Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

Università degli studi di Trieste

LAUREA MAGISTRALE IN GEOSCIENZE

Classe Scienze e Tecnologie Geologiche

Curriculum: Esplorazione Geologica

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Analisi di Bacino e Stratigrafia Sequenziale (426SM)

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Modulo 1.3
BASIN FORMATION MECHANISMS AND STRUCTURE

Docente: Emanuele Lodolo

BASIN FORMATION MECHANISMS AND STRUCTURE

- Introduction
- Mechanisms of basin formation
- Basin classification
- Examples of basin geometry and structure
- Methods in basin studies
- Summary

What is a basin in the geologic context?

Repository for sediment formed by crustal subsidence relative to surrounding areas

Basins have many different shapes, sizes and mechanisms of formation

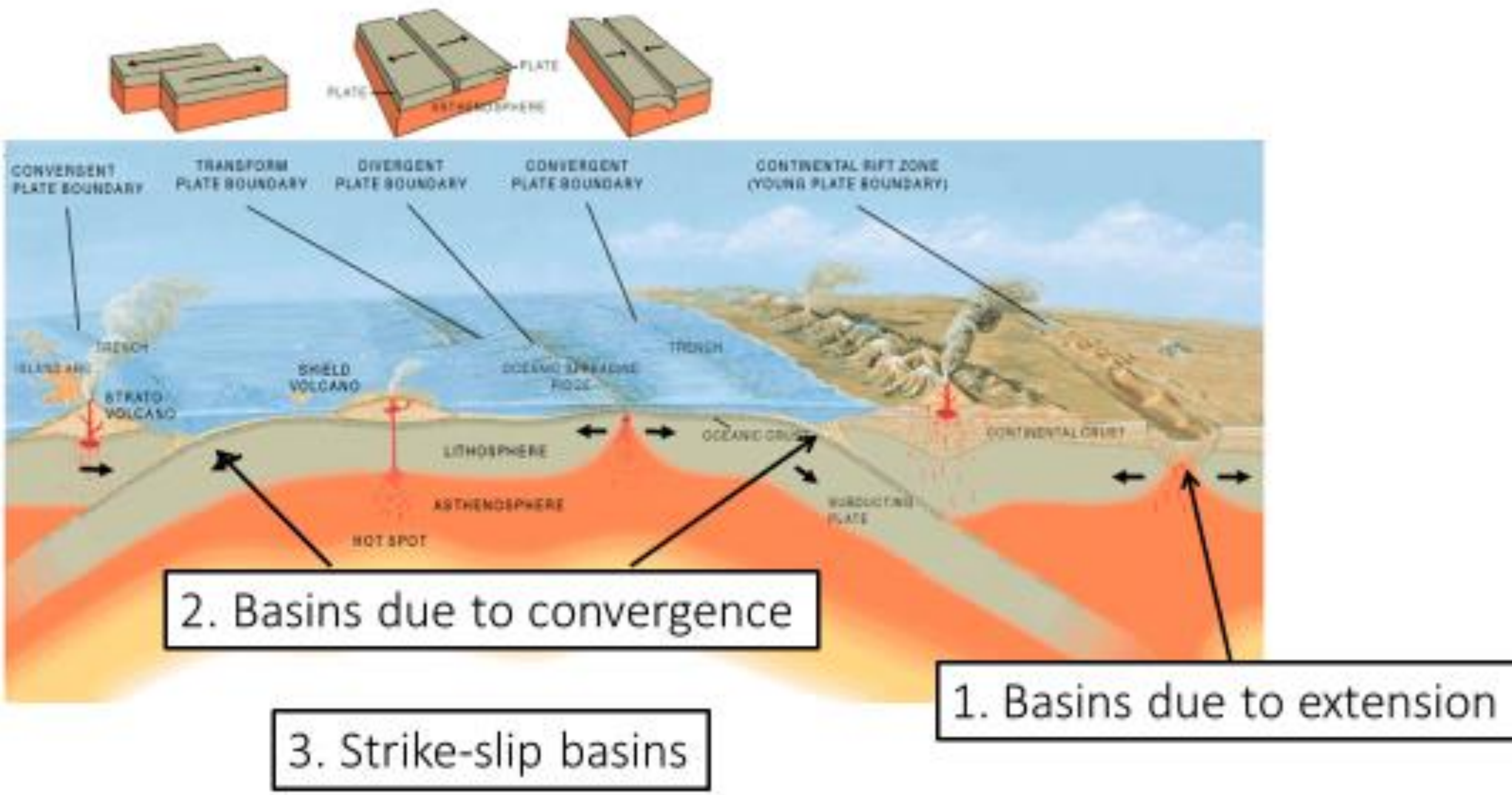
Vertical motions (subsidence, uplift) in sedimentary basins are primarily in response to deformation of lithosphere and asthenosphere

Plate-plate interactions can generate vertical crustal movements

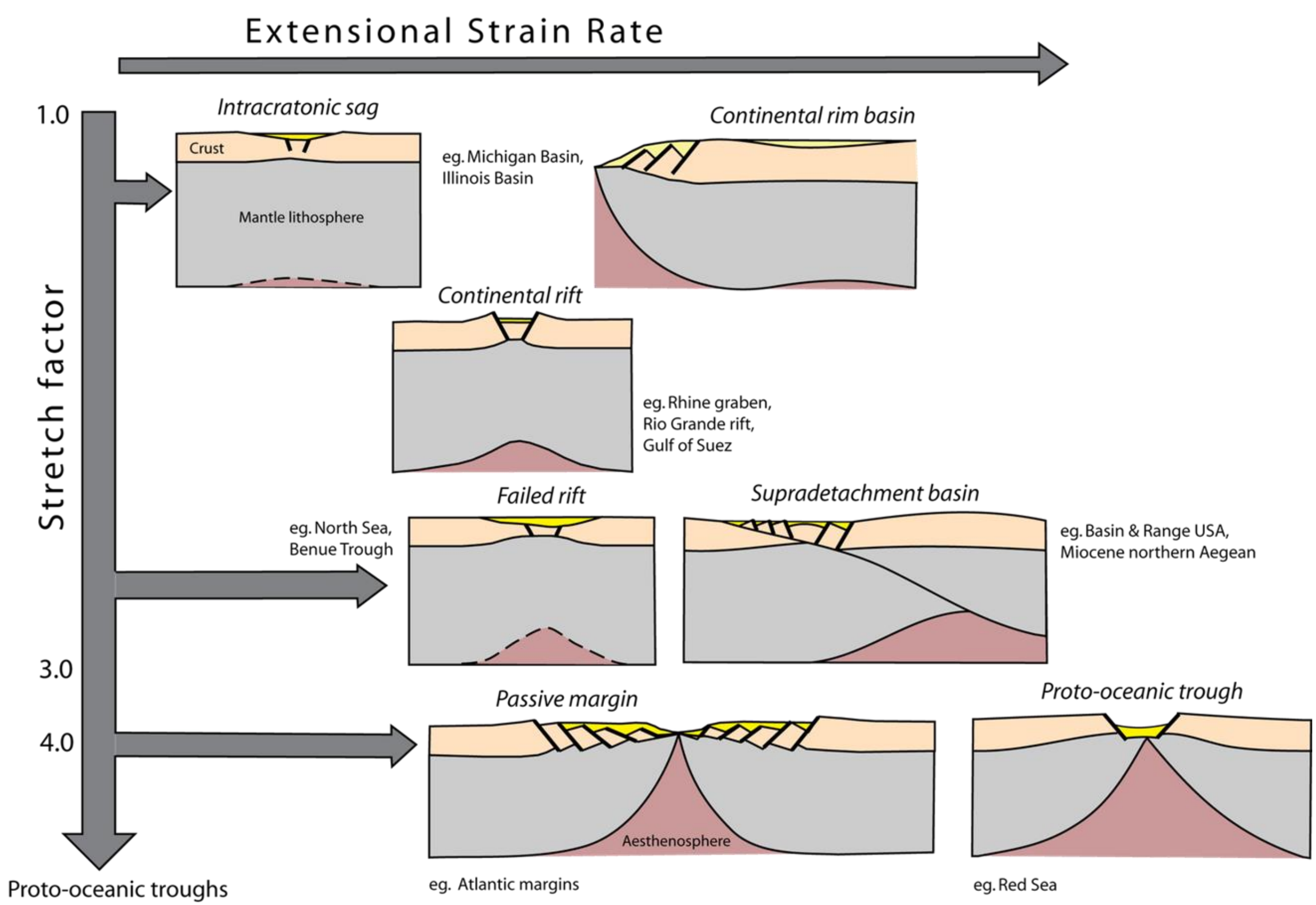
Three types of plate boundaries exist:

- **Divergent – plates moving apart (mid-ocean ridges, rifts)**
- **Convergent – plates moving towards each other (subduction zones)**
- **Conservative – plates move parallel to each other (strike-slip systems)**

Most (but not all) sedimentary basins occur in areas of active plate tectonics



Basins due to extension



Crustal extension leads to rift basins and ultimately to passive margins.

Subsidence driven by crustal thinning and heat flow changes vs. time

Major mechanisms for regional subsidence/uplift

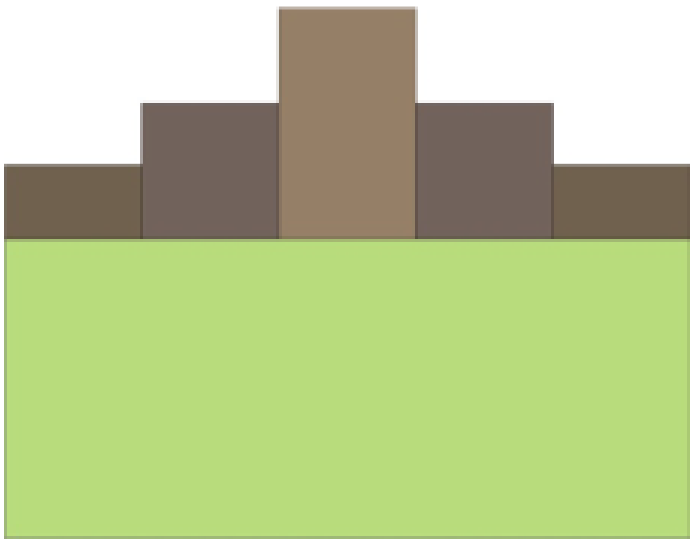
- **Isostatic – changes in crustal or lithospheric thickness**
- **Loading – by thrust sheets, volcanic piles, sediment**
- **Dynamic effects – asthenospheric flow, mantle convection, plumes**

Isostatic processes

- **Crustal thinning due to extensional stretching, erosion during uplift, magmatic withdrawal**
- **Mantle-Lithosphere thickening due to cooling of lithosphere, following cessation of stretching or cessation of heating**
- **Crustal densification due to density increase (related to changing pressure/temperature conditions and/or emplacement of higher density melts into lower density crust)**

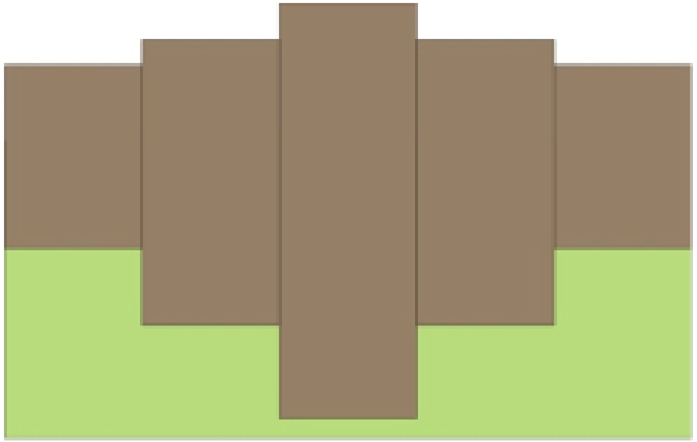
Physical mechanisms of subsidence:

1. Isostasy



Pratt isostasy

Topography is a function of lithospheric density

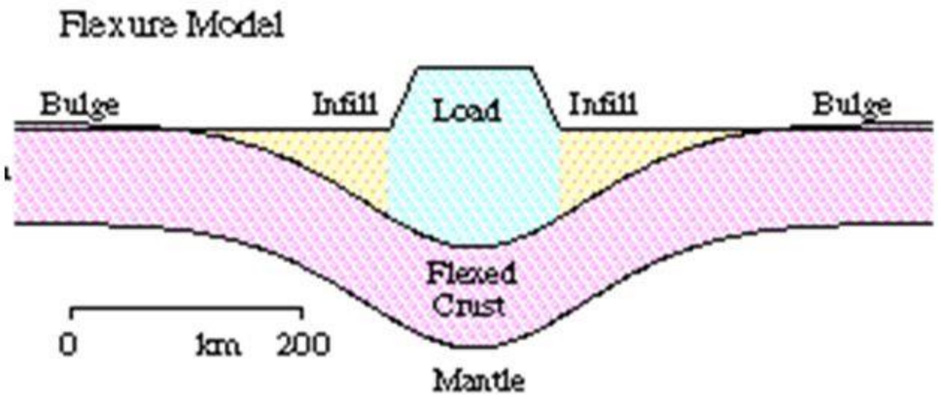


Airy isostasy

Topography is a function of lithospheric thickness

Physical mechanisms of subsidence:

2. <u>Flexure</u> (also called regional isostasy)



Earth's rigid lithosphere acts as an elastic plate. When loaded (by a mountain range, sediment column, other tectonic plate), it flexes.

