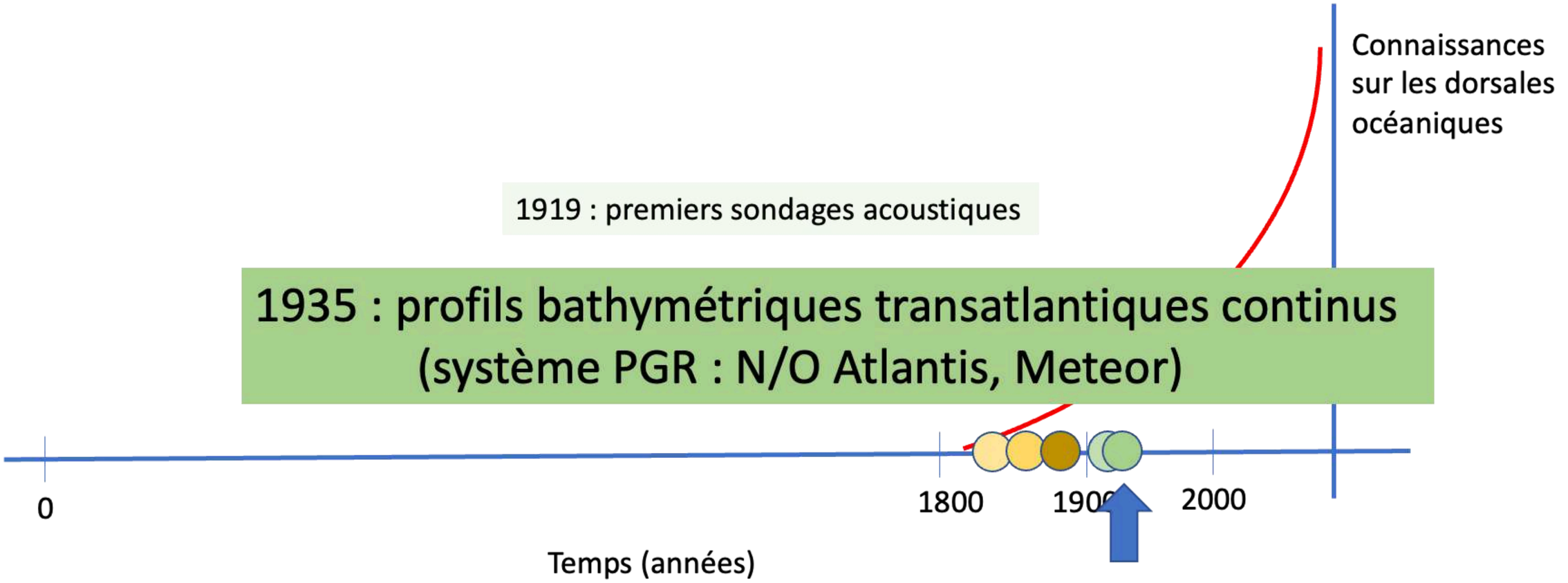
1876

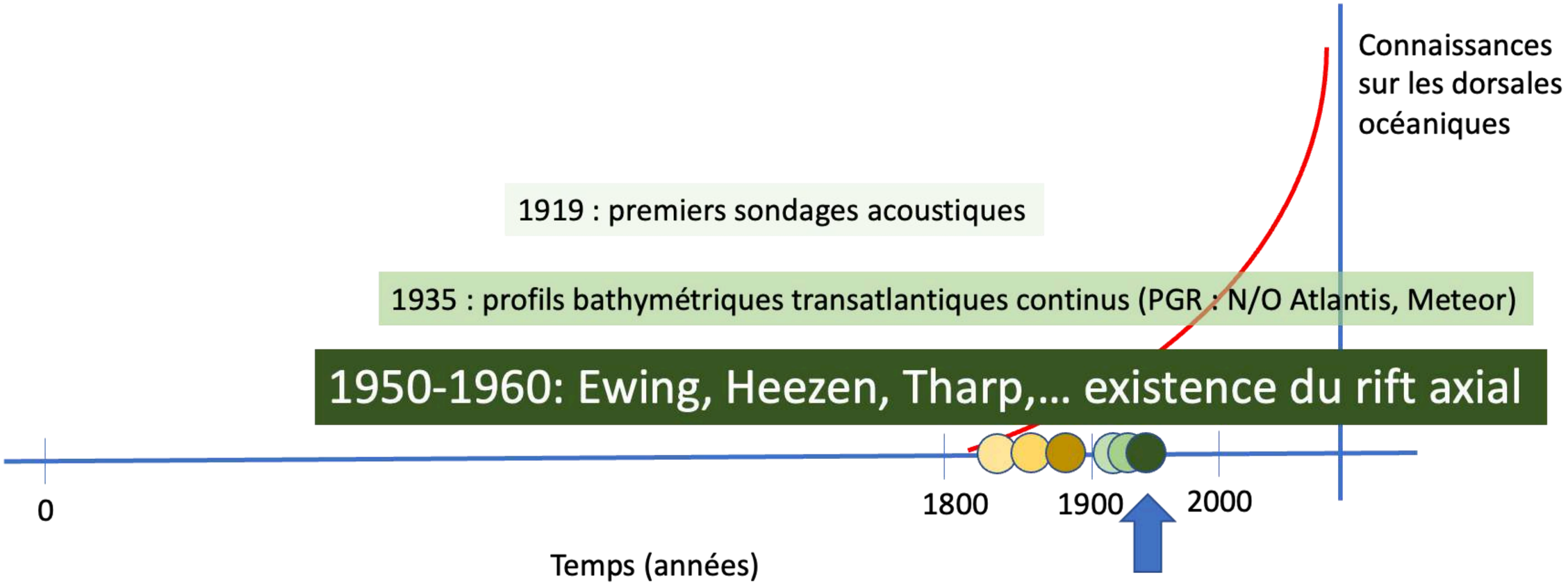


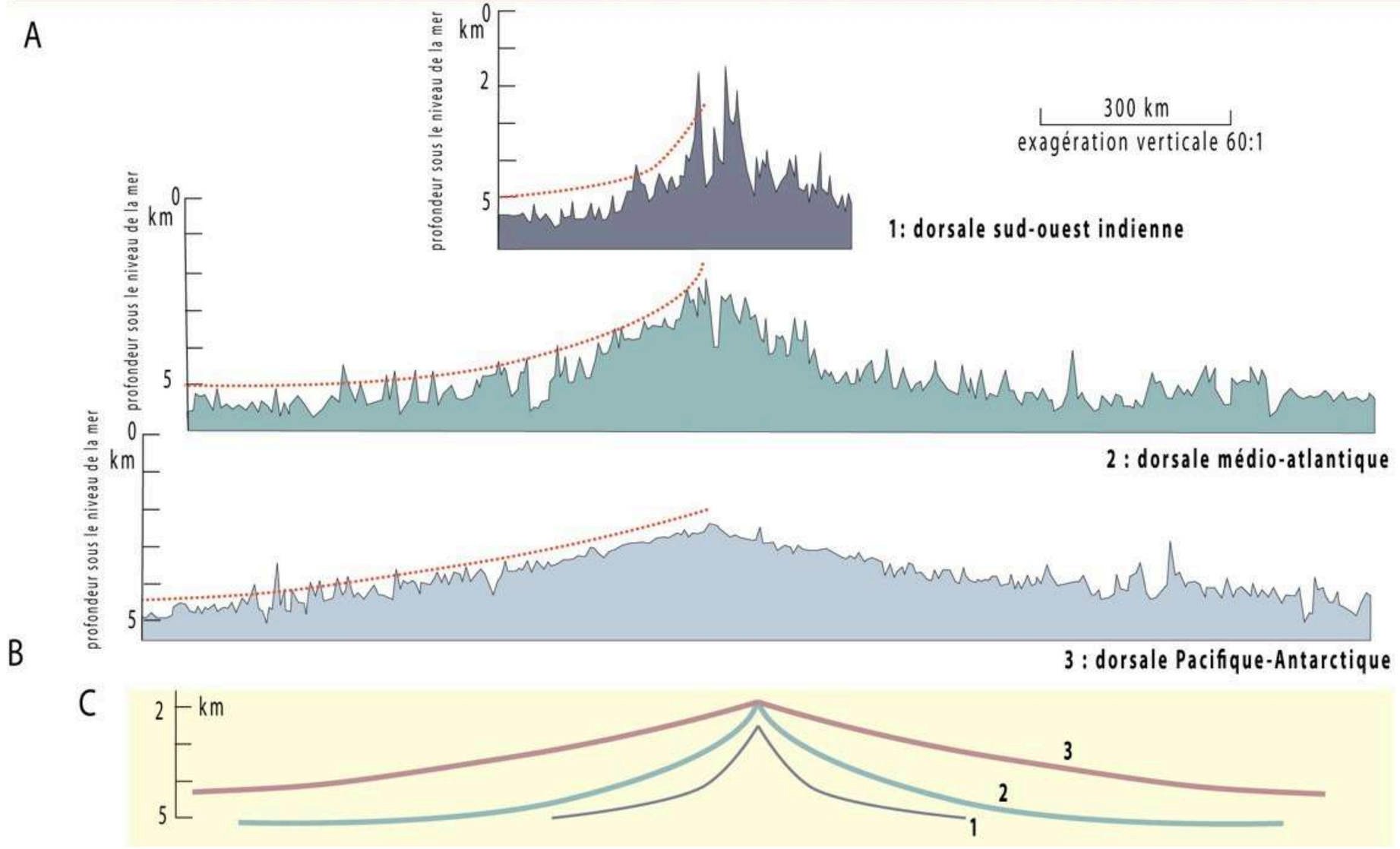
1894

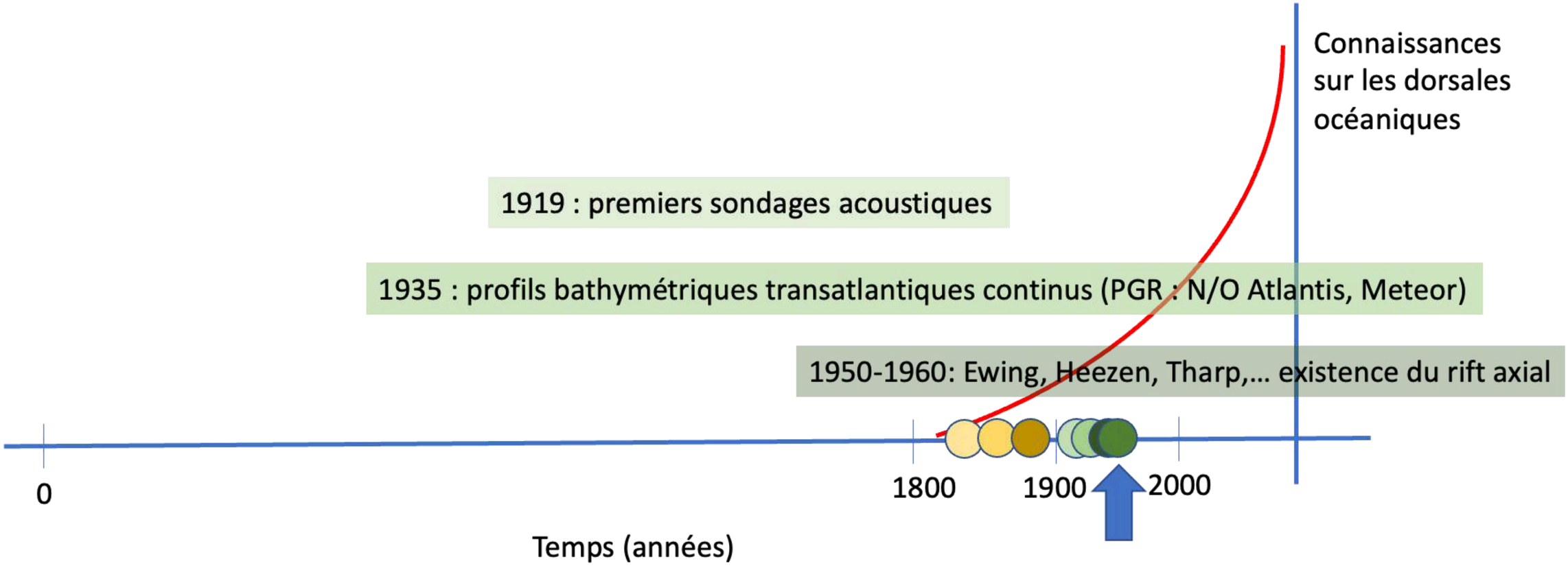
In-depth study: Wyville Thomson's map shows that the *Challenger* expedition revealed the Mid-Atlantic Ridge.


Connaissances sur les dorsales océaniques
1919 : premières sondes acoustiques (sans filin)
0
1800
1900
2000
Temps (années)

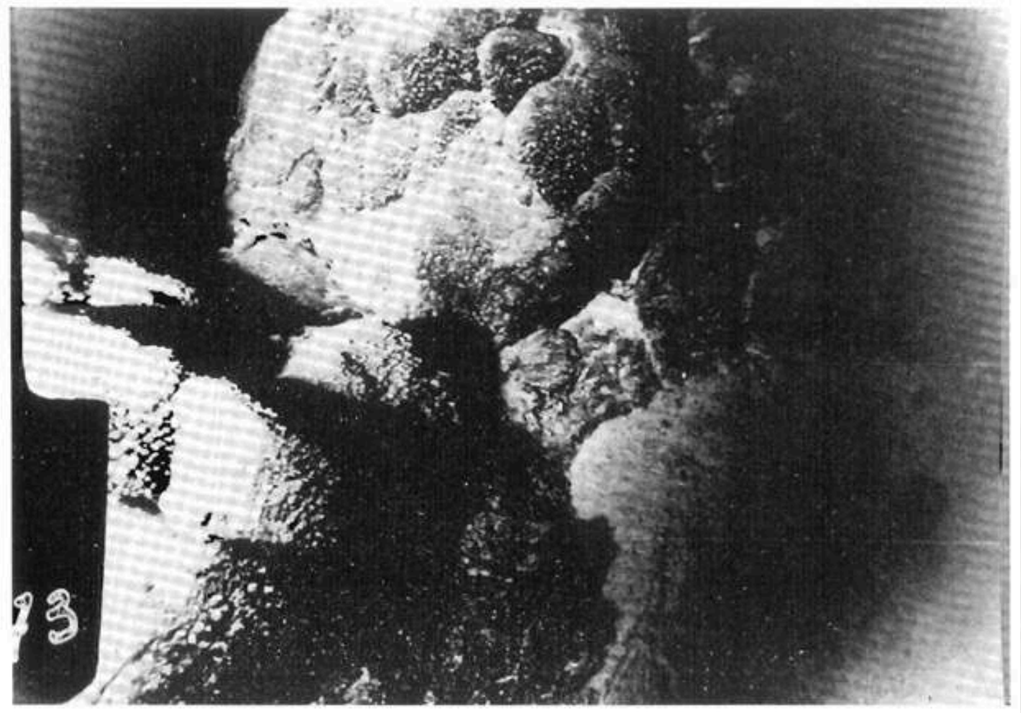

Connaissances sur les dorsales océaniques
1919 : premiers sondages acoustiques
1935 : profils bathymétriques transatlantiques continus (système PGR : N/O Atlantis, Meteor)
0
1800
1900
2000
Temps (années)


Connaissances sur les dorsales océaniques
1919 : premiers sondages acoustiques
1935 : profils bathymétriques transatlantiques continus (PGR : N/O Atlantis, Meteor)
1950-1960: Ewing, Heezen, Tharp,… existence du rift axial
0
1800
1900
2000
Temps (années)


A
profondeur sous le niveau de la mer
km
0
2
5
300 km
exagération verticale 60:1
1: dorsale sud-ouest indienne
profondeur sous le niveau de la mer
km
0
5
2 : dorsale médio-atlantique
profondeur sous le niveau de la mer
km
0
5
3 : dorsale Pacifique-Antarctique
B
C
km
2
5
3
2
1



1959 : premières photos de pillows à l'axe du rift (Cousteau)



Laves en coussin.
Photo prise dans le rift Atlantique par la Troïka de Cousteau, - 2500 m, 1959.
Présentation au Congrès International d'Océanographie de New York, 1959

Interview of Marie Tharp by Tanya Levin on 1997 June 28,Niels Bohr Library & Archives, American Institute of Physics,College Park, MD USA,www.aip.org/history-programs/niels-bohr-library/oral-histories/22896-4

ω

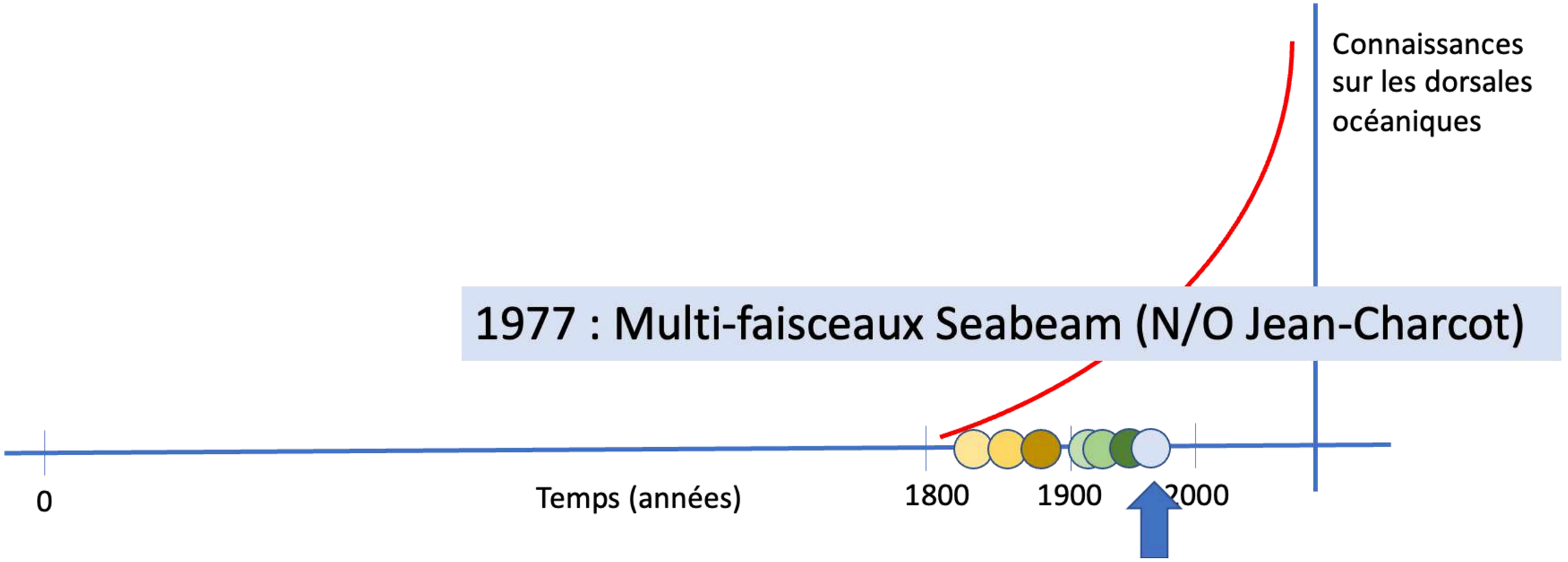
L’oméga!

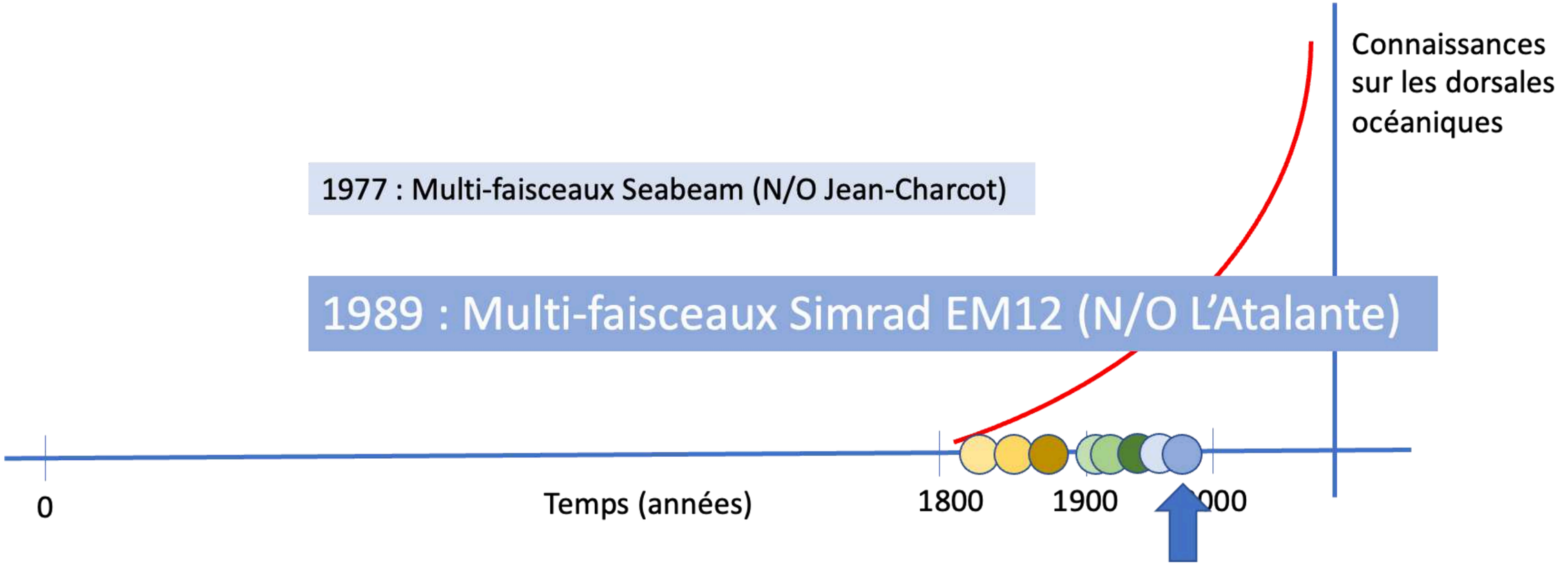
Carte de Heezen et Tharp

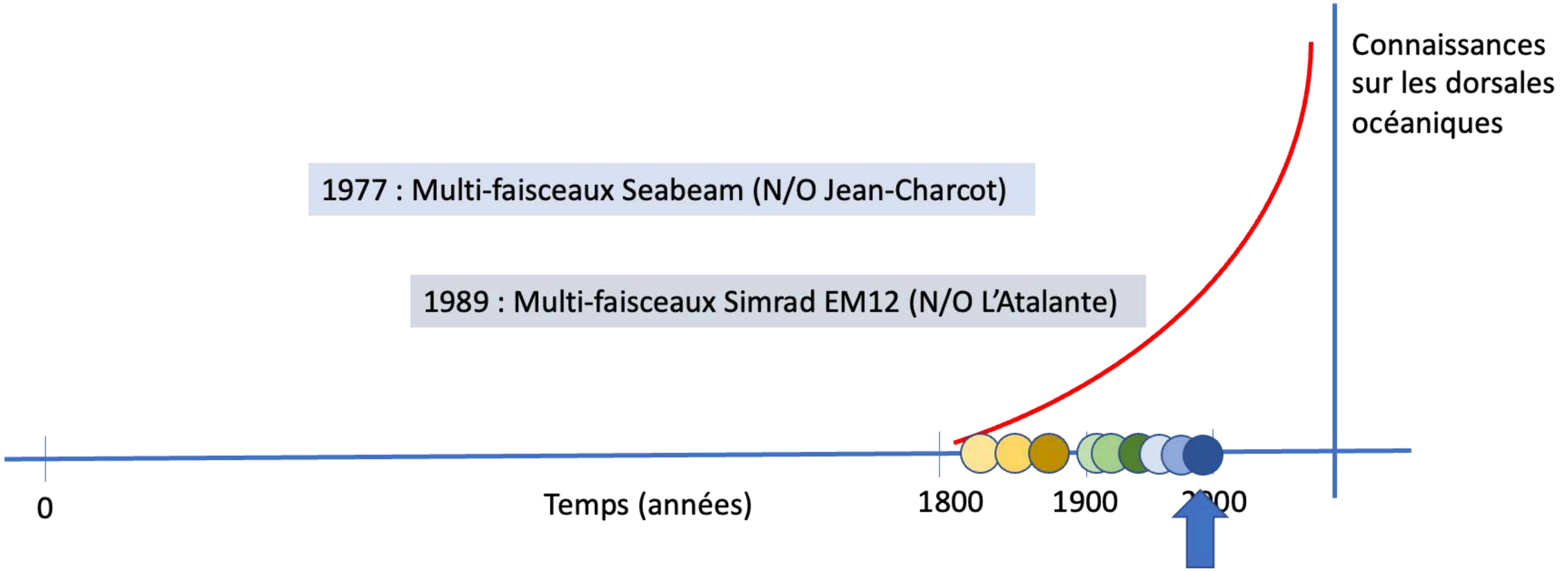
C’est une compilation de profils bathymétriques mono-faisceaux en vue d’artiste

Elle fut achevée en 1977

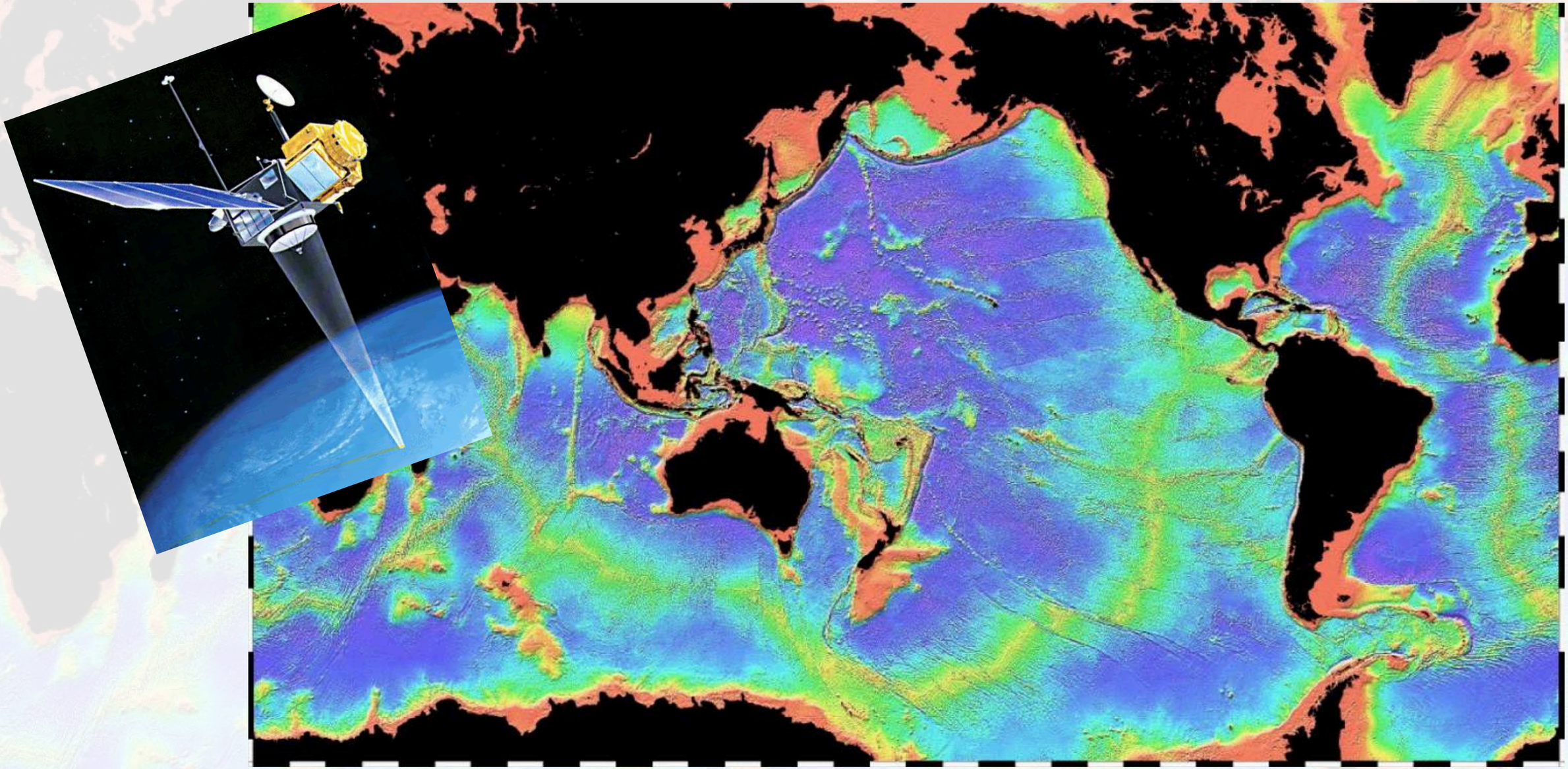
1973 : Publication de « *Plate Tectonics* »
Le Pichon, Francheteau, Bonnin


Connaissances sur les dorsales océaniques
1977 : Multi-faisceaux Seabeam (N/O Jean-Charcot)
0
Temps (années)
1800
1900
2000


Connaissances sur les dorsales océaniques
1977 : Multi-faisceaux Seabeam (N/O Jean-Charcot)
1989 : Multi-faisceaux Simrad EM12 (N/O L'Atalante)
0
Temps (années)
1800
1900
000

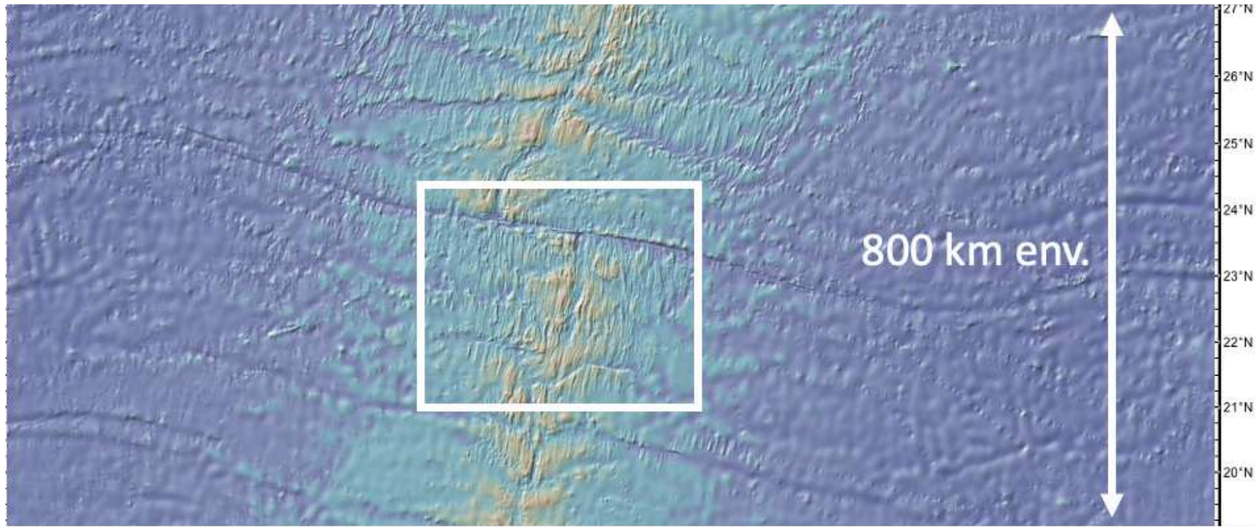


1997. Smith, W. H. F., and D. T. Sandwell,
Global seafloor topography from satellite altimetry and ship depth soundings, Science, v. 277.

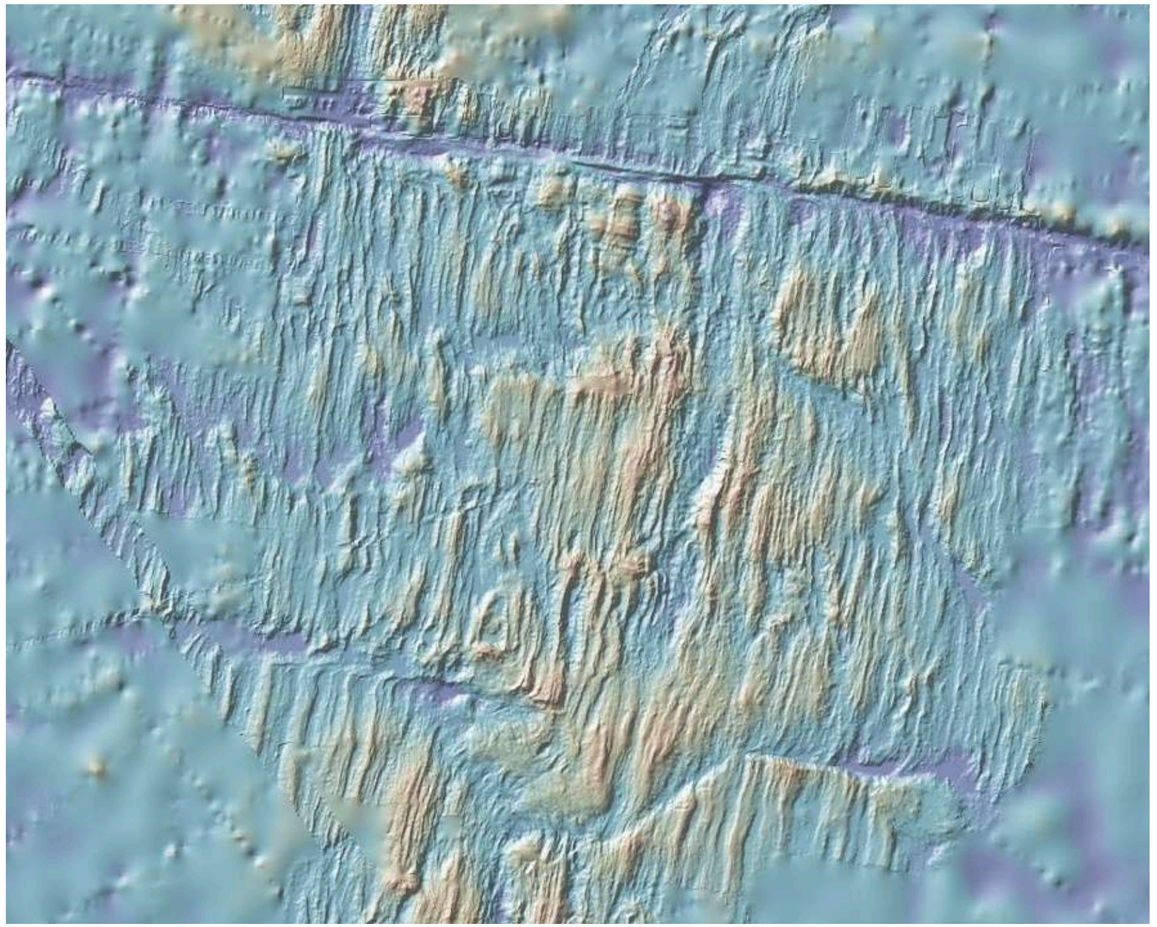


Smith, W. H. F., and D. T. Sandwell, Global seafloor topography from satellite altimetry and ship depth soundings, Science, v. 277, p. 1957-1962, 26 Sept., 1997