Loading

Local isostatic compensation of crust and regional lithospheric flexure (dependent on flexural rigidity of lithosphere)

Sedimentary or volcanic loading

Tectonic loading during overthrusting and/or underpulling

Subcrustal loading due to lithospheric flexure during underthrusting of dense lithosphere

Dynamic effects

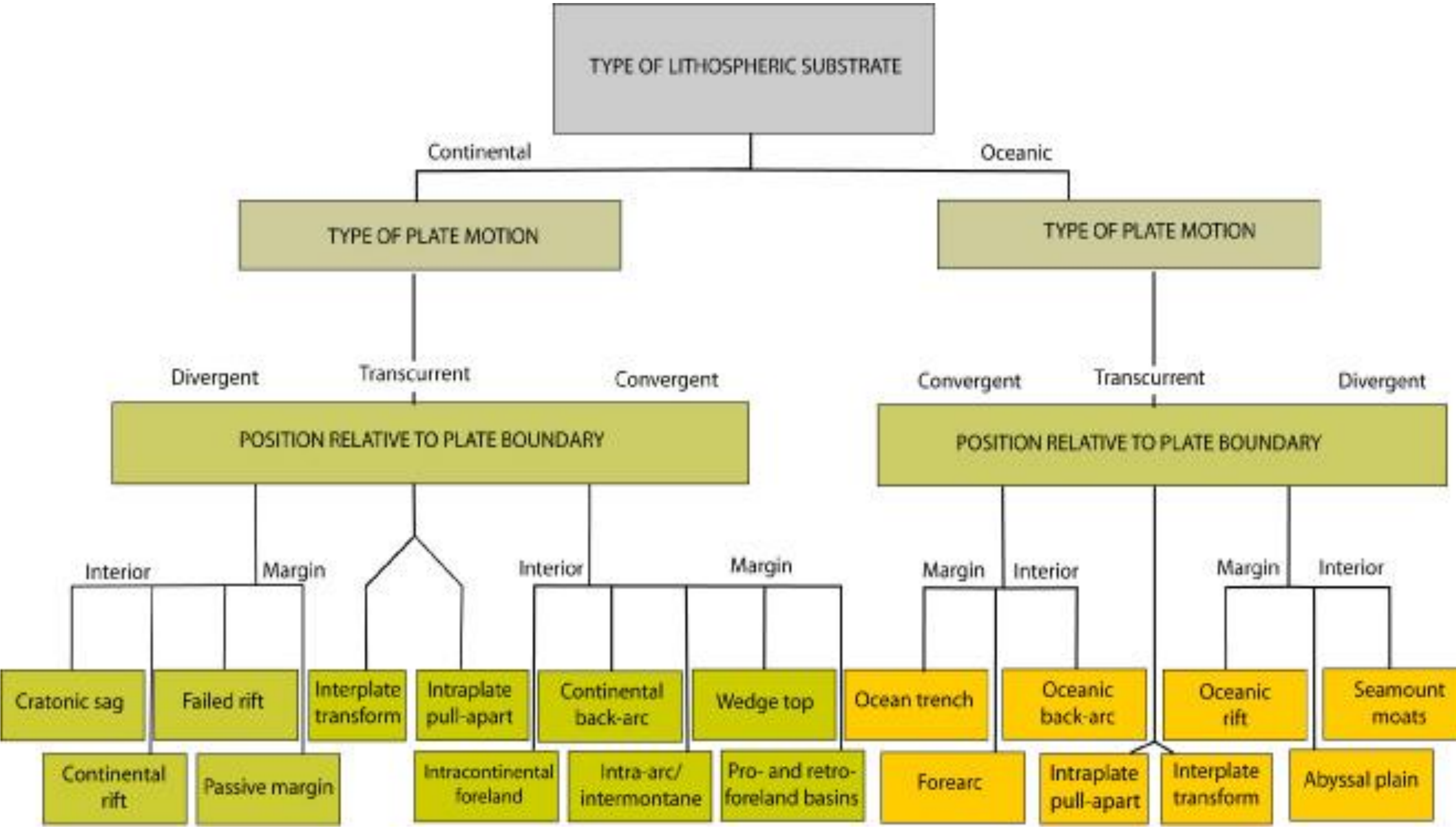
- **Asthenospheric flow (descent or delamination of subducted lithosphere)**
- **Mantle convection**
- **Plumes**

Basin classification

Many different classification systems have been proposed, on the basis of:

- **Position of the basin in relation to plate margins**
- **Crustal/lithospheric substratum**
- **Oceanic, continental crust**
- **Type of plate boundary**

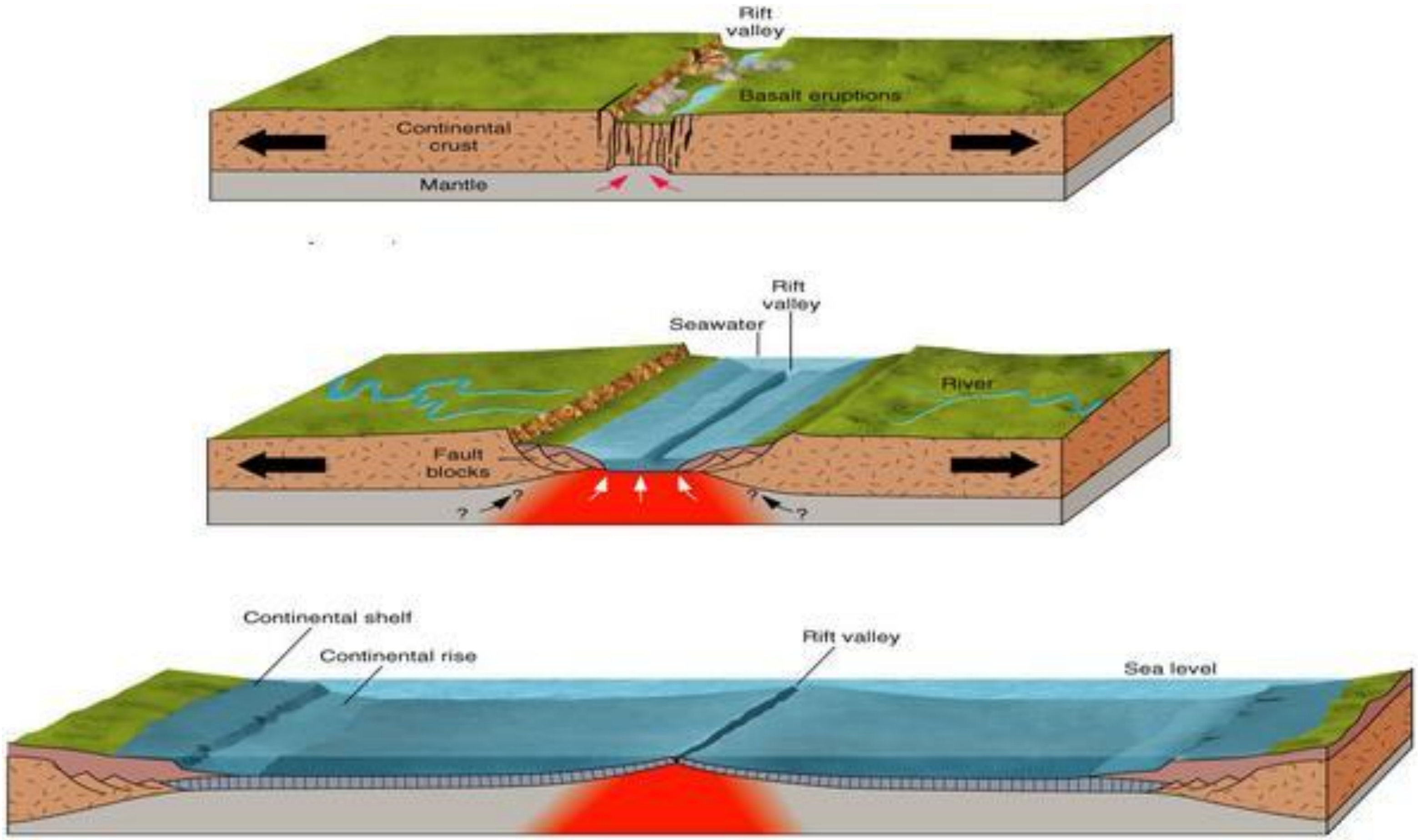
*** In this course: focus on basin-forming processes**