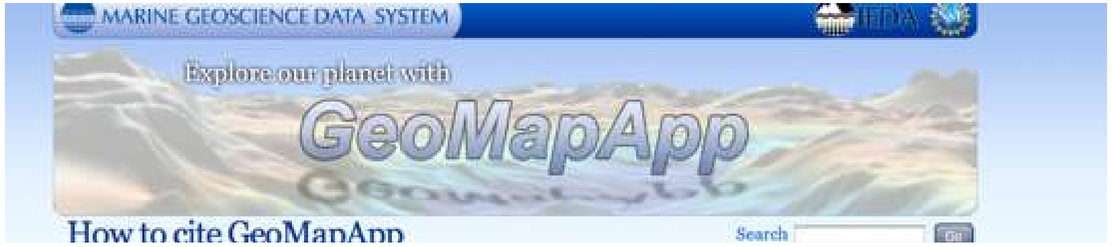
ZF Kane



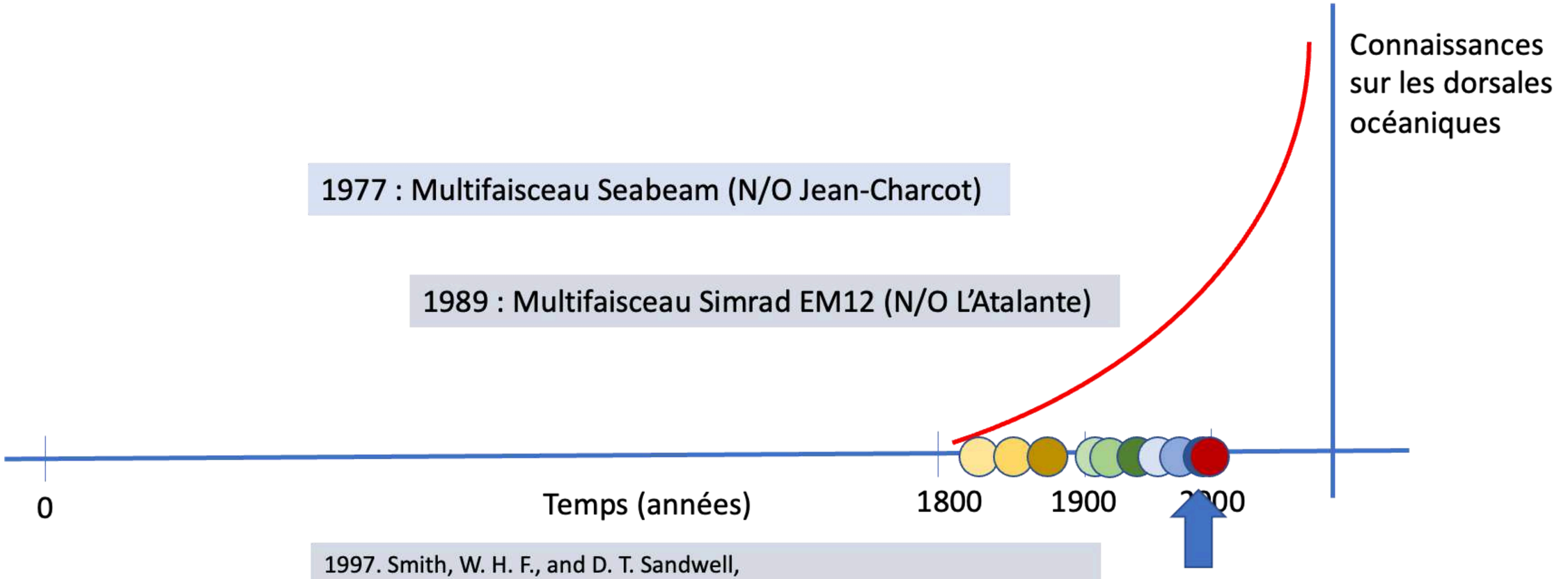
Données mixées Alti+Bathy



Données Bathy de l’Atalante

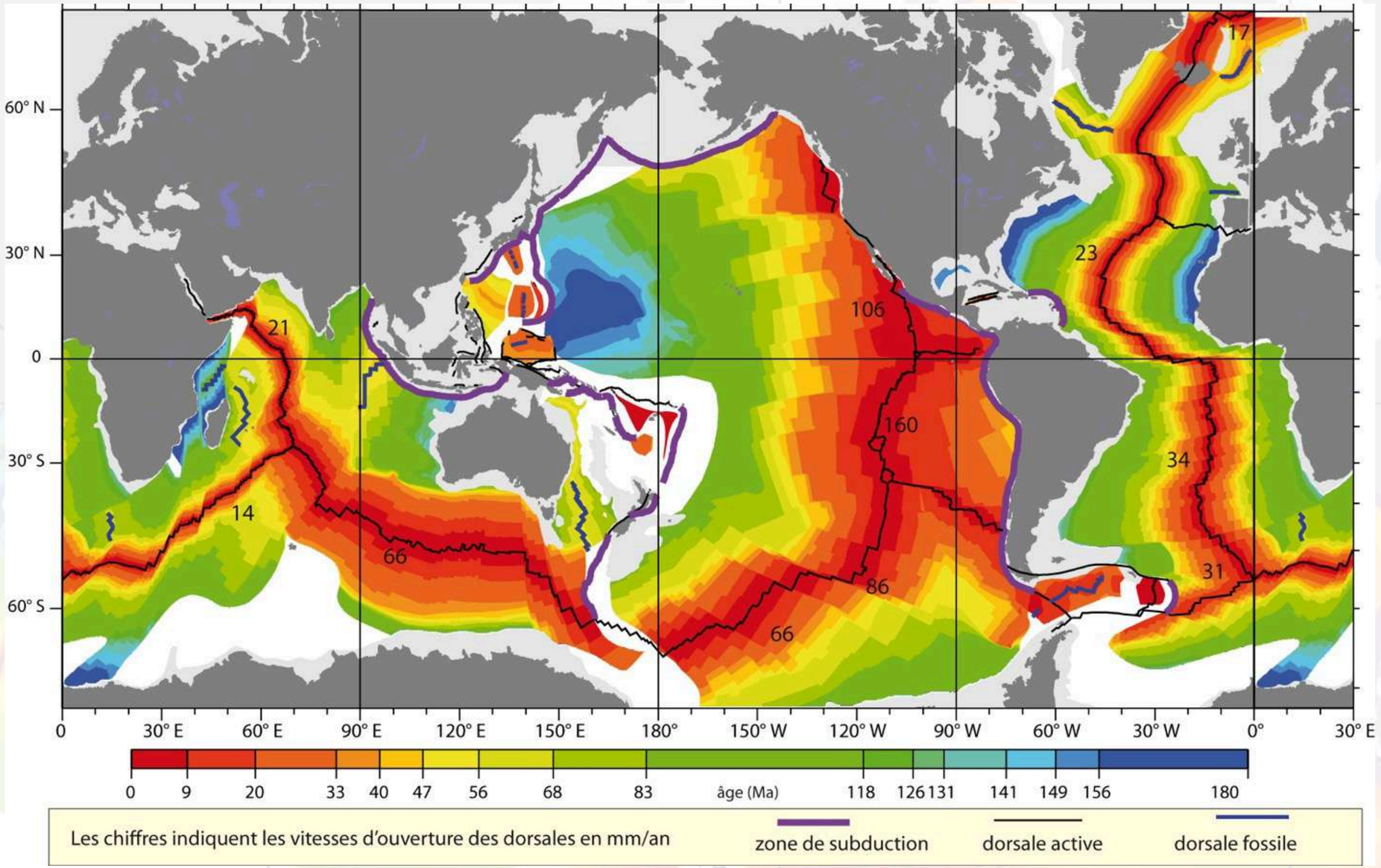


Campagne TAMMAR, documents P. Gente, Brest

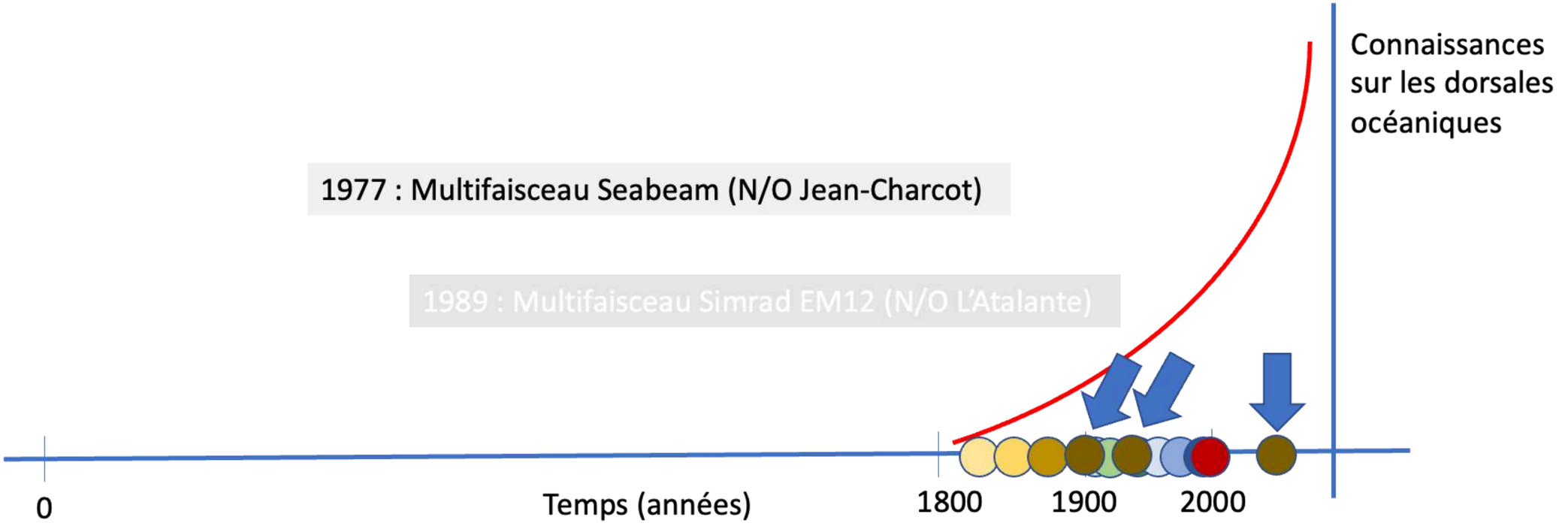


1997. Smith, W. H. F., and D. T. Sandwell,
Global seafloor topography from satellite altimetry and ship depth soundings, Science, v. 277.

1997. Müller et al., Carte des isochrones océaniques



Dorsales lentes
Dorsales rapides



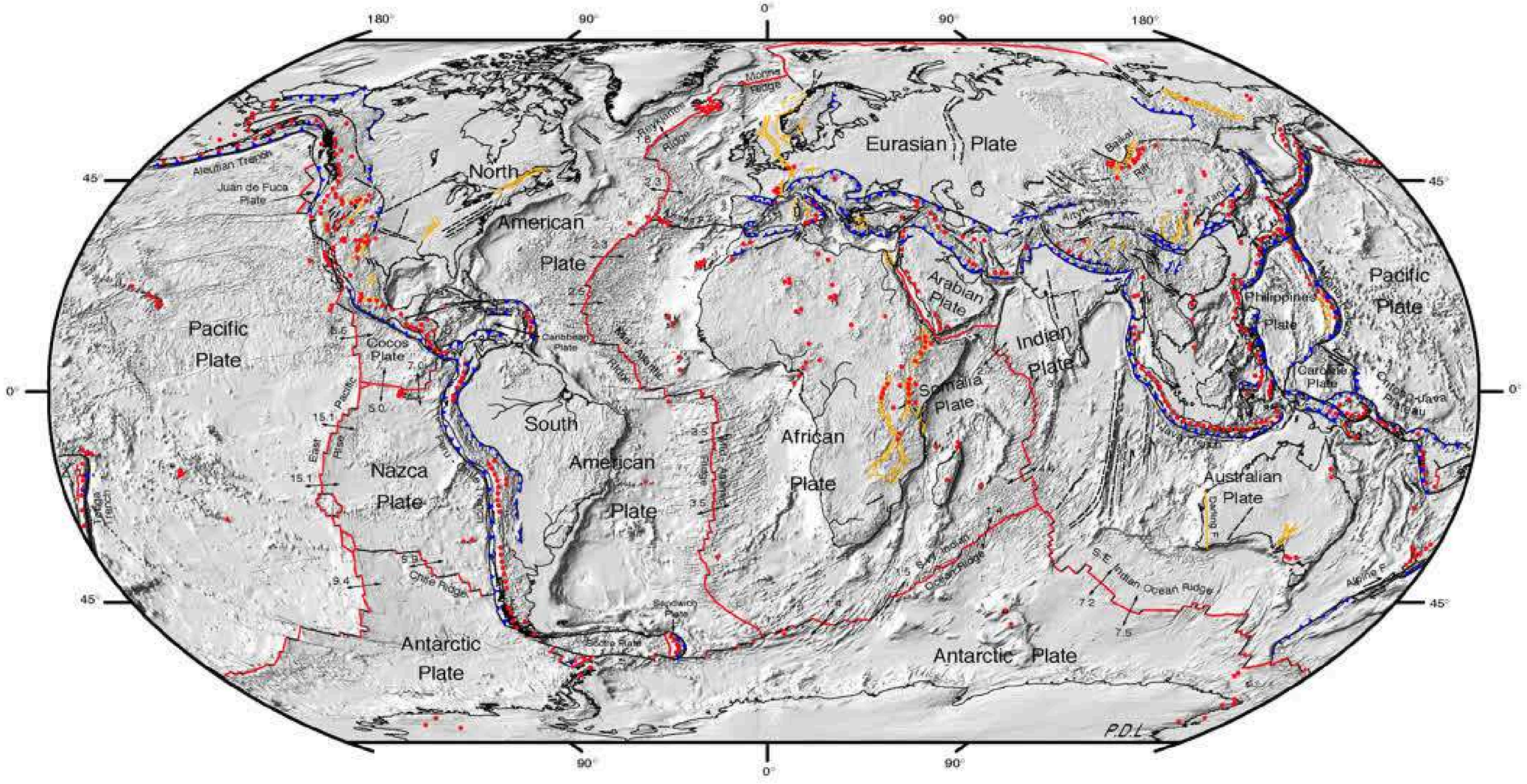
1997. Smith, W. H. F., and D. T. Sandwell,
Global seafloor topography from satellite altimetry and ship depth soundings, Science, v. 277.

1997. Müller et al., Carte des isochrones océaniques

Modèles cinématiques Nuvel (1990), Nuvel 2A (1994), Morvel (2010)

DIGITAL TECTONIC ACTIVITY MAP OF THE EARTH

Tectonism and Volcanism of the Last One Million Years



Actively-spreading ridges and transform faults

Total spreading rate, cm/year

1.4

Major active fault or fault zone; dashed where nature, location, or activity uncertain

Normal fault or rift; hachures on downthrown side

Reverse fault (overthrust, subduction zones); generalized; barbs on upthrown side

Volcanic centers active within the last one million years; generalized. Minor basaltic centers and seamounts omitted.

PARTIE 2

La mobilité du manteau terrestre à l’axe des dorsales océaniques n’était pas envisagée dans la Tectonique des Plaques!

Cette année là, en 1980 !

Une thèse sur les ophiolites des Alpes

Une thèse sur les ophiolites des Alpes

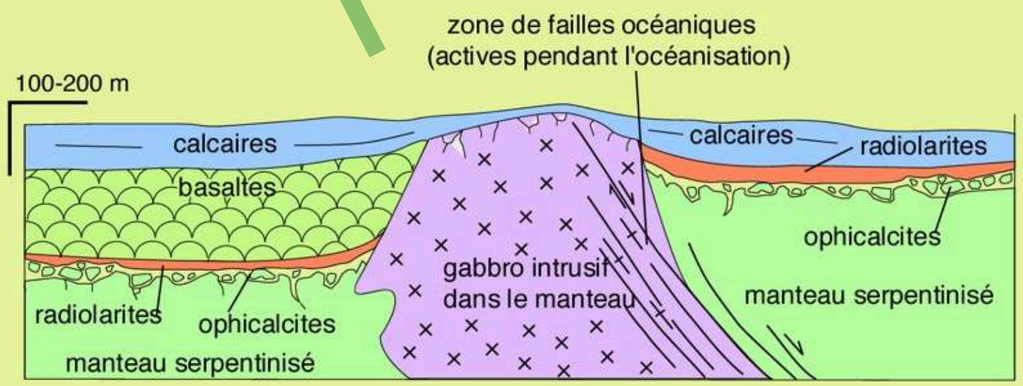
Sous la direction de Marcel Lemoine (CNRS)

1970-1971 :
Première mention de séquence ophiolitique « **complète »** dans les Alpes françaises

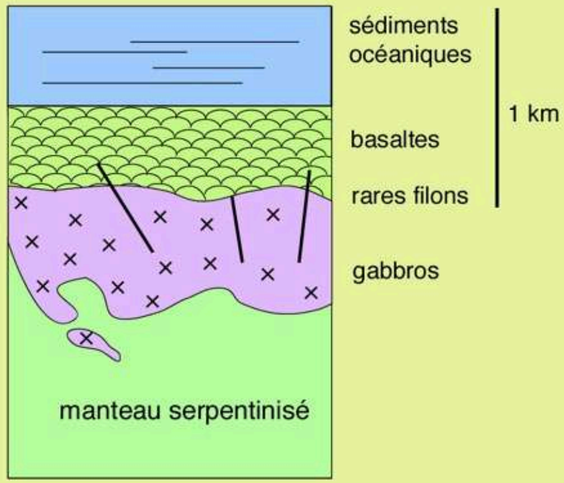
Les Ophiolites des Alpes occidentales

Unités riches en sédiments (schistes bleus)

Unités riches en ophiolites (éclogitiques)



succession de type Queyras-Chenaillet
(partie magmatique de la croûte réduite ou absente)



succession de type Mont Viso
(croûte magmatique mince mais continue)

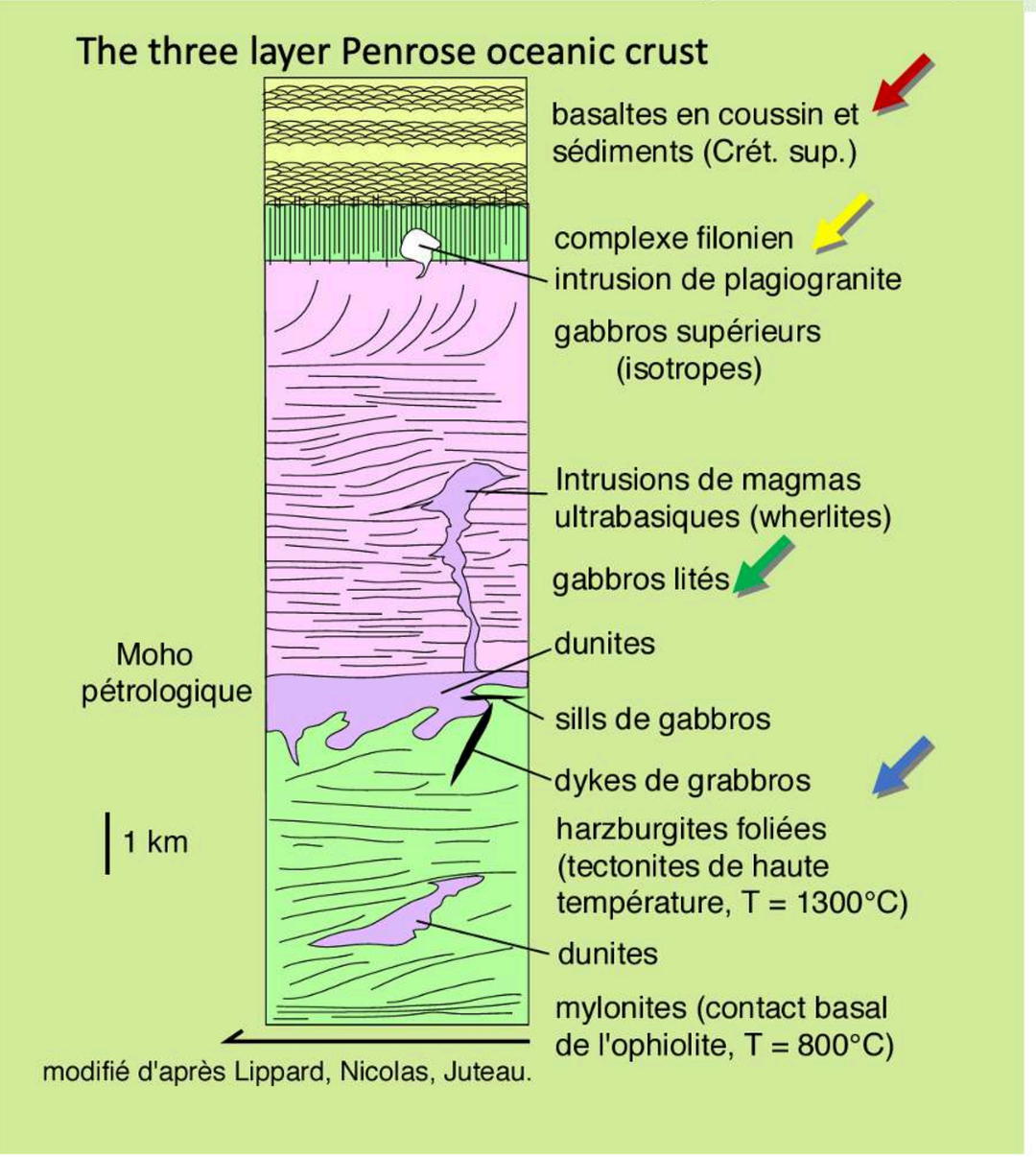
1972 : Le dogme de la Penrose Conference sur les ophiolites (GSA)

'Ophiolite', as used by those present at the GSA Penrose Conference on ophiolites, refers to a distinctive assemblage of mafic to ultramafic rocks. It should not be used as a rock name or as a lithologic unit in mapping. In a completely developed ophiolite the rock types occur in the following sequence, starting from the bottom and working up:

- Ultramafic complex, consisting of variable proportions of harzburgite, lherzolite and dunite, usually with a metamorphic tectonic fabric (more or less serpentinized).
- Gabbroic complex, ordinarily with cumulus textures commonly containing cumulus peridotites and pyroxenites and usually less deformed than the ultramafic complex.
- Mafic sheeted dike complex.
- Mafic volcanic complex, commonly pillowed.

Associated rock types include (1) an overlying sedimentary section typically including ribbon cherts, thin shale interbeds, and minor limestones; (2) podiform bodies of chromite generally associated with dunite; (3) sodic felsic intrusive and extrusive rocks.

Faulted contacts between mappable units are common. Whole sections may be missing. An ophiolite may be incomplete, dismembered, or metamorphosed, in which case it should be called a partial, dismembered, or metamorphosed ophiolite. Although ophiolite generally is interpreted to be oceanic crust and upper mantle the use of the term should be independent of its supposed origin.



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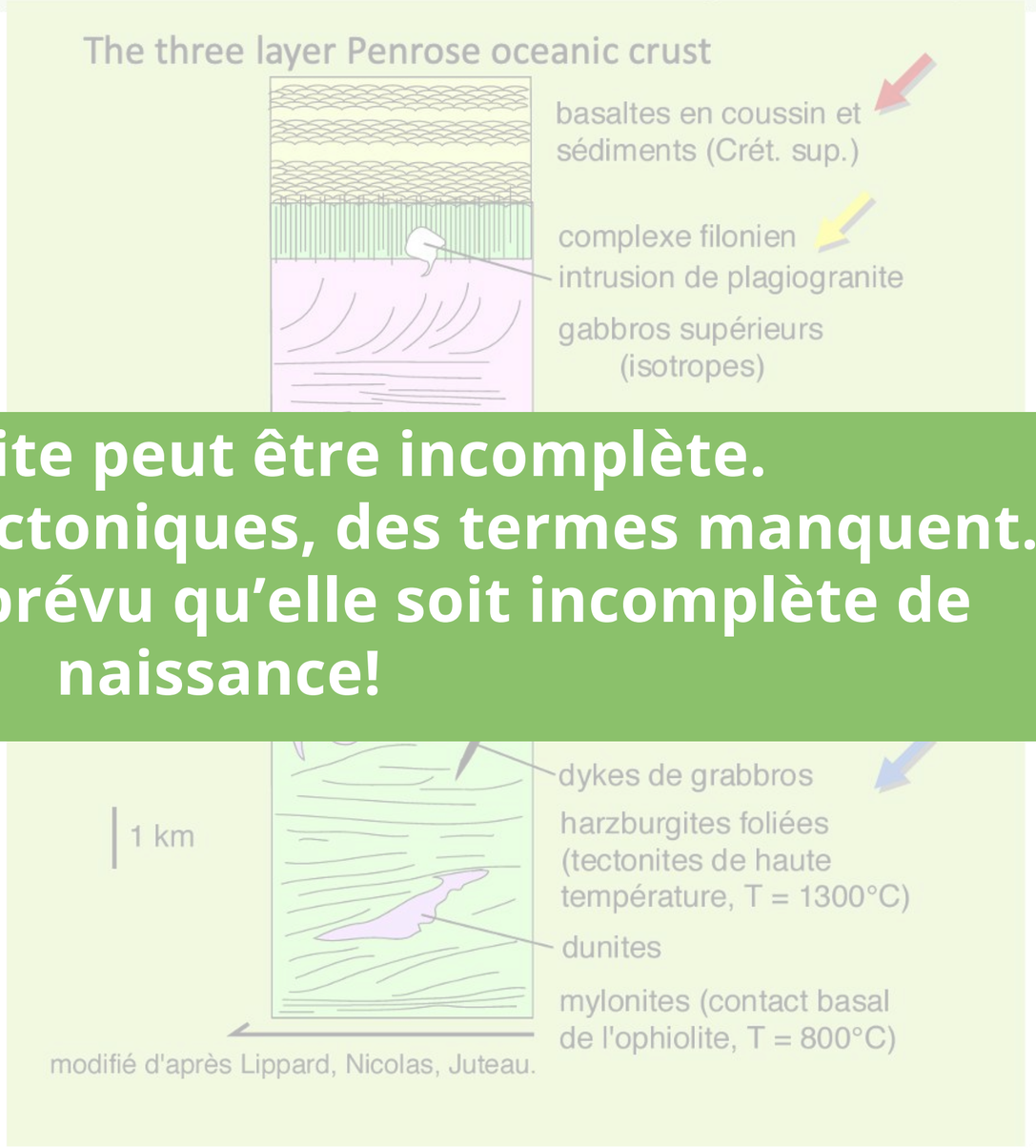


Une ophiolite peut être incomplète.
Pour des raisons tectoniques, des termes manquent.
Mais il n'est pas prévu qu'elle soit incomplète de naissance!

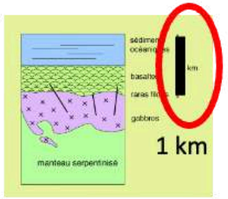
Deux difficultés pour les ophiolites alpines :

1. La séquence ophiolitique la plus complète présente une faible épaisseur et peu de produits crustaux (peu de gabbros, pas de complexe filonien).

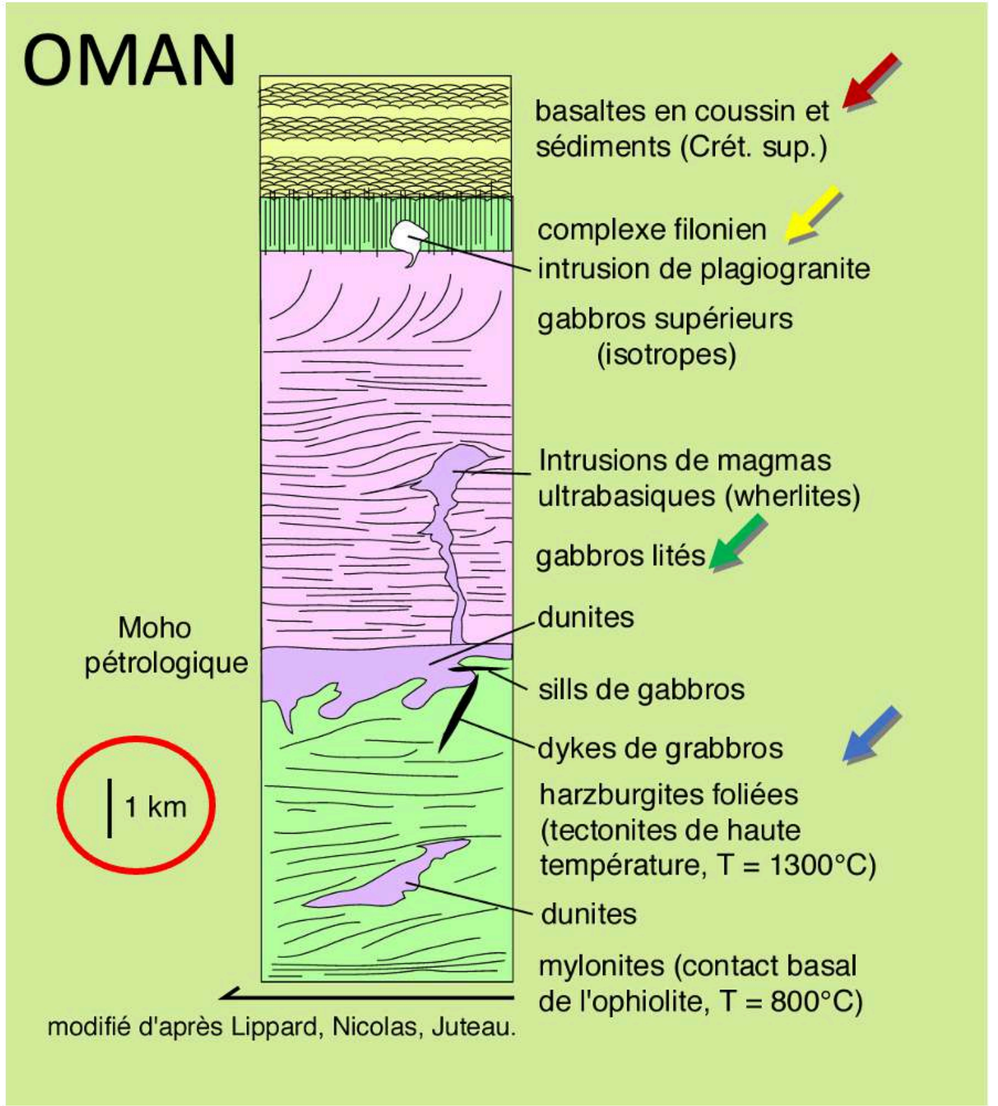
2. Dans toutes les unités schistes bleus, les ophiolites sont très incomplètes et les sédiments océaniques reposent sur tous les termes ophiolitiques.

Difficulté 1

ALPES (VISO)

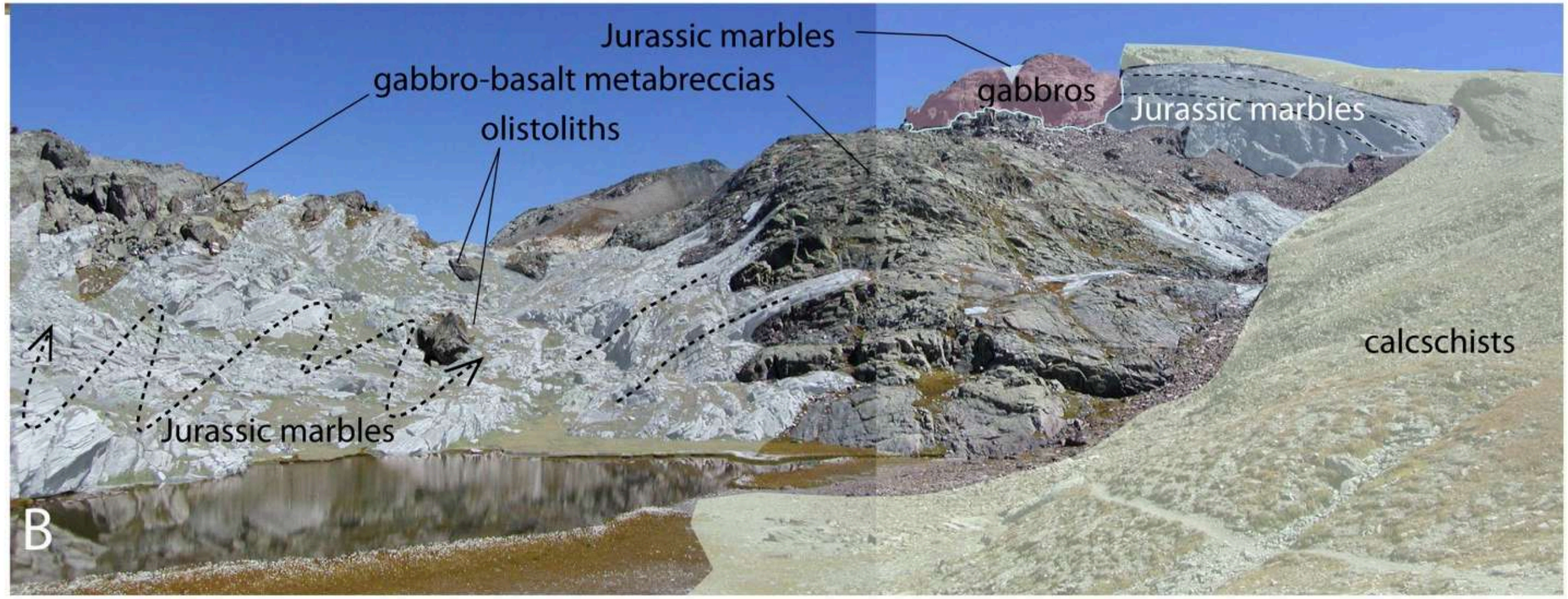


OMAN



Difficulté 2

Le massif de Rocca Bianca, Queyras



Période 1980-1990.

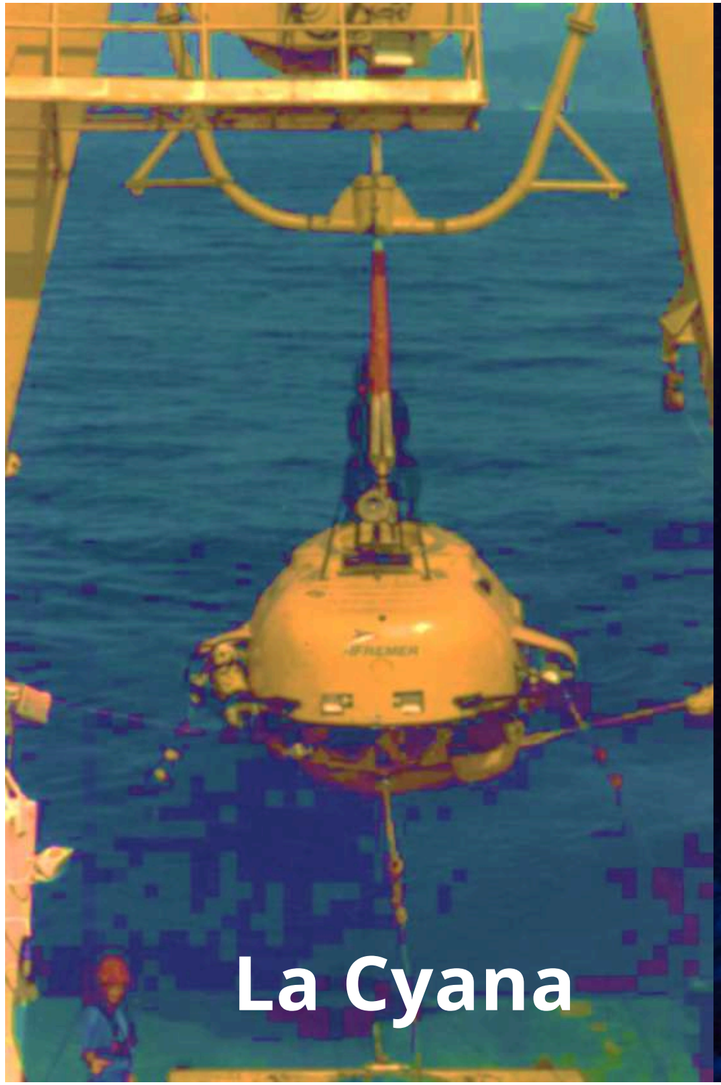
Une seule question pour valider ce modèle d’ophiolite « sans croûte ».

Période 1980-1990.

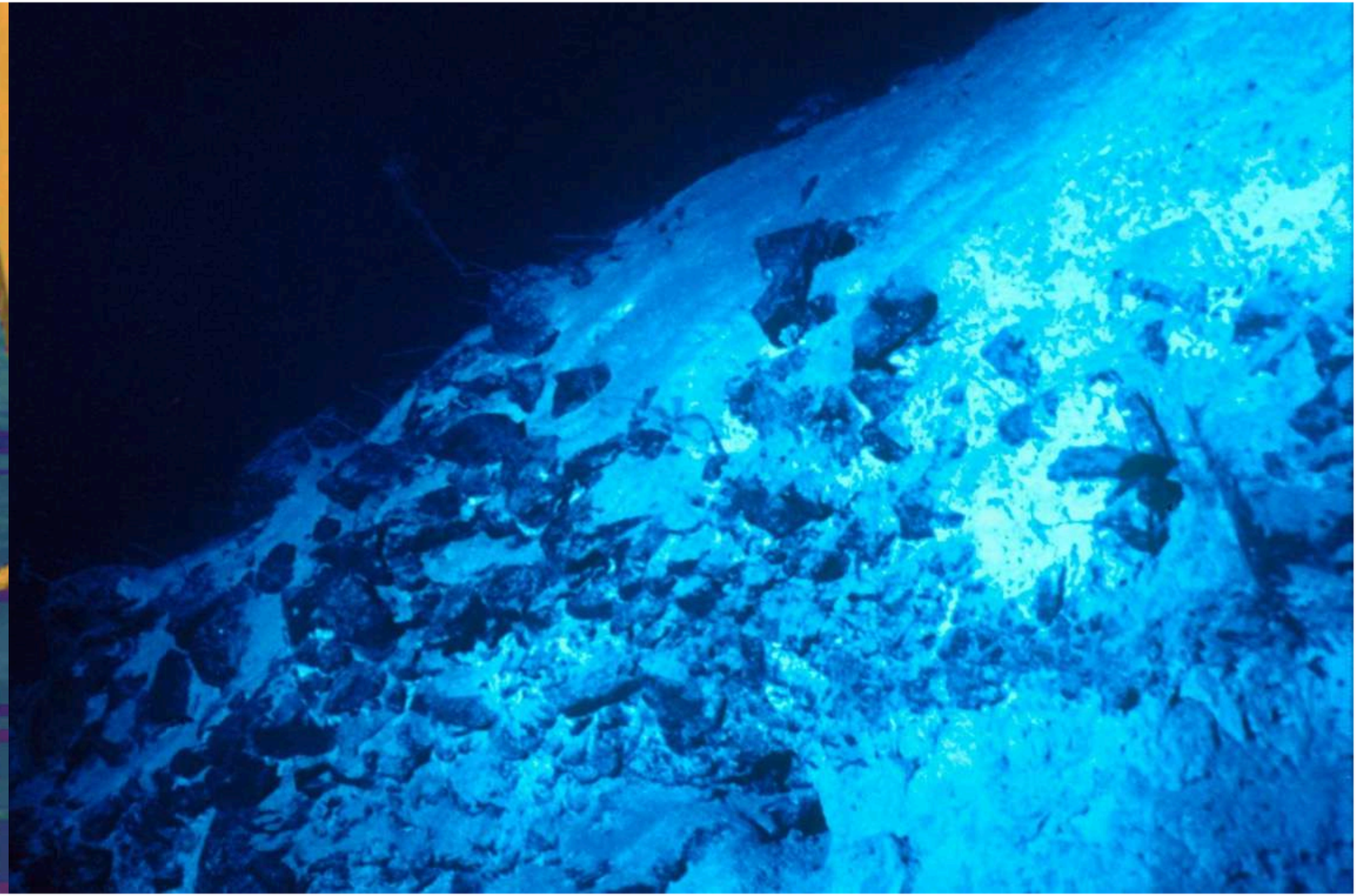
Une seule question pour valider ce modèle d’ophiolite « sans croûte ».

Le manteau est-il parfois dénudé à l’axe des dorsales lentes?

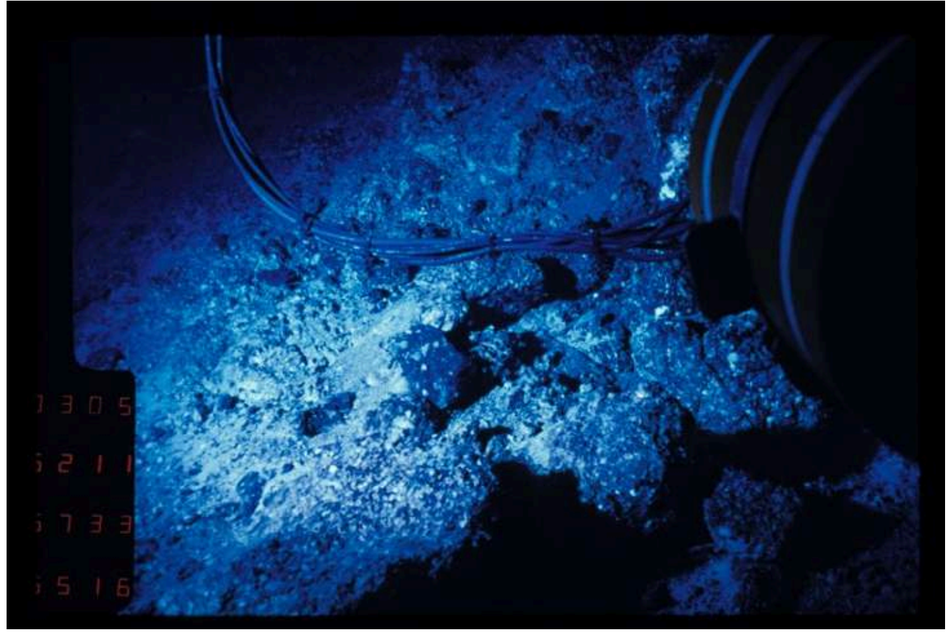
Que répondent les océans?



La Cyana



Banc de Gorringe, 1981



Lagabrielle and Auzende, *Nature*, 1982

Reprinted from Nature, Vol. 297, No. 5866, pp. 490-493, June 10 1982

Active *in situ* disaggregation of oceanic crust and mantle on Gorringe Bank: analogy with ophiolitic massives

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The *Cyagor II* cruise (May 1981) using submersible *Cyana SP 3000* on Gorringe Bank off south-west Portugal confirmed the scheme proposed at the end of *Cyagor I* cruise[1,2] that during the middle Cretaceous (110 Myr BP), Gorringe Bank, an old transform fault of Triassic–Liassic age, appears to have tilted to the north-east leading to the exposure of a section of oceanic mantle and crust. Due to its location at the boundary between European and African plates, Gorringe Bank suffered tectonic reactivation and uplifting during compressive and shearing-type events that occurred at the Cretaceous–Tertiary boundary and during the Tertiary (Eocene–Miocene). During the 12 dives of the *Cyagor II* cruise (Fig. 1), phenomena linked to the disintegration of serpentinites and gabbros in the deep-sea domain have been studied *in situ* with more detail than before[3]. Such processes have been suggested from studies on samples dredged or cored in oceans, or from observations in ophiolitic belts but direct observation had not enabled the magnitude of such phenomena to be measured. The observations on Gorringe Bank suggest that the processes described here are active in many oceanic sites. They help us to understand better the significance of many ophiolitic detritic beds more or less closely associated with pelagic sediments. We now compare the observations made at sea, especially on Gorringe Bank with similar observations in ophiolitic zones in mountain belts, which suggests that the ophiolite complexes have formed in a similar way to the breccias seen on the ocean floor.