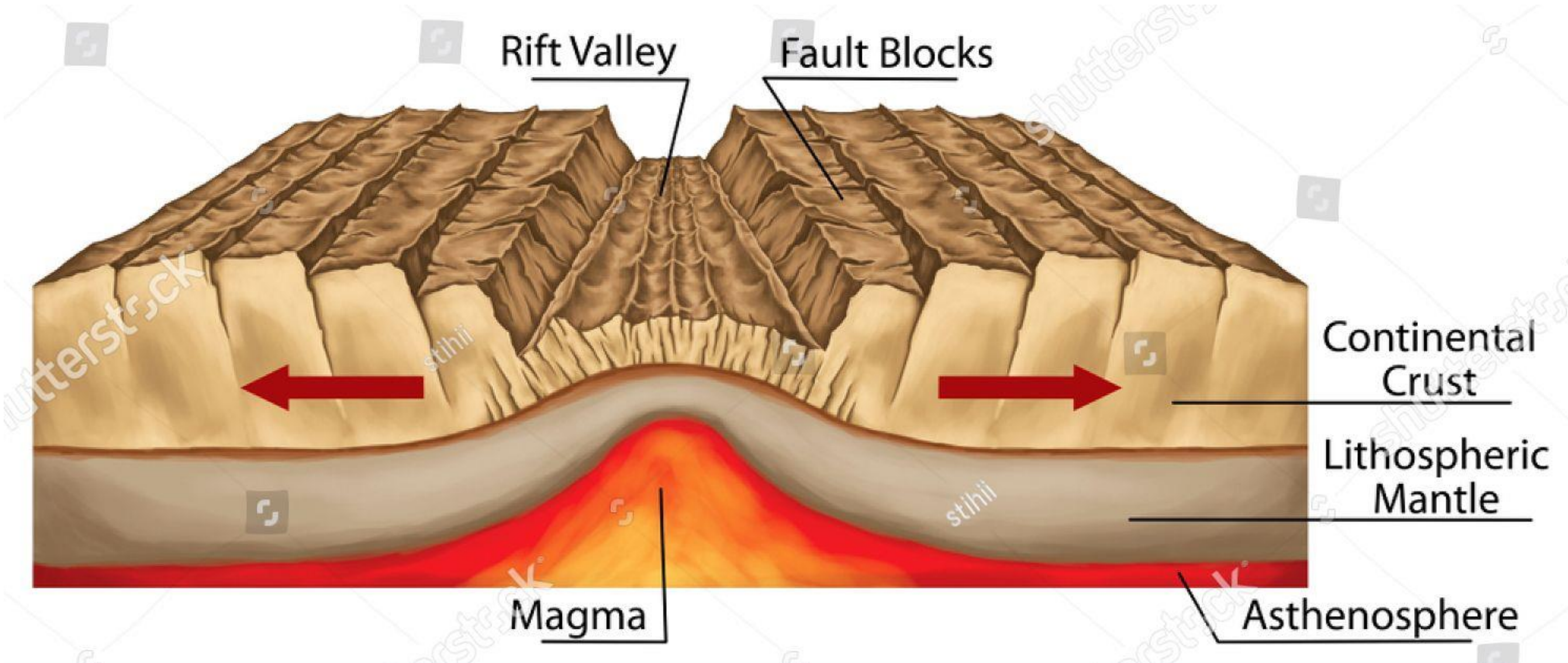

TYPE OF LITHOSPHERIC SUBSTRATE
Continental
Oceanic
TYPE OF PLATE MOTION
TYPE OF PLATE MOTION
Divergent
Transcurrent
Convergent
Convergent
Transcurrent
Divergent
POSITION RELATIVE TO PLATE BOUNDARY
POSITION RELATIVE TO PLATE BOUNDARY
Interior
Margin
Interior
Margin
Margin
Interior
Margin
Interior
Cratonic sag
Failed rift
Interplate transform
Intraplate pull-apart
Continental back-arc
Wedge top
Ocean trench
Oceanic back-arc
Oceanic rift
Seamount moats
Continental rift
Passive margin
Intracontinental foreland
Intra-arc/ intermontane
Pro- and retro- foreland basins
Forearc
Intraplate pull-apart
Interplate transform
Abyssal plain