Nine dives in areas where gabbros (Ormonde) and serpentinites (Gettysburg) outcrop revealed a very jagged deep-sea

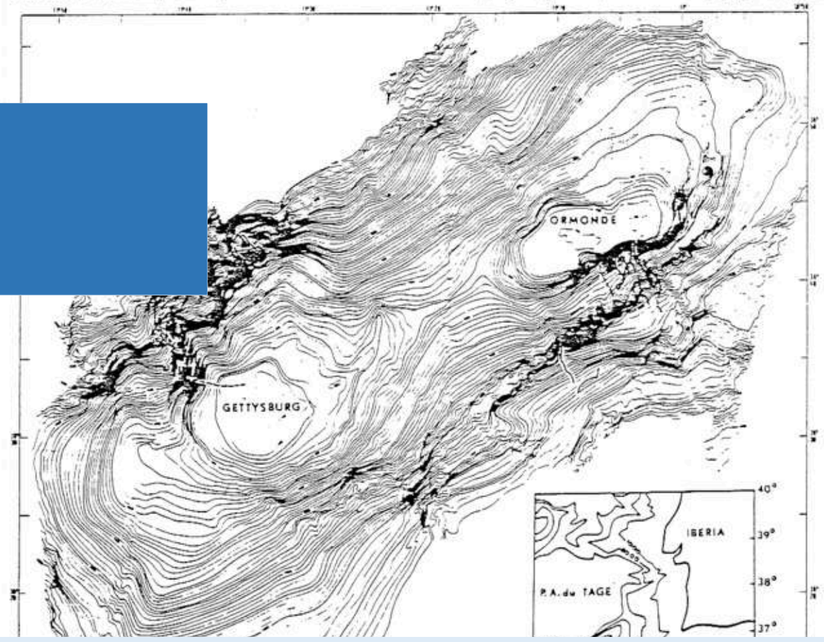


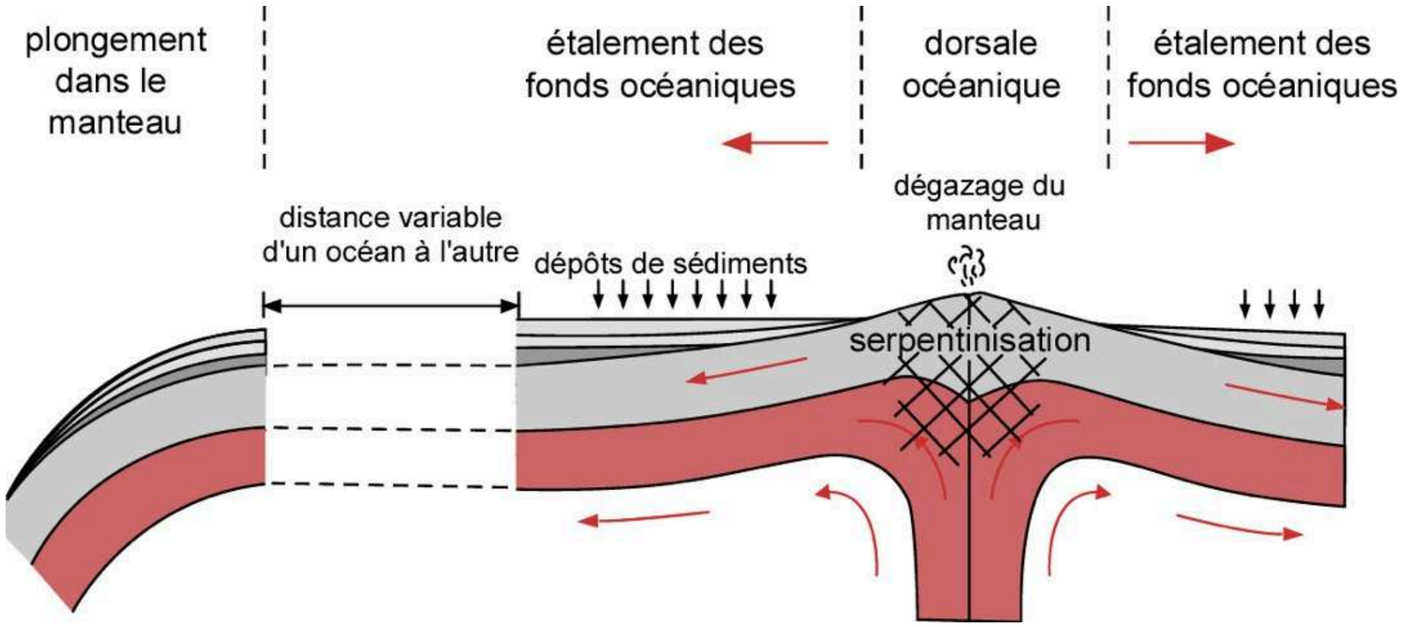
Fig. 1 Bathymetric map of Gorringe Bank with locations of *Cyana SP 3000* dives. Solid lines, *Cyagor II* cruise 1981; dashed line, *Cyagor I* cruise 1977.

Le détritisme ophiolitique

Le manteau et les gabbros sont remaniés sur les fonds océaniques

Cela venait confirmer des contributions anciennes restées dans l'oubli après la tourmente de la Tectonique des Plaques!

Par exemple : schéma de Hess, 1952



Les fonds océaniques résultent de la transformation d'un flux montant de manteau chaud en une translation horizontale de manteau refroidi.

Donc le manteau et les gabbros sont bien présents à l'affleurement le long des dorsales lentes.

Ceci a permis de proposer en 1990 une première correspondance entre la dorsale de l'Atlantique Central (archétype des dorsales lentes) et les ophiolites alpines

Alpine Jurassic ophiolites resemble the modern central Atlantic basement.
Geology.

Lagabrielle and Cannat, 1990

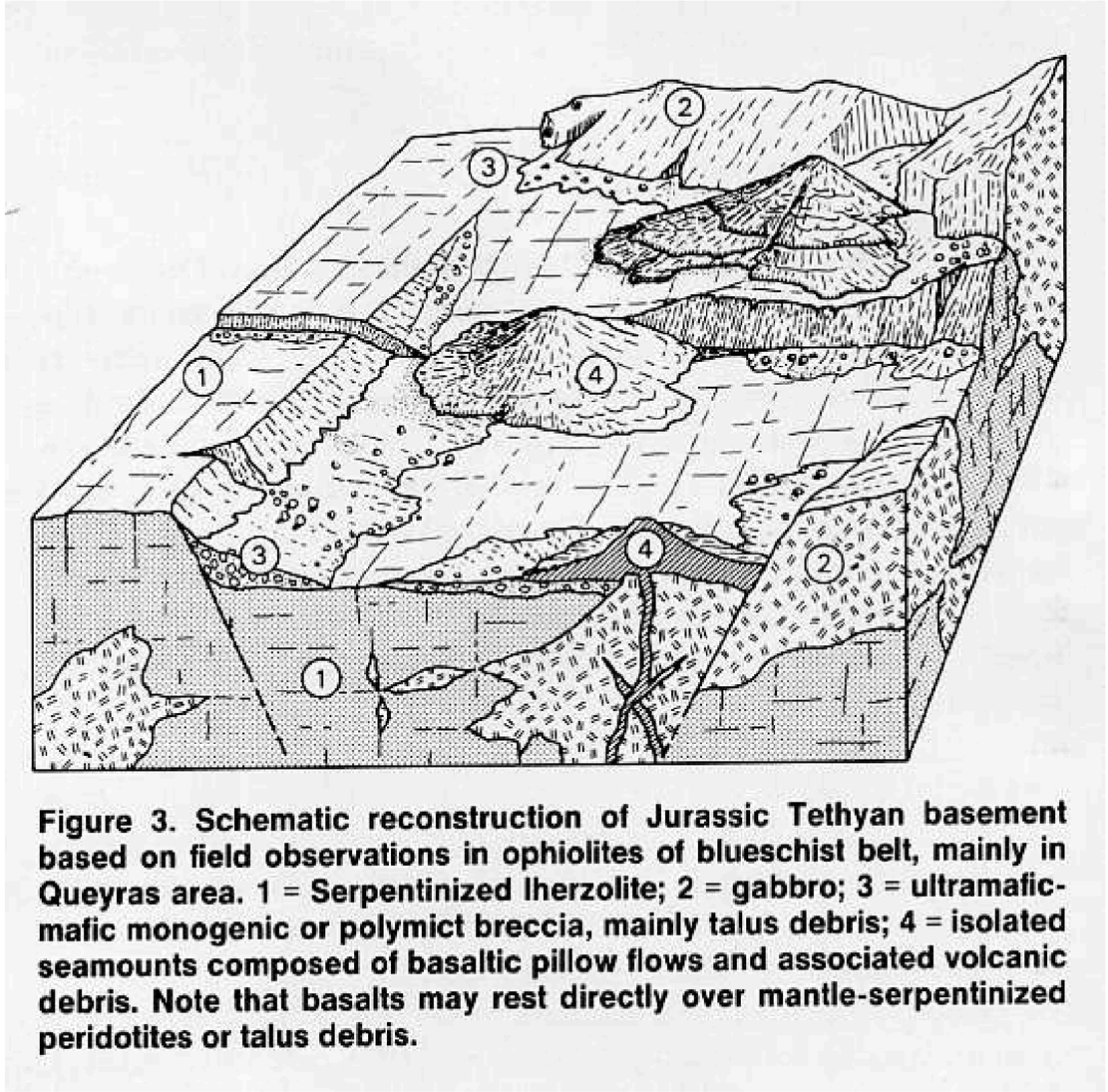
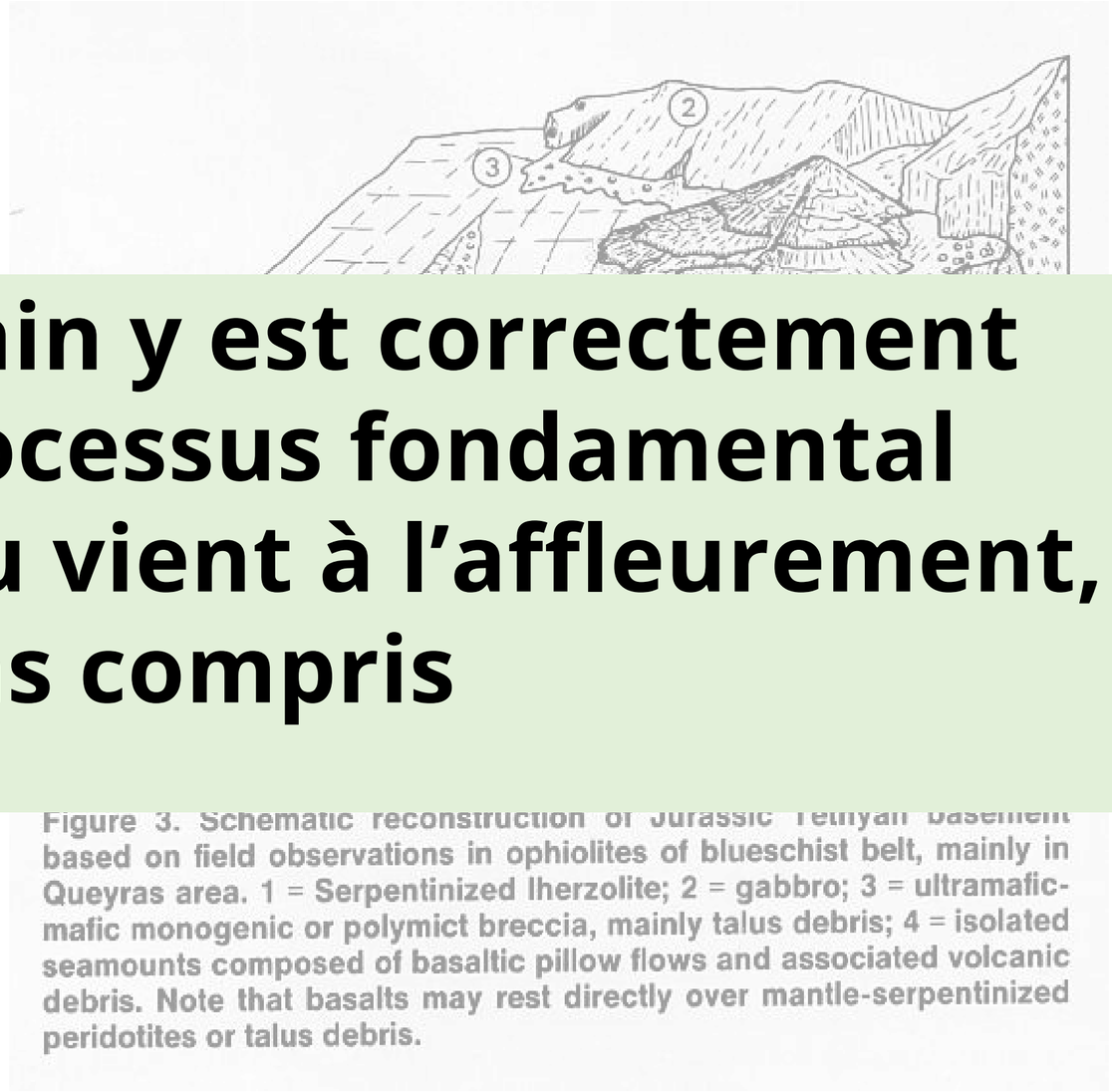


Figure 3. Schematic reconstruction of Jurassic Tethyan basement based on field observations in ophiolites of blueschist belt, mainly in Queyras area. 1 = Serpentinized lherzolite; 2 = gabbro; 3 = ultramafic-mafic monogenic or polymict breccia, mainly talus debris; 4 = isolated seamounts composed of basaltic pillow flows and associated volcanic debris. Note that basalts may rest directly over mantle-serpentinized peridotites or talus debris.



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La géologie du terrain y est correctement décrite, mais le processus fondamental par lequel le manteau vient à l'affleurement, n'est pas compris

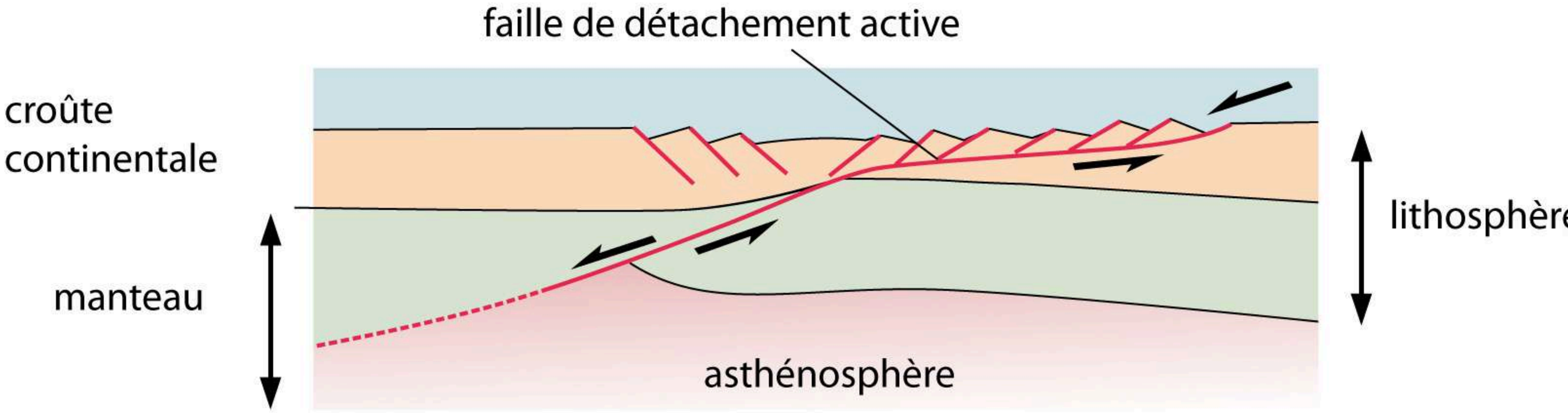
Lagabrielle and Cannat, 1990

PARTIE 3

Quand les failles normales se couchèrent!
Le salut vient du continent!

Le cisaillement simple

B. Wernicke, 1985



marge de type Galice

Une application immédiate!

Le **leg ODP 109** en 1986, puis **le leg 153** en 1993 au sud de la ZF Kane, le long d'un segment de la dorsale, montrent que le manteau est exhumé par processus tectonique le long de l'axe et en dehors des zones de fracture.

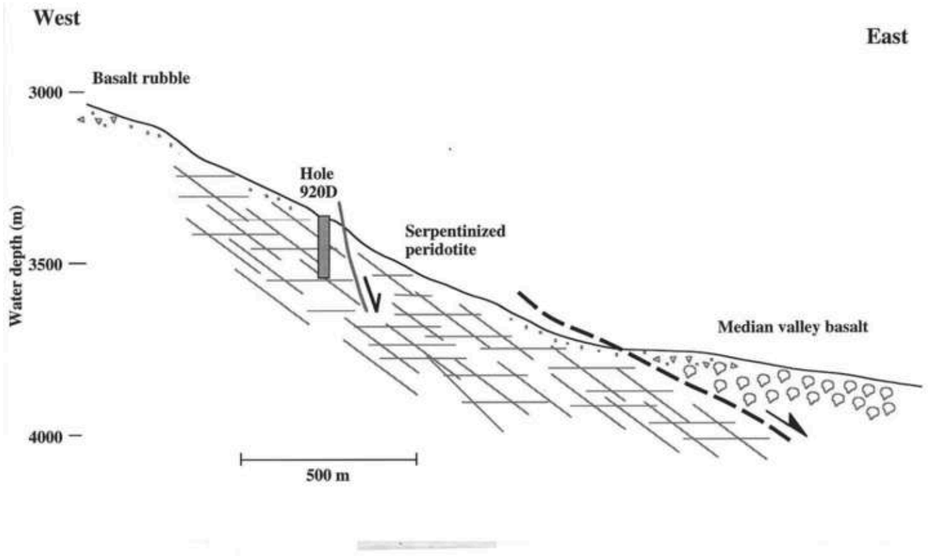


Figure 3. Schematic cross section of the western median valley wall at 23°20.32'N, from *Nautile* dive HS 13 and Site 920 camnera survey. No vertical exaggeration.

Probing the Foundation of the Mid-Atlantic Ridge

ODP Leg 153 Shipboard Scientific Party

Leg 153 of the Ocean Drilling Program drilled five sites on the western wall of the Mid-Atlantic Ridge (MAR) between 23°20'N and 23°30'N, at distances of 5–35 km south of the Kane Transform (Figure 1). This area—referred to as the MARK—is one of the most extensively studied portions of the mid-ocean-ridge system. Core recovered on Leg 153 represents the most continuous sampling to date through a section of sub-oceanic mantle, as well as temporally and spatially diverse sections of the lower crustal plutonic rocks. Results from postcruise research programs will specifically address models of magma evolution, tectonic activity, and hydrothermal alteration in slow-spreading oceanic crust.

The targets of Leg 153 were extensive exposures of serpentinized peridotites and gab-

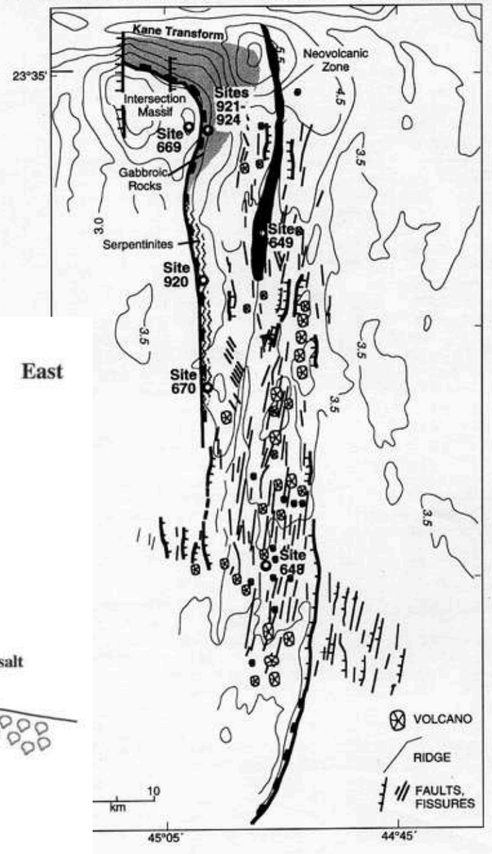
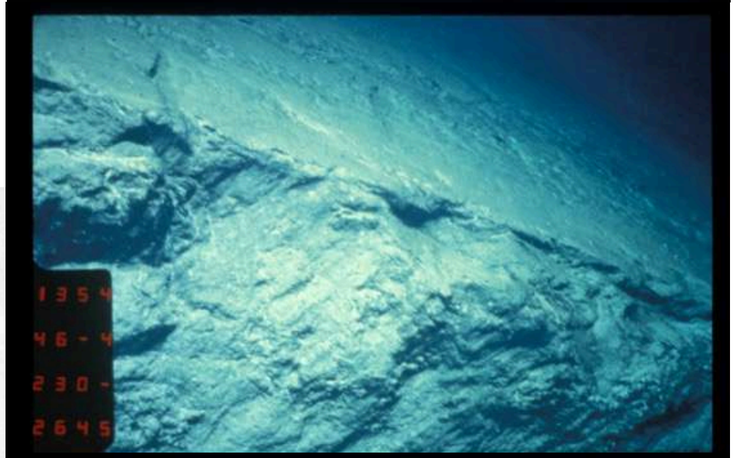
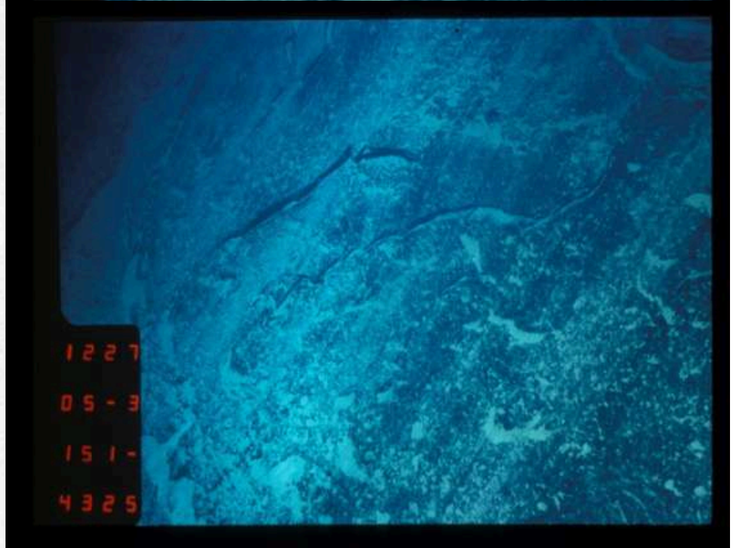
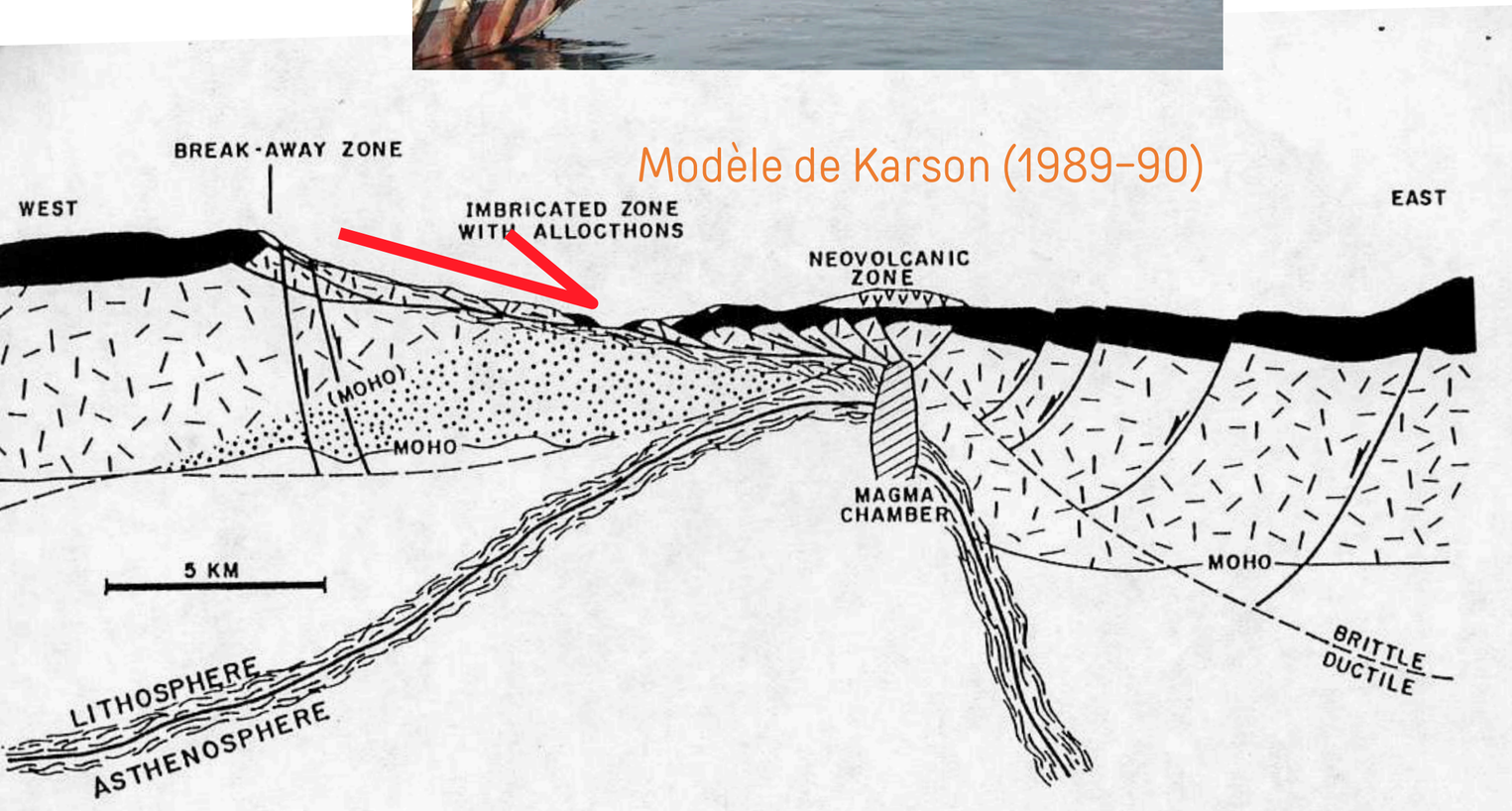


Fig. 1. Highly generalized tectonic map of the MARK area, showing the locations of ODP drill sites from Leg 106, 109, and 153 with respect to major geologic features. Bathymetric contours in kilometers.

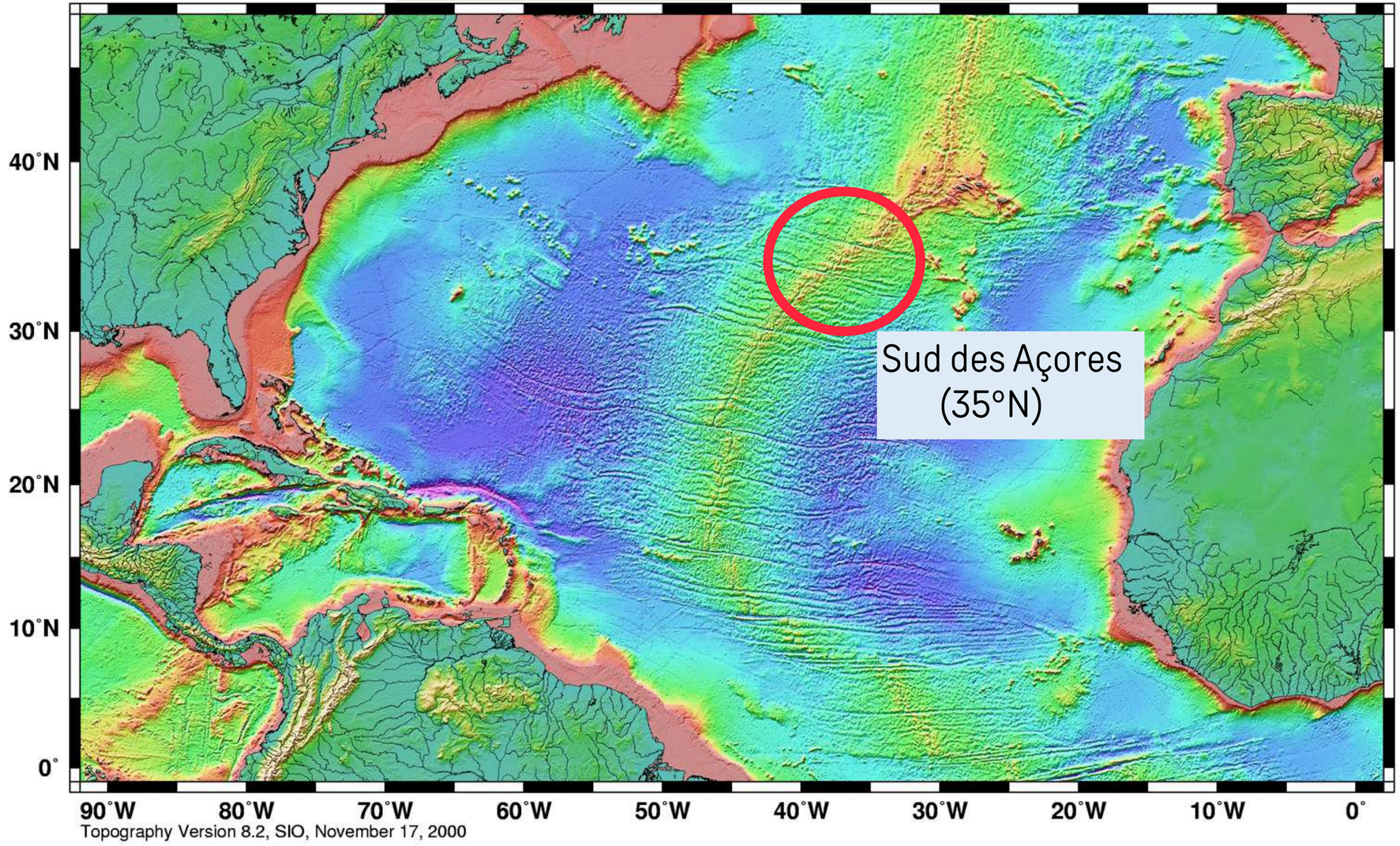




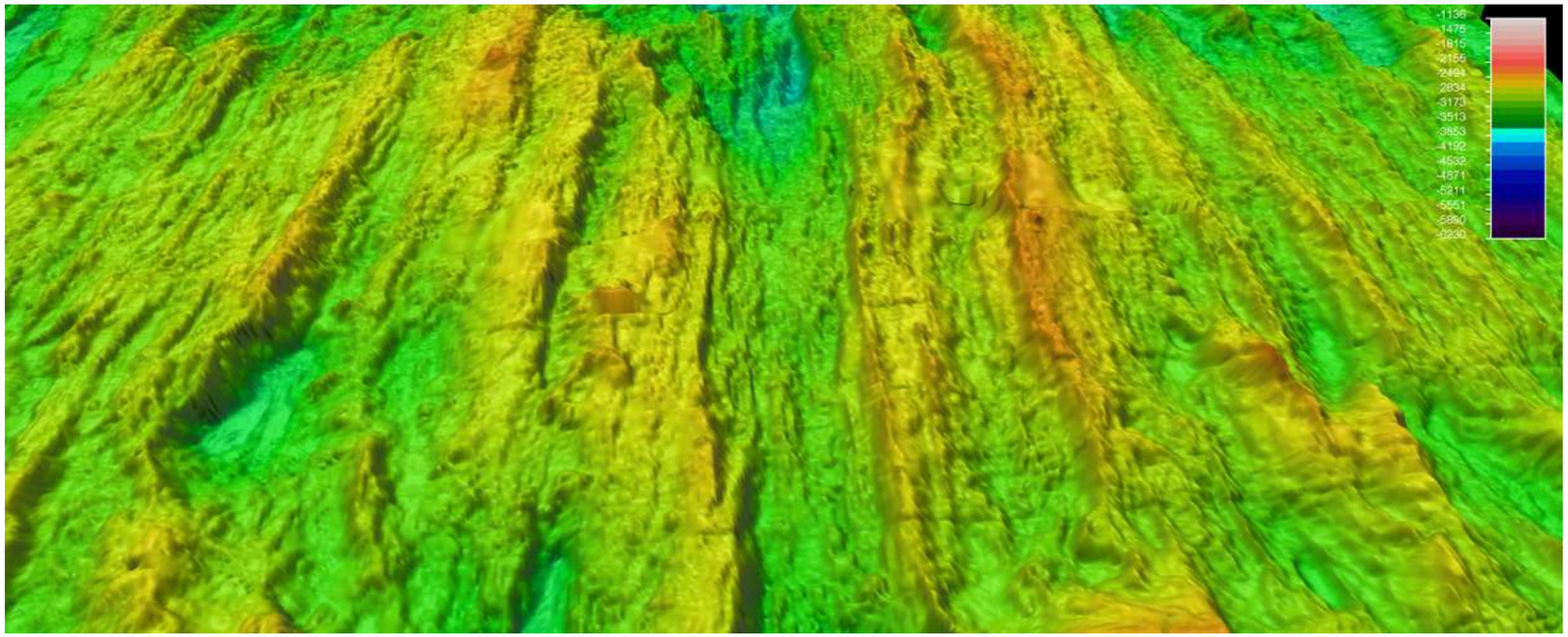
Modèle de Karson (1989-90)



Les dorsales lentes

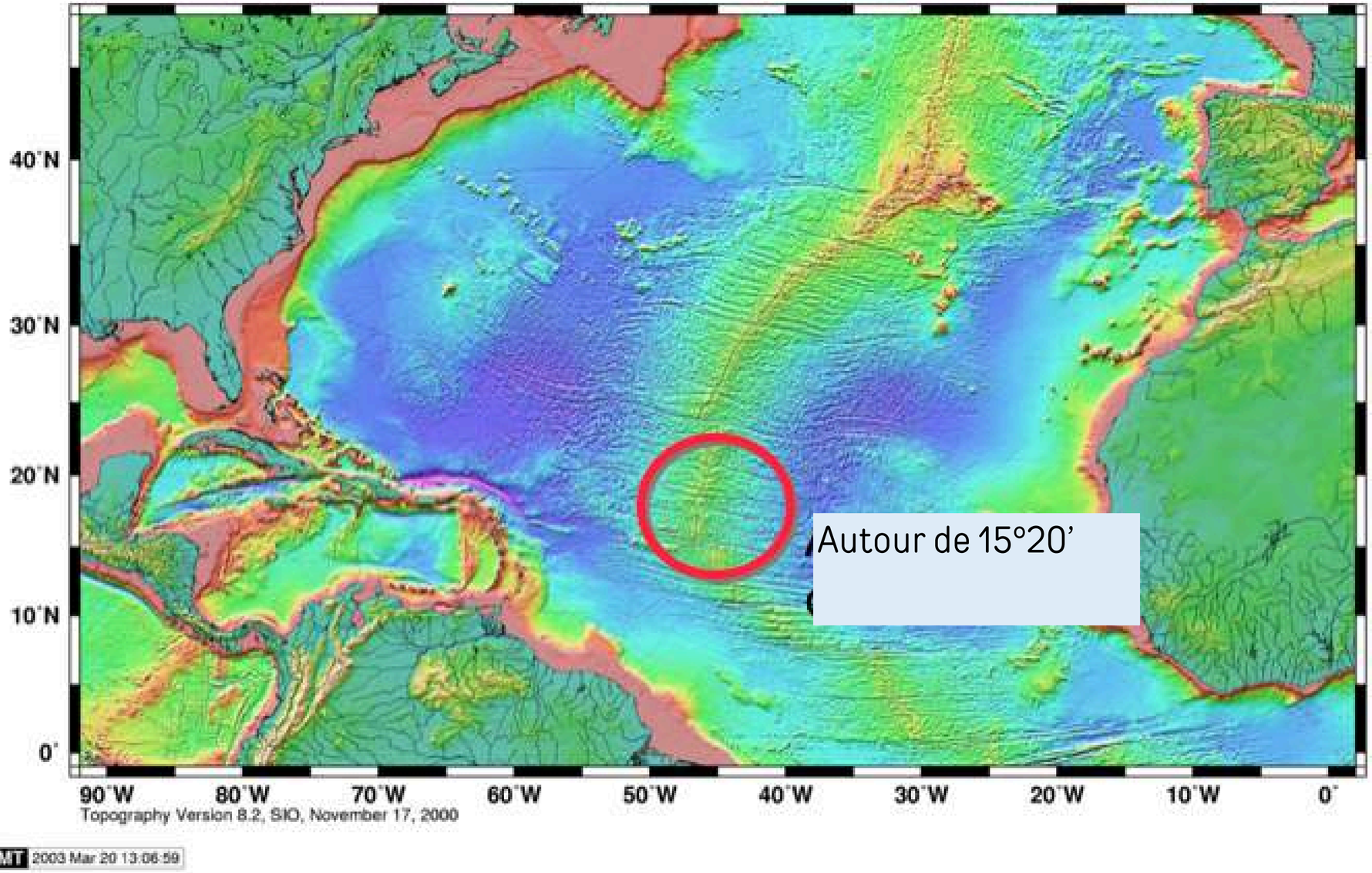


Des segments symétriques, magmatiques… (normaux)