Divergent plate boundaries

Continental rifting may lead to opening of an ocean with a mid-ocean ridge

Rift basin evolves into passive margin





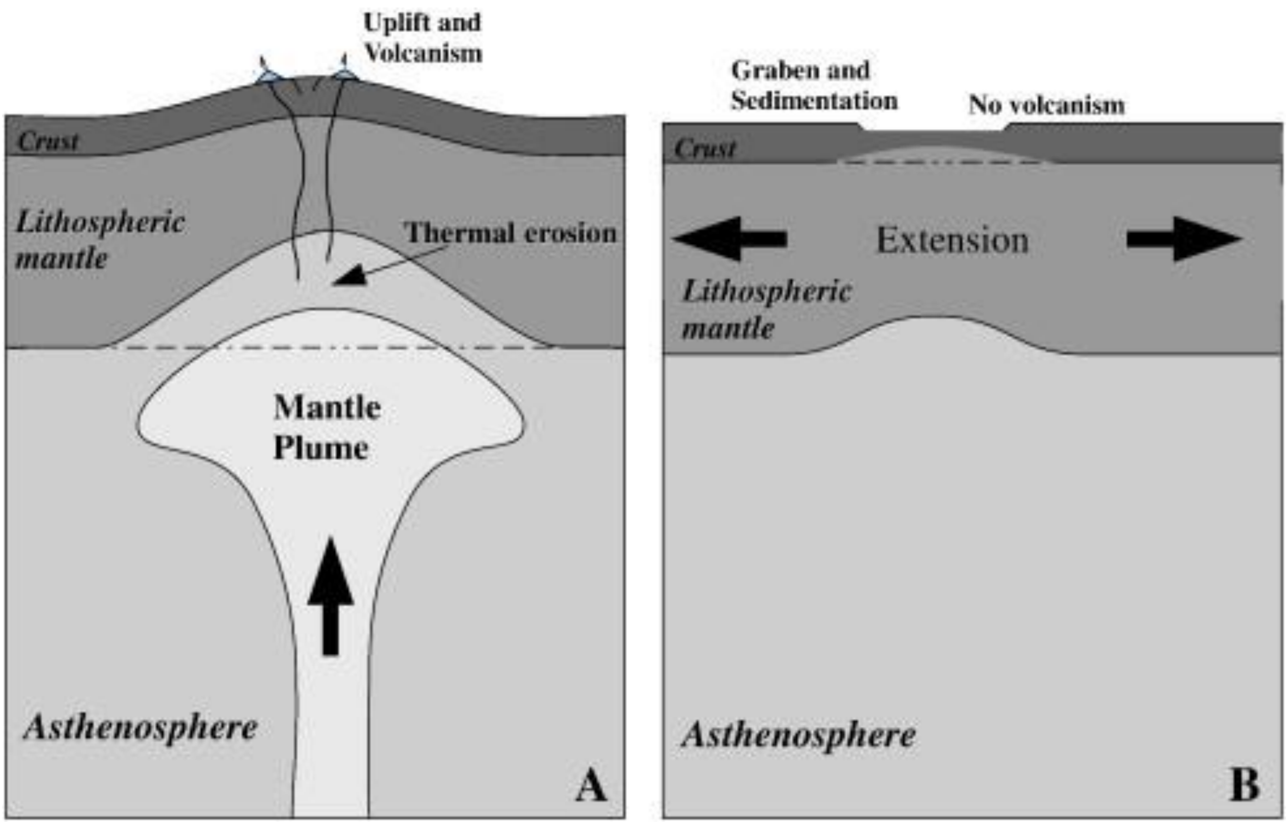
Rift basins are characterized by elongate valleys bounded by normal faults (few km -> 10s of km wide)
(length – up to 1000s of km)
Occur in many plate settings, but most common in divergent settings
Seismic studies indicate rifts overlie thinned crust (evidence for thermal anomalies at depth - negative Bouguer gravity anomalies - high heat flow)

A. Active rifting

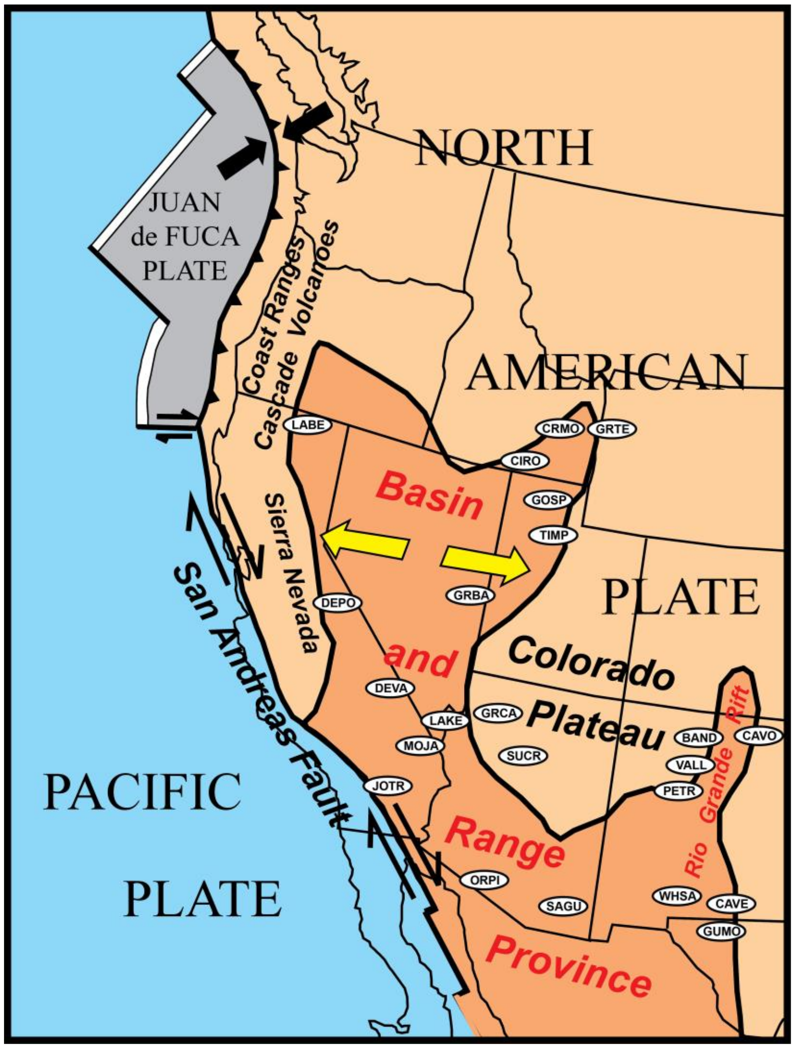
Mantle upwelling causes crustal thinning (heating) that leads to uplift
Then, uplift leads to tension and rifting