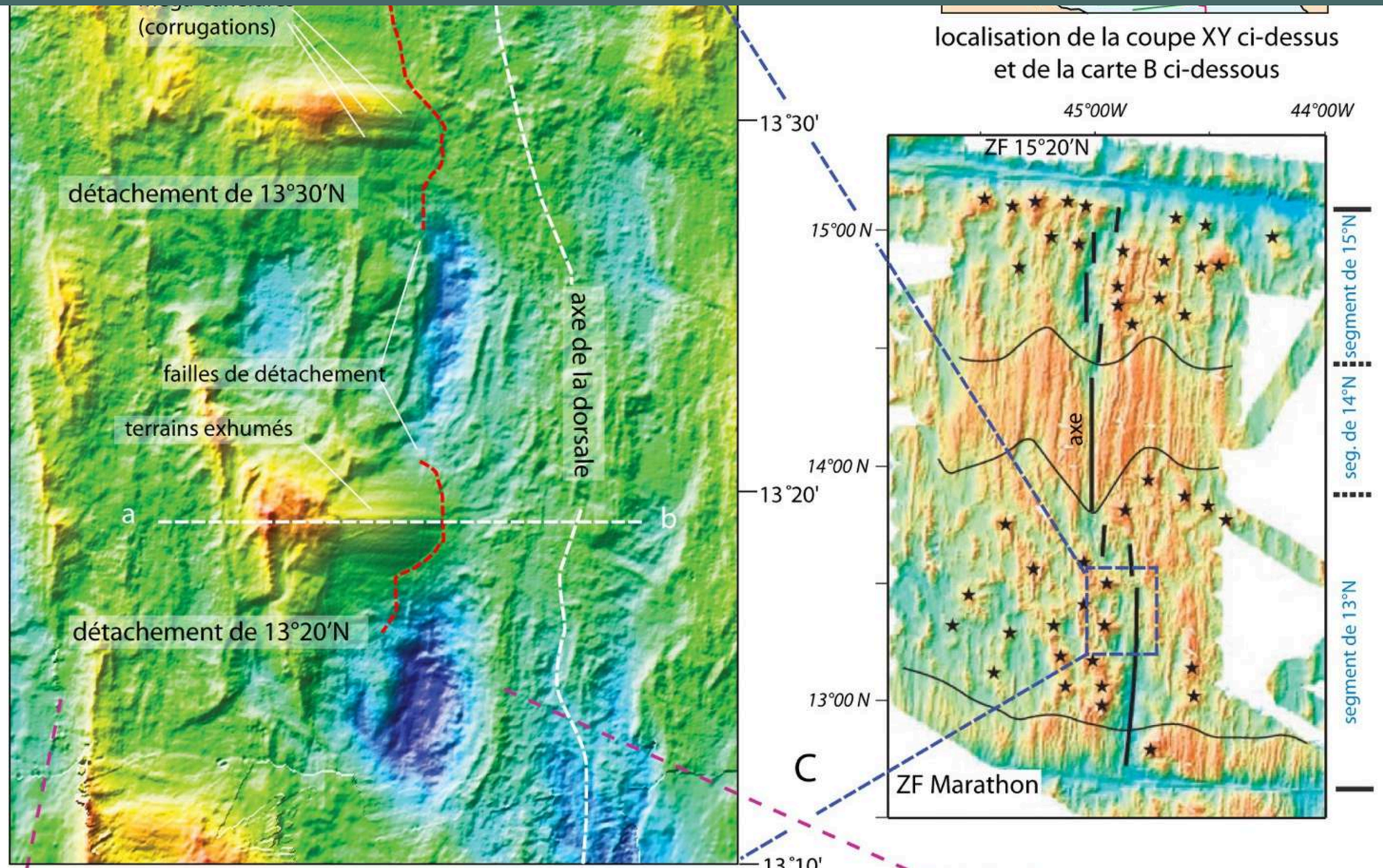
EE

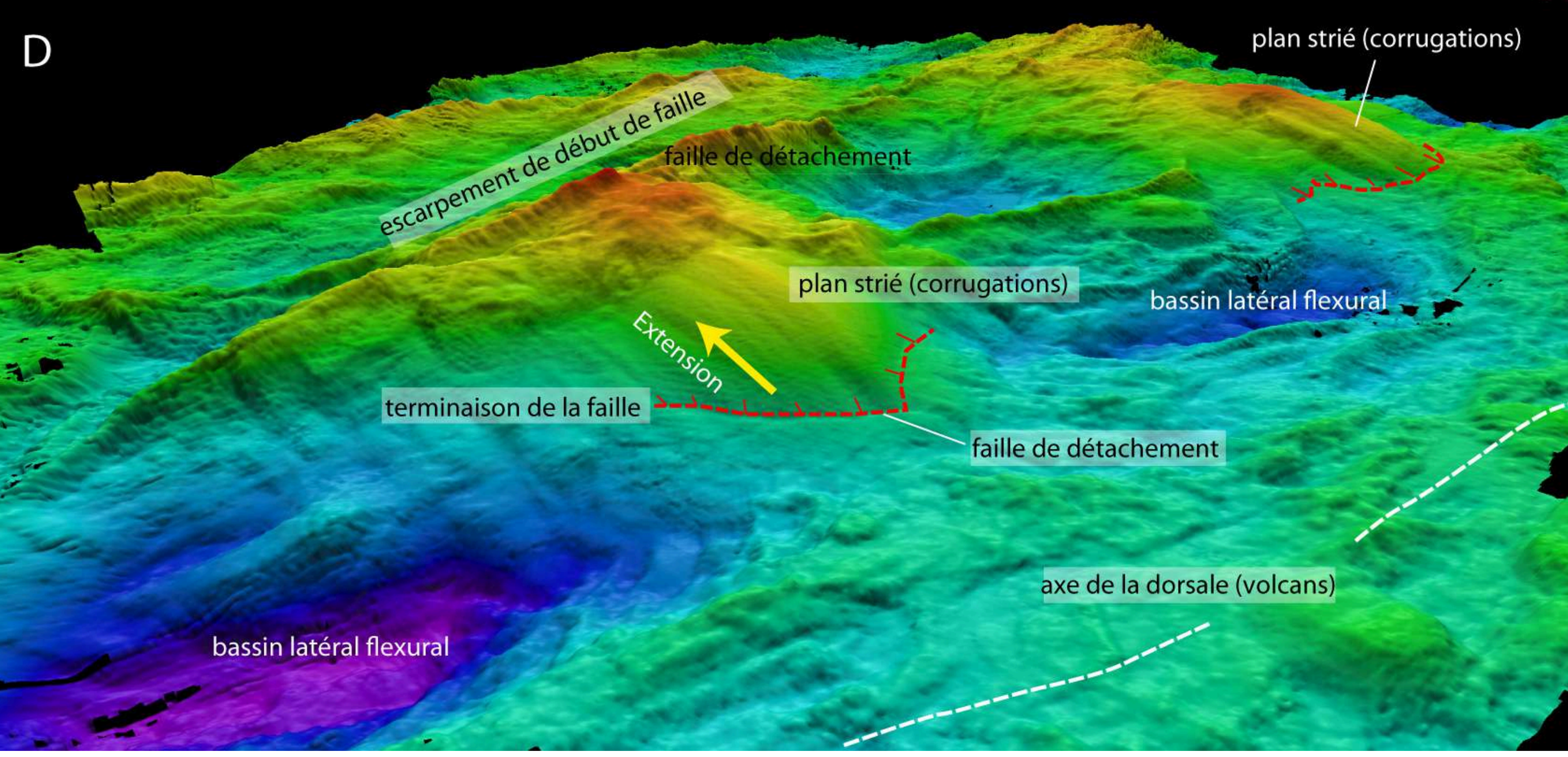
Les dorsales lentes



Les OCC, oceanic core complexes

ZF 15°20




D
plan strié (corrugations)
escarpement de début de faille
faille de détachement
plan strié (corrugations)
bassin latéral flexural
Extension
terminaison de la faille
faille de détachement
axe de la dorsale (volcans)
bassin latéral flexural

Corrugated slip surfaces formed at ridge–transform intersections on the Mid-Atlantic Ridge

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** Department of Earth Sciences, University of Leeds, Leeds LS2 9JT, UK*

† Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543, USA

Nature, 1997

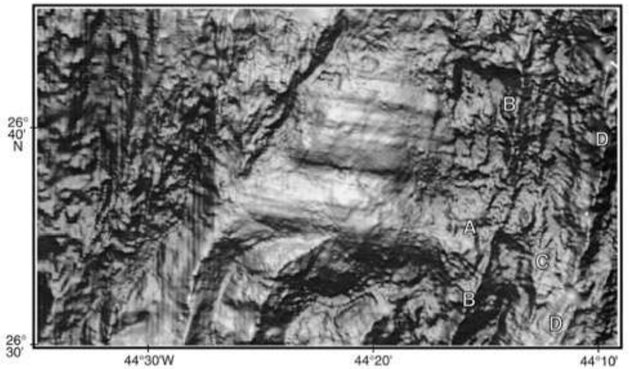
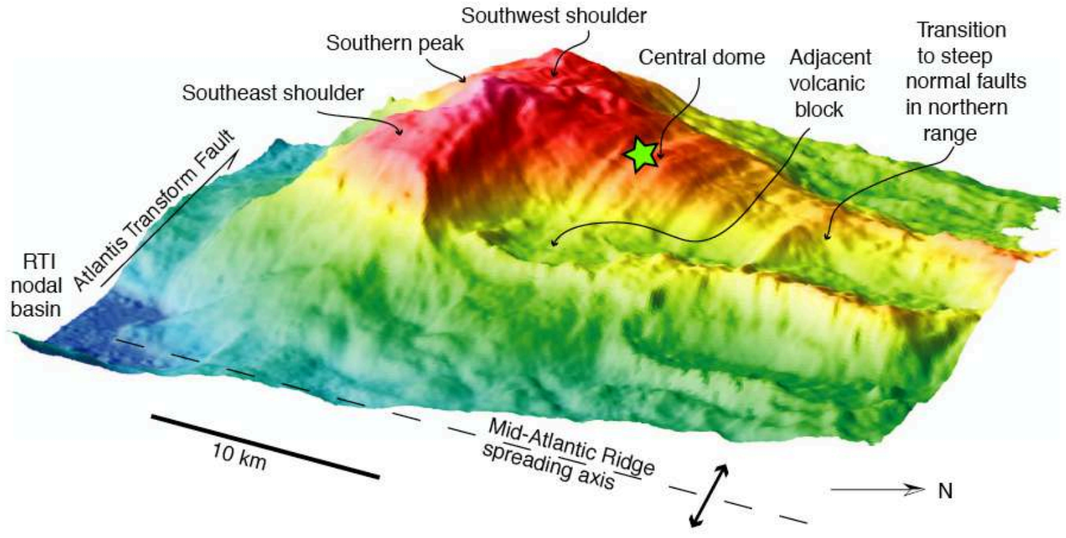
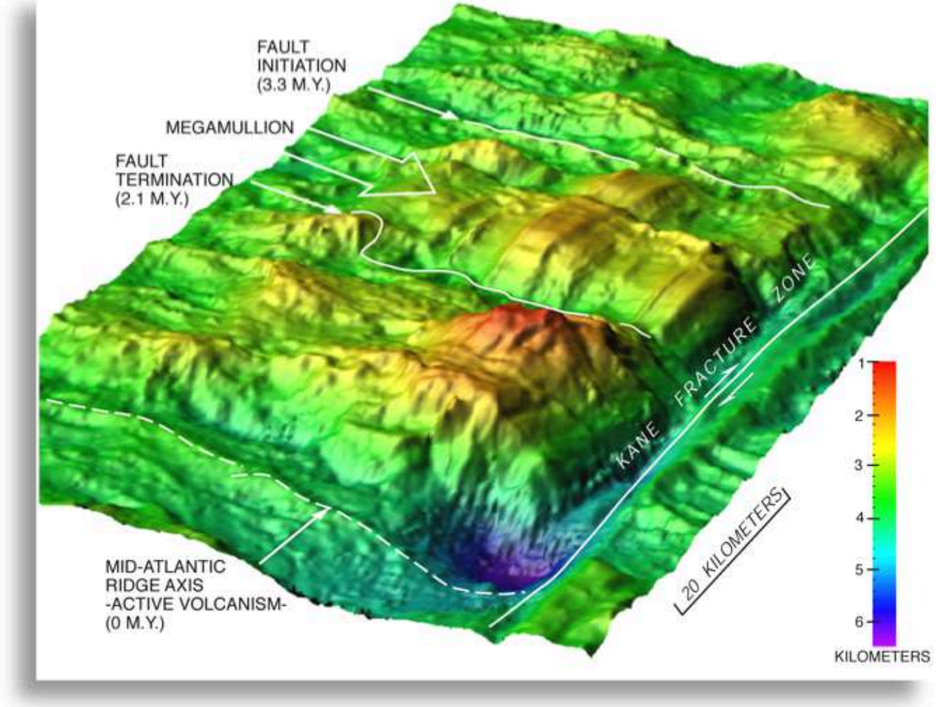


Figure 2. Shaded relief bathymetry of Dante's Domes megamullion on the east flank of the Mid-Atlantic Ridge near 26°35'N. The map is constructed from Hydrosweep multibeam bathymetry gridded at 100-m intervals and illuminated from the north. The neovolcanic zone in the axis of the rift valley is at the upper left. The domed structure at center is interpreted to be the footwall of a long-lived detachment fault. Its surface is corrugated by ~E-W flow line parallel structures with amplitudes less than a few tens of meters, and these are interpreted to be fault mullions; ship tracks were oriented NW-SE, so it is clear that the mullions are not beam-point artifacts. Letters A–D locate ridges identified in Figure 3 and discussed in the text. For additional structural interpretations including fault breakaway and termination, see Figure 3.

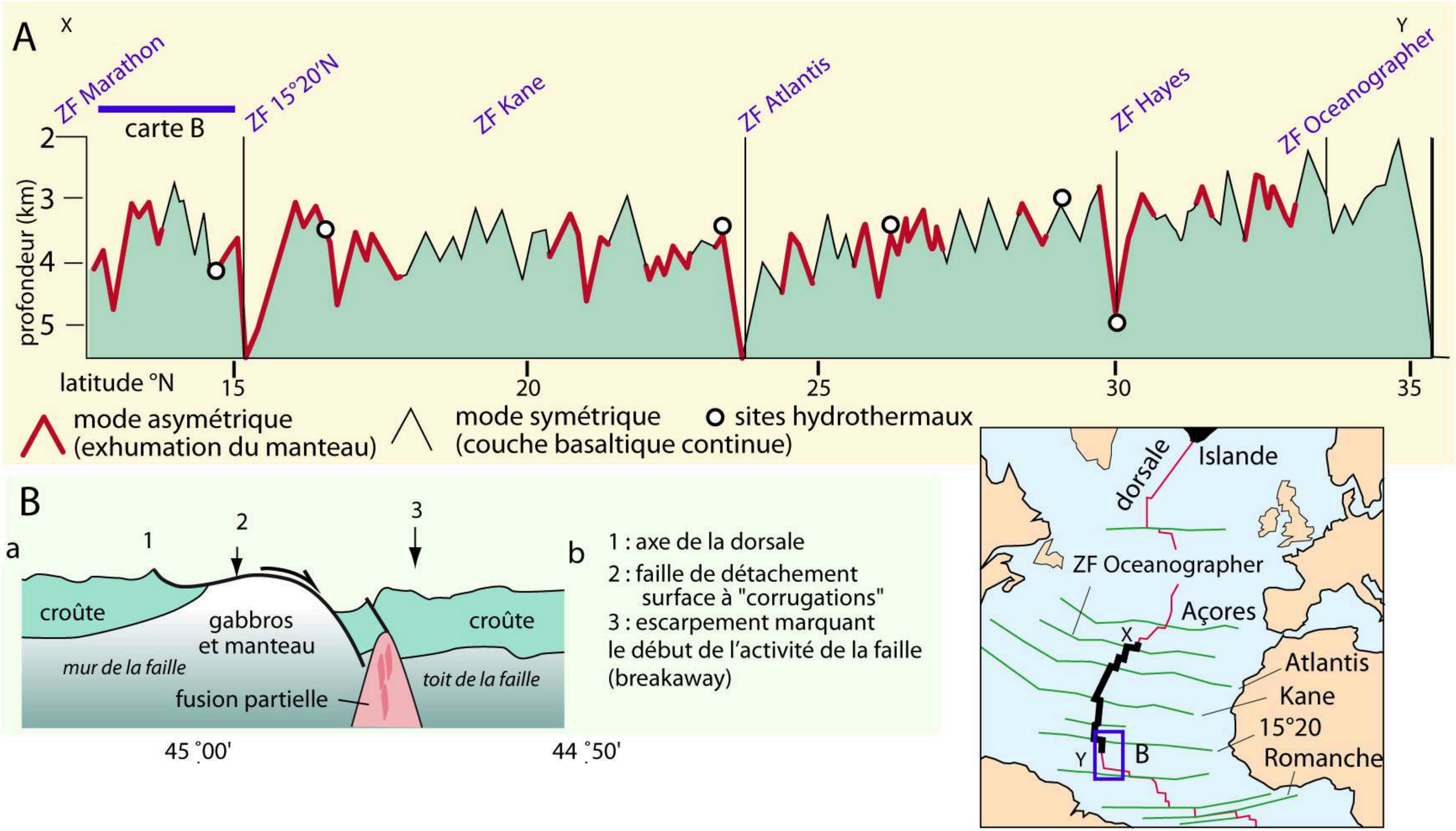
26°40’N



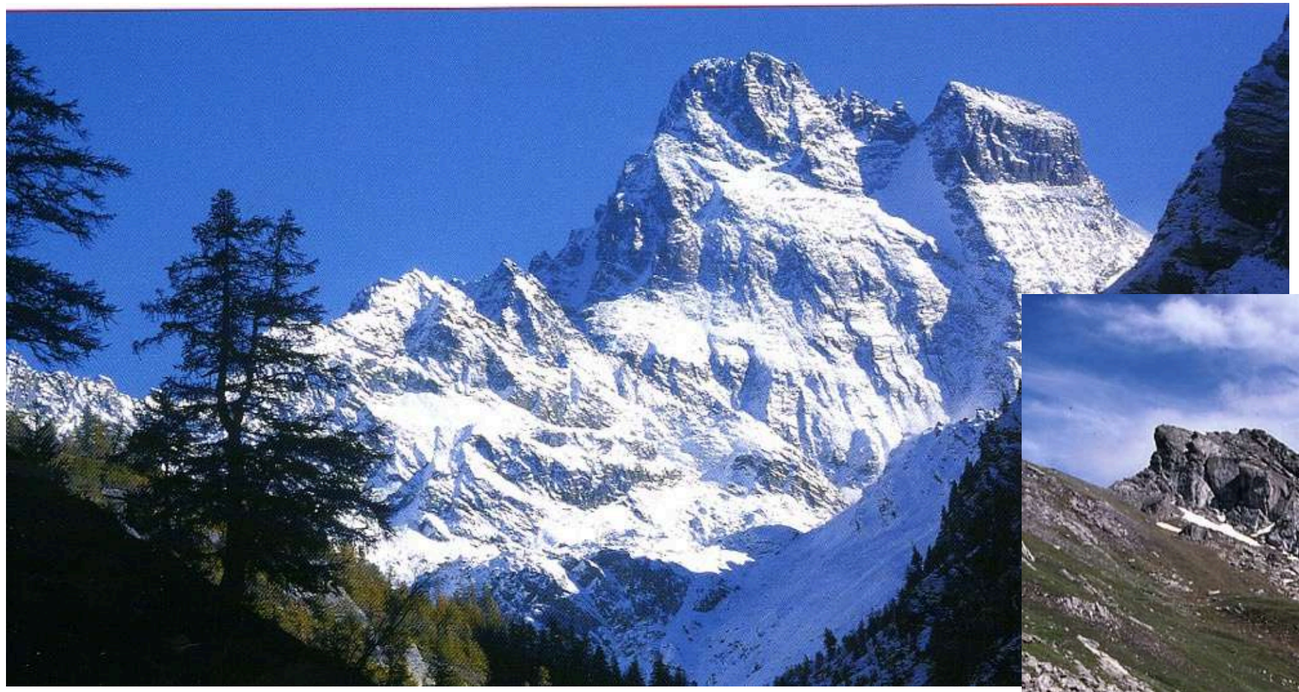
ZF Atlantis



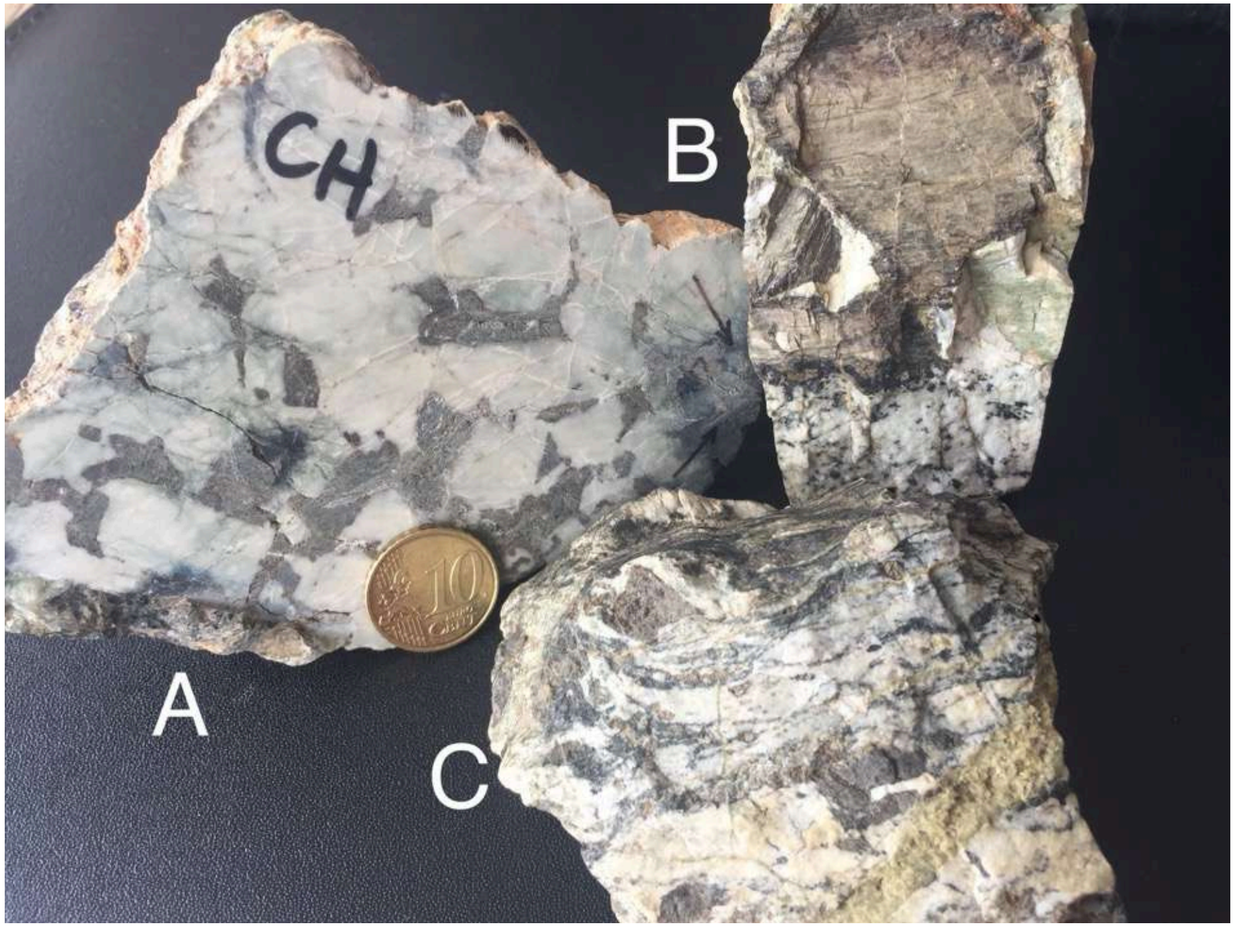
ZF Kane

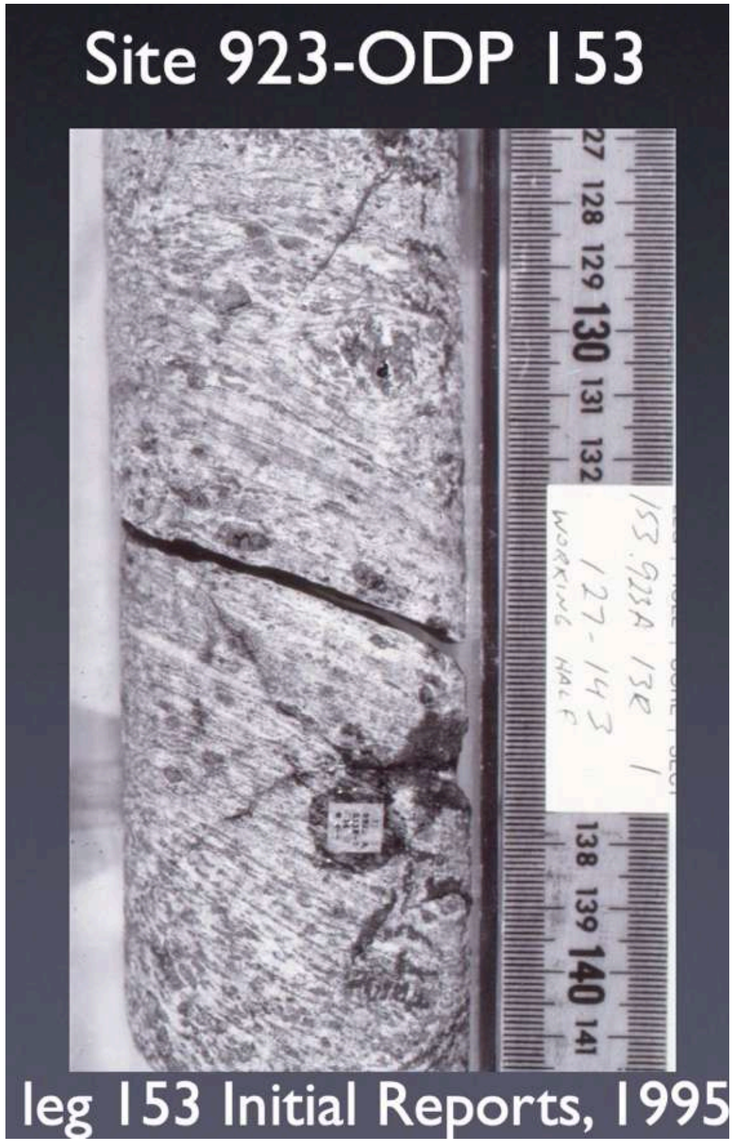

A
X
Y
ZF Marathon
carte B
ZF 15°20'N
ZF Kane
ZF Atlantis
ZF Hayes
ZF Oceanographer
profondeur (km)
2
3
4
5
latitude °N
15
20
25
30
35
mode asymétrique
(exhumation du manteau)
mode symétrique
(couche basaltique continue)
sites hydrothermaux
B
a
1
2
3
croûte
gabbros
et manteau
croûte
mur de la faille
toit de la faille
fusion partielle
45 °00'
44 °50'
b
1 : axe de la dorsale
2 : faille de détachement
surface à "corrugations"
3 : escarpement marquant
le début de l'activité de la faille
(breakaway)
dorsale
Islande
ZF Oceanographer
Açores
X
Atlantis
Kane
15°20
Romanche
Y
B

Retour sur les ophiolites alpines



Les flaser gabbros





Un nouveau modèle pour les ophiolites alpines basé sur l'étude des OCC

Lagabrielle et al., 2015

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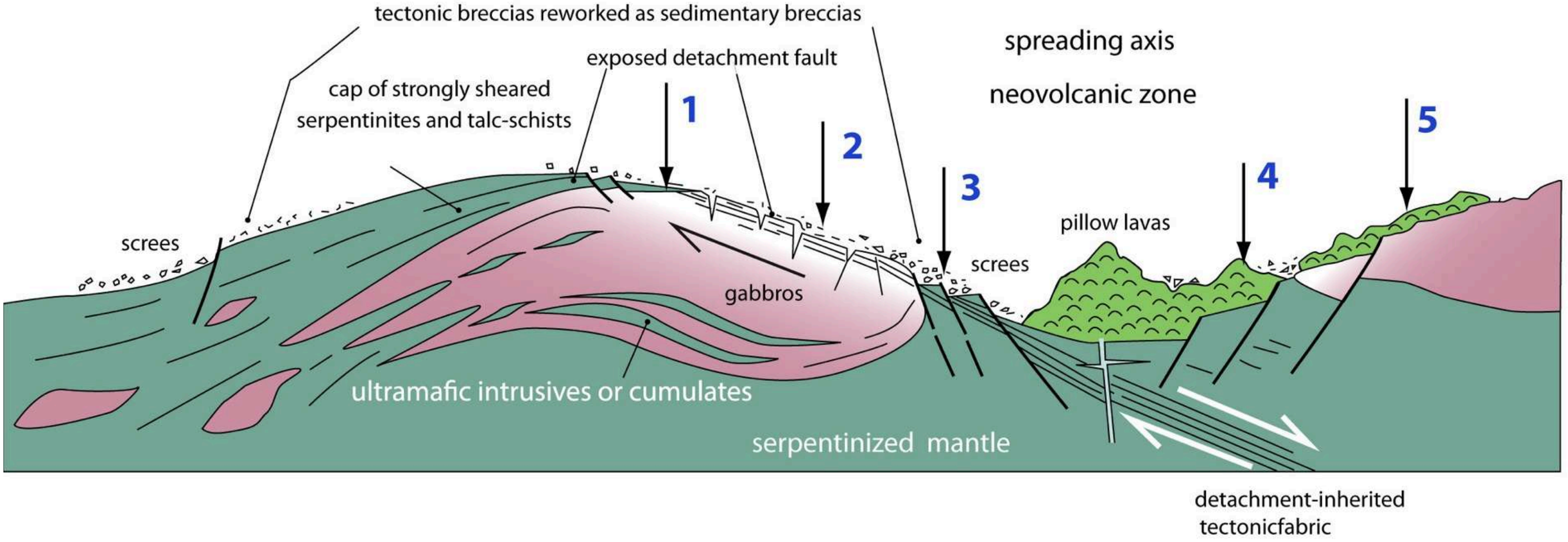
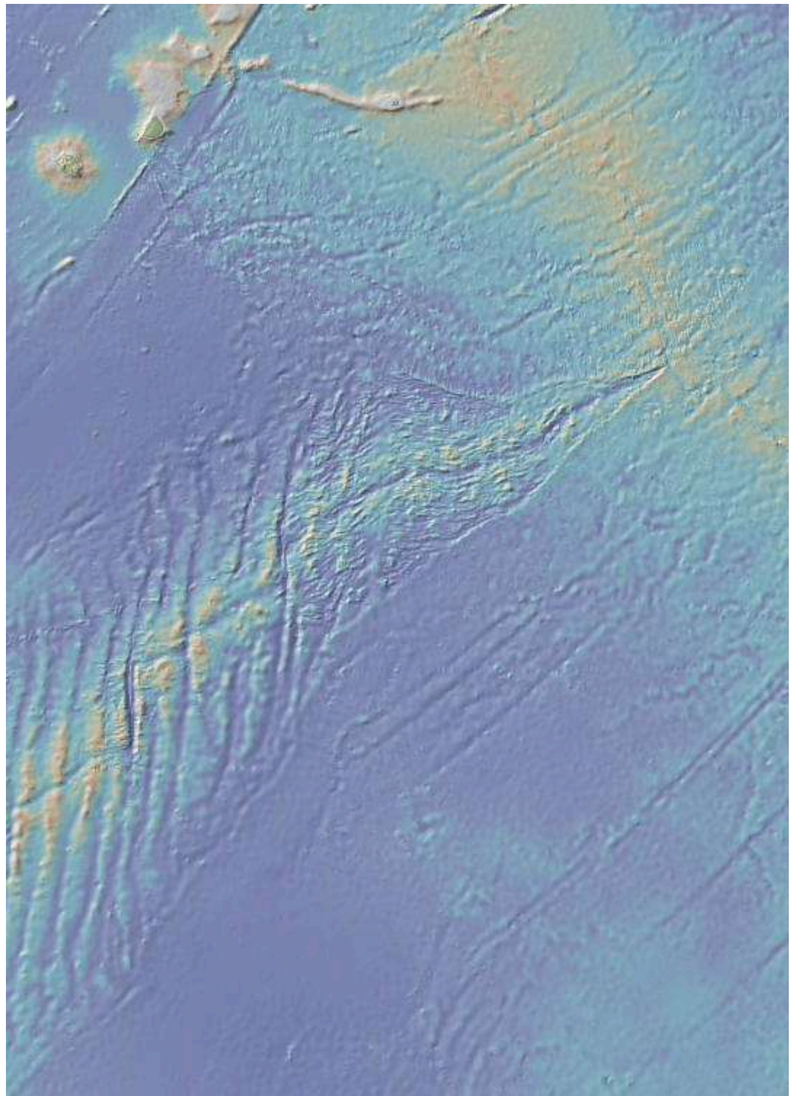
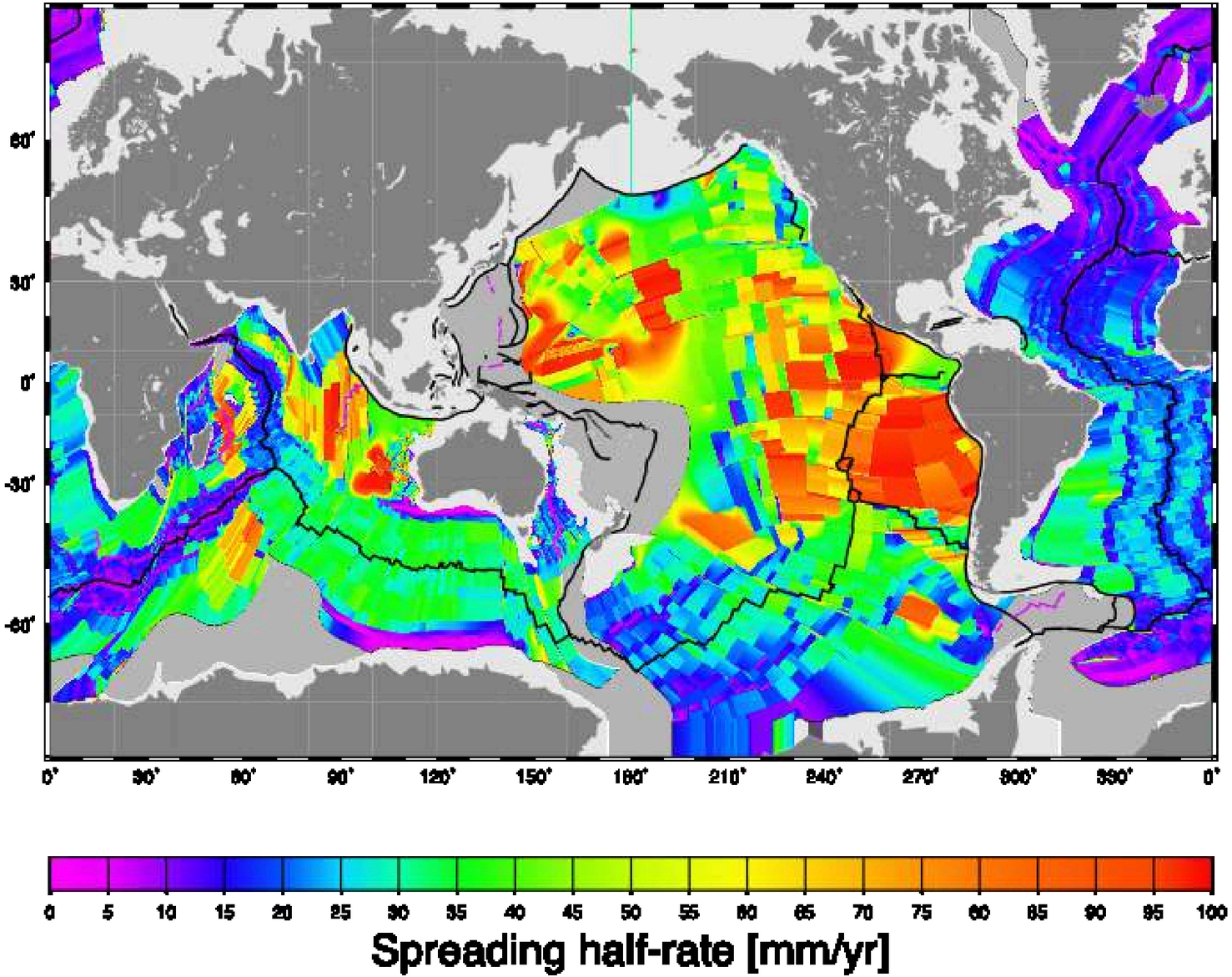
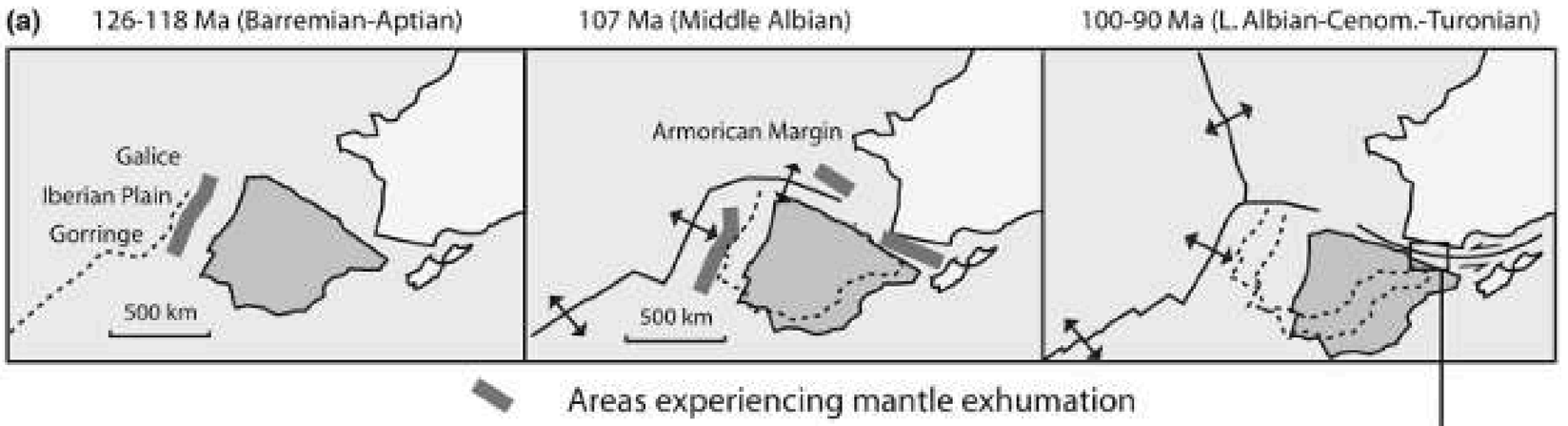


Sur la dorsale sud-ouest indienne le manteau exhumé est omniprésent

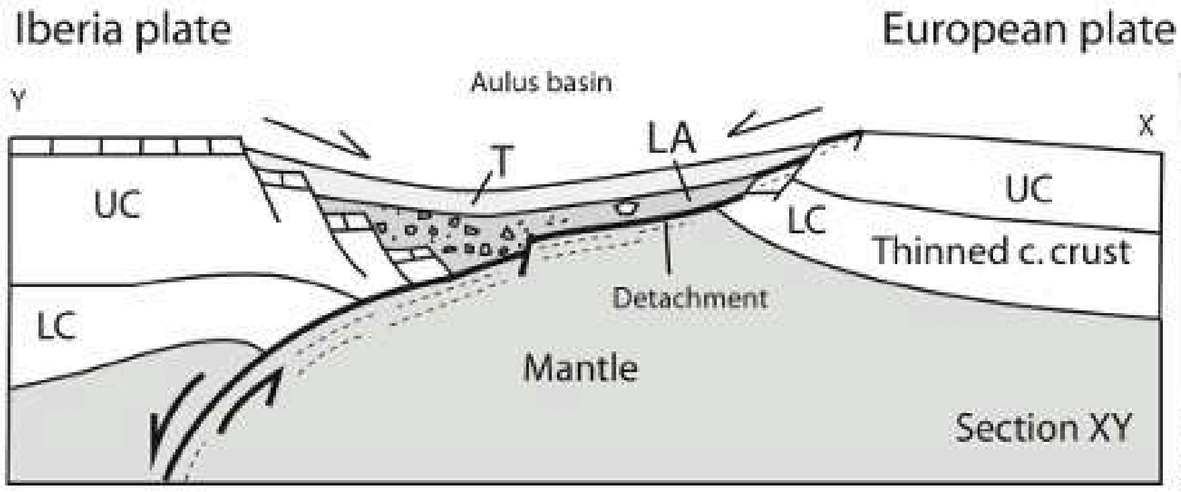


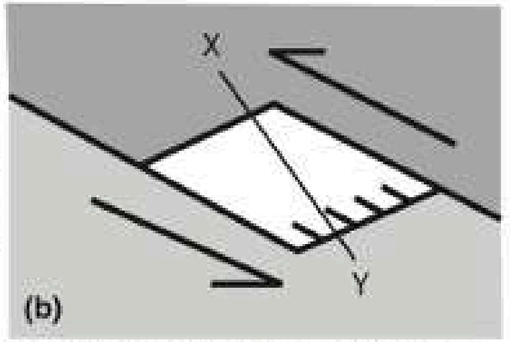


Sur les marges continentales : un cheminement identique depuis 1980



Lagabrielle et Bodinier, 2008





Mantle exhumation possible along one (short) edge of pull apart basin

Conclusions

•Les progrès réalisés dans notre compréhension de la dynamique du globe sont directement liés à l'essor technologique. A l'échelle de l'humanité ils sont fulgurants!

•Dans le cas de la dorsale atlantique, c'est l'intérêt économique et l'entreprise privée (câbles) qui ont initié les premières découvertes.

•La Tectonique des Plaques a permis de définir la notion de frontières divergentes. Mais la Penrose Conference a imposé un modèle ophiolitique uniquement « omanais ». Il a fallu alors initier des recherches terre/mer pour faire fructifier les comparaisons ophiolites-océan et ouvrir les yeux de la communauté sur la réalité des dorsales lentes.

•Les 20 années post-Tectonique des Plaques ont été plus ou moins mal vécues par les géologues dont les objets d'étude ont une taille inadaptée pour rentrer dans le cadre global de la théorie.