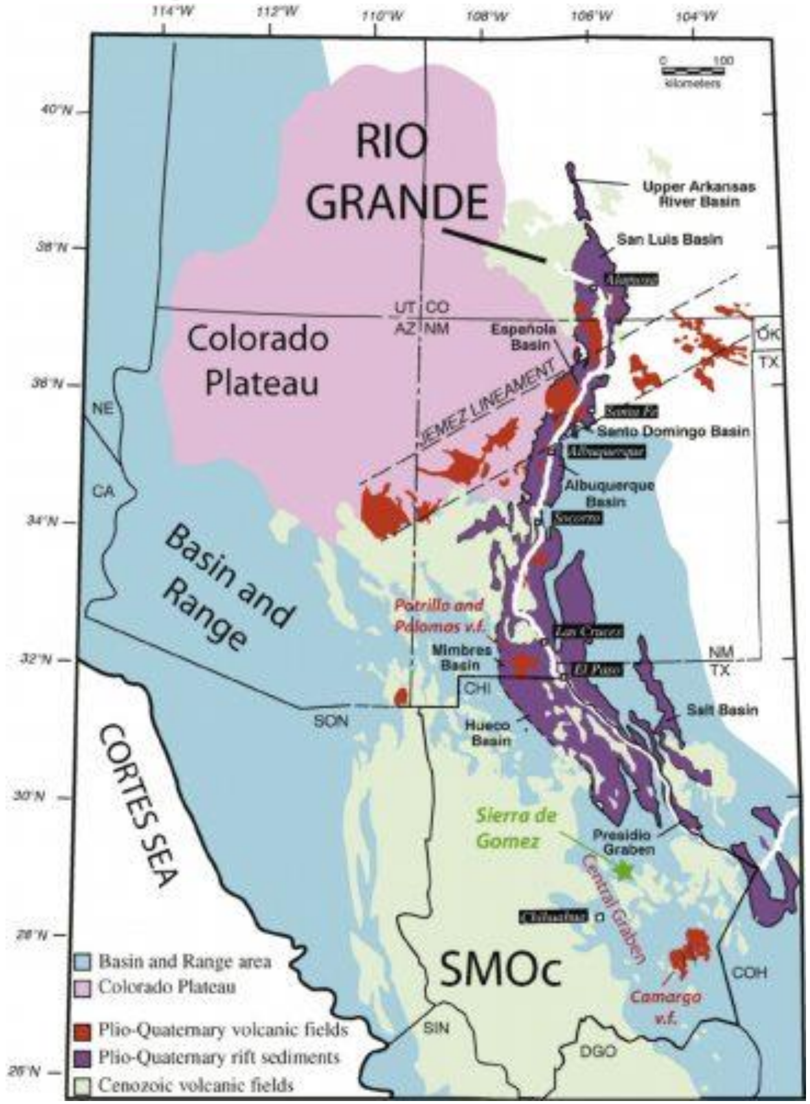
B. Passive rifting

Regional extension causes failure, so hot mantle rocks rise and penetrate lithosphere

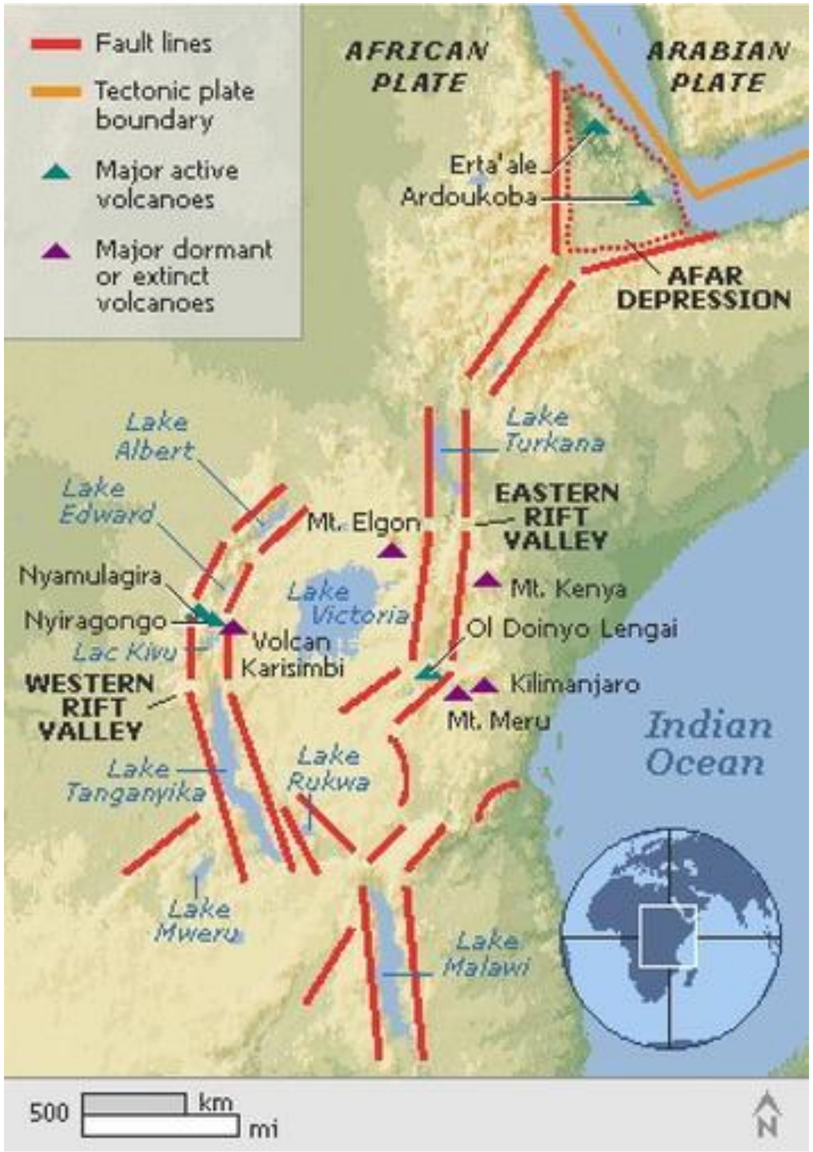


Example of a passive rift (Rio Grande Rift)



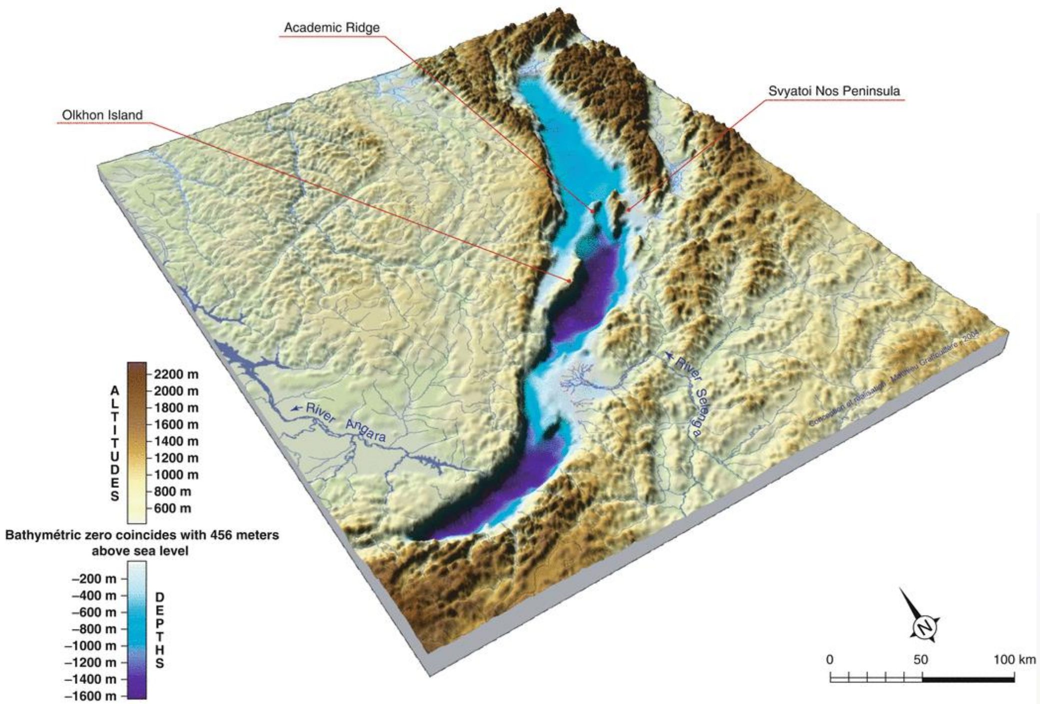


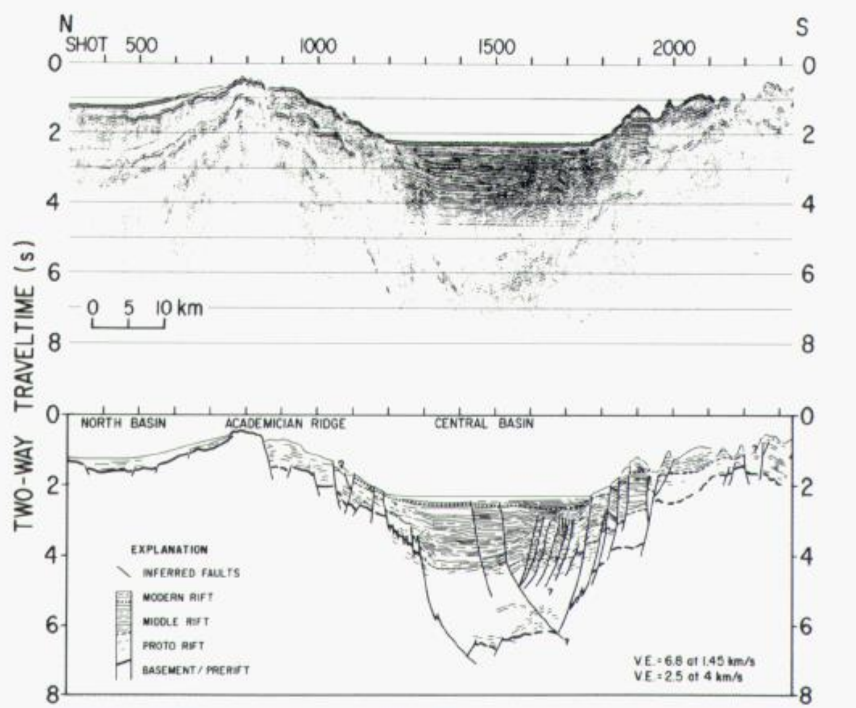
Example of an active rift (East African Rift)



Baikal rift

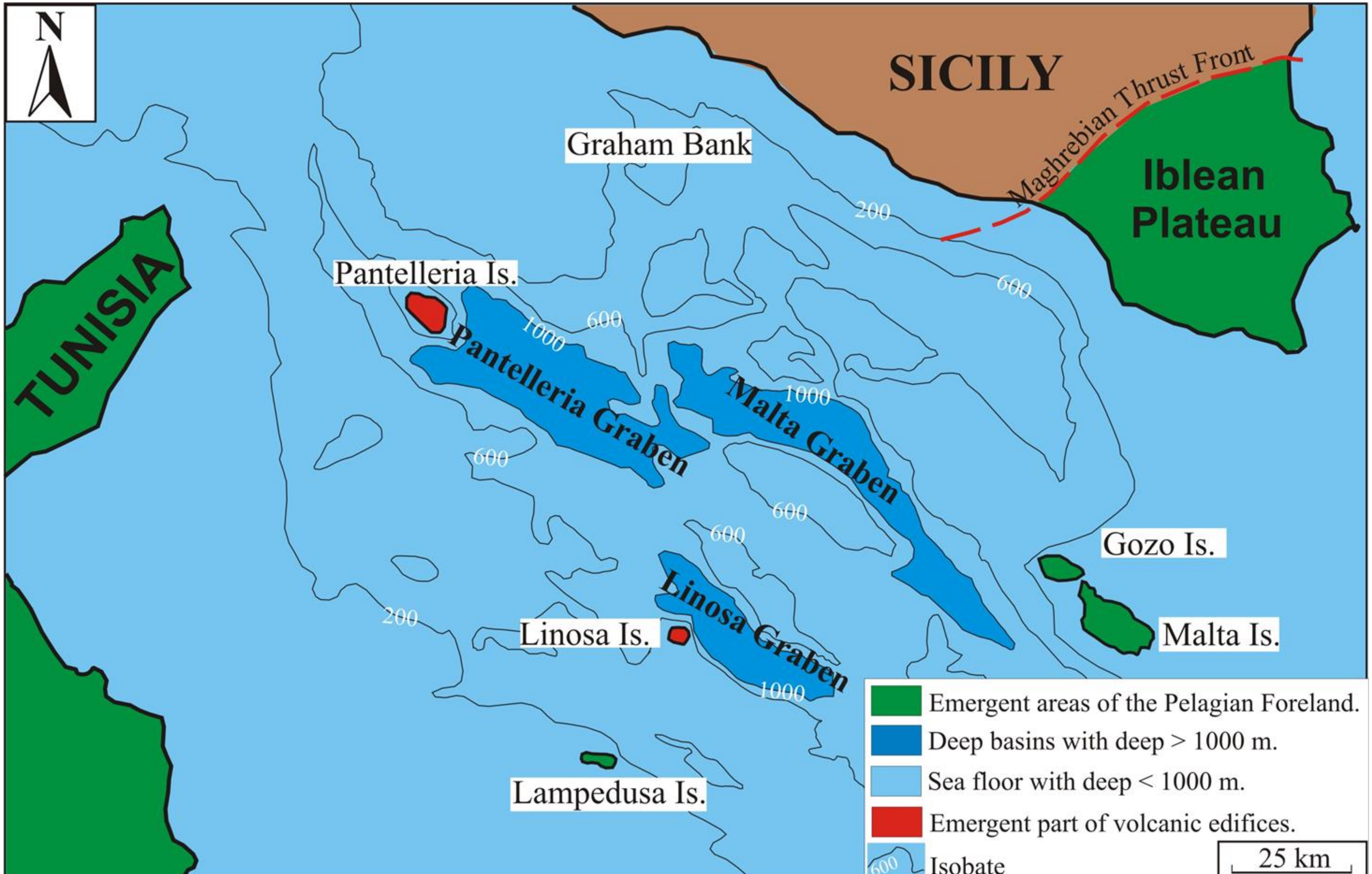
M. Graffouillère, 2004, after Soviet topographic and bathymetric maps 1/200000 (courtesy L. Touchart) and GLOBE-NGDC



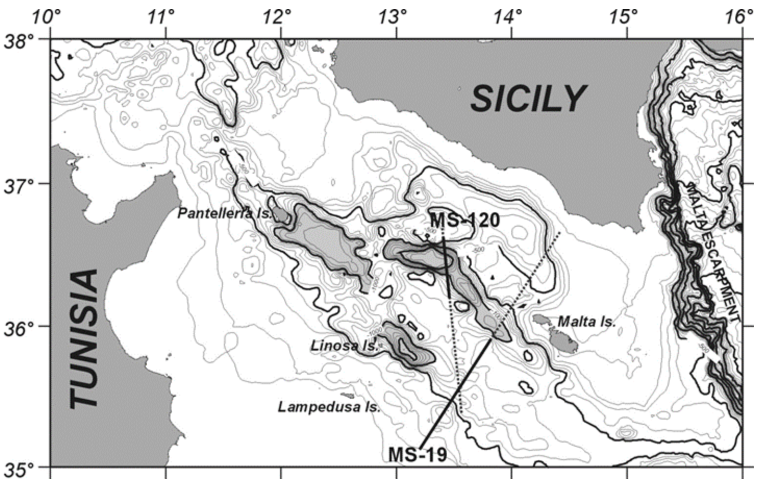


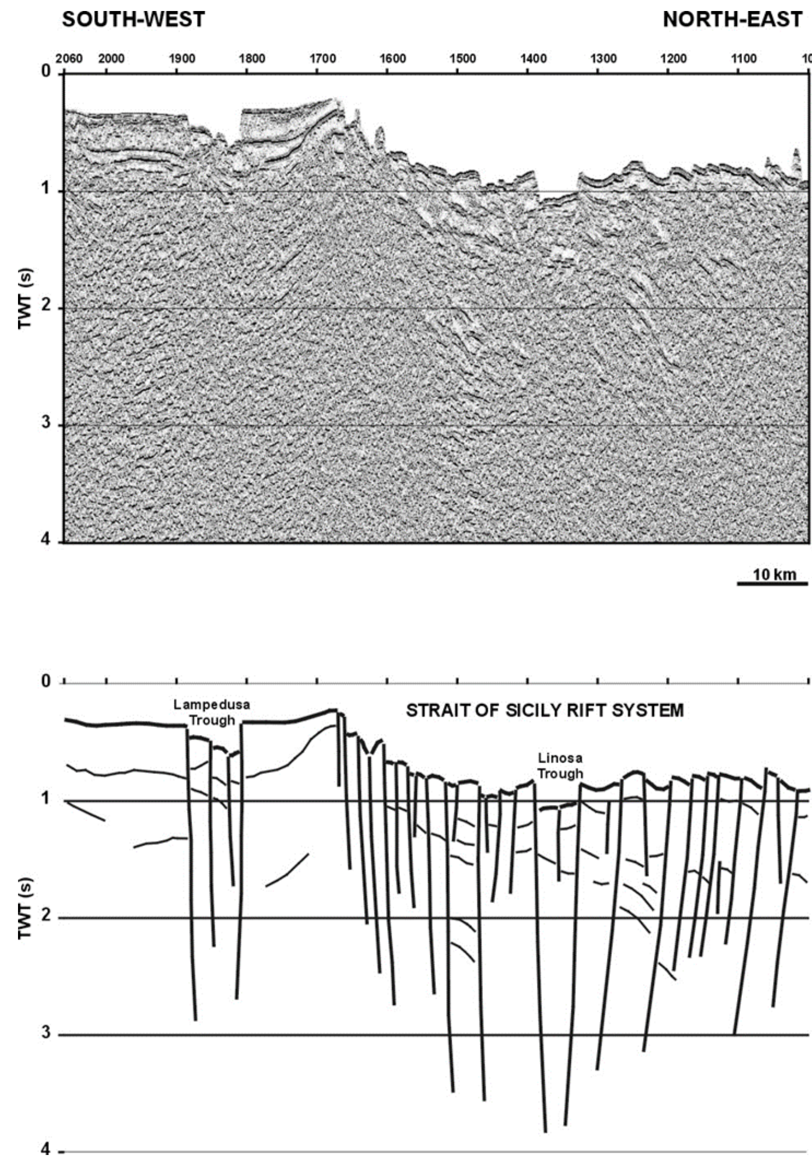
Multichannel seismic reflection line across central part of Lake Baikal showing seismic data (top) and interpretation (bottom). The thickest deposits are confined to a narrow trough that is 15 to 20 kilometers (9 to 12 miles) wide.

Sicilian Channel Rift System

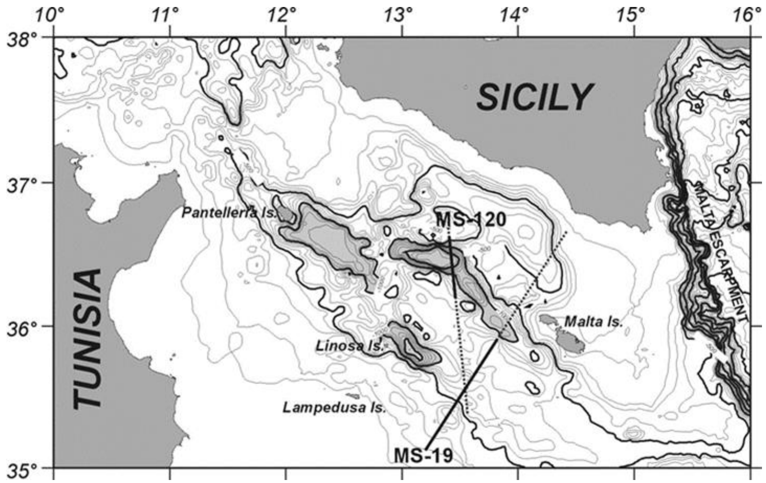


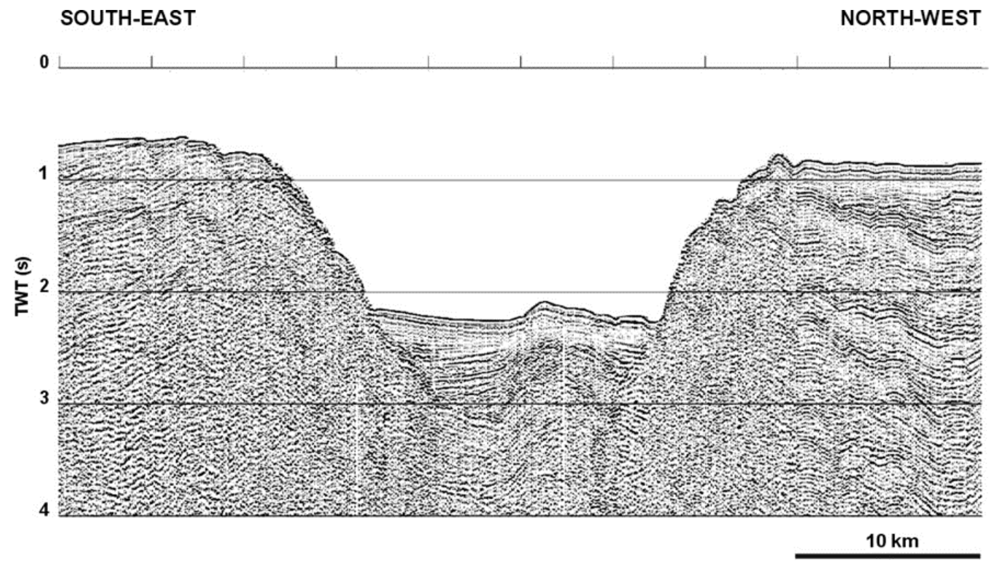
Linosa graben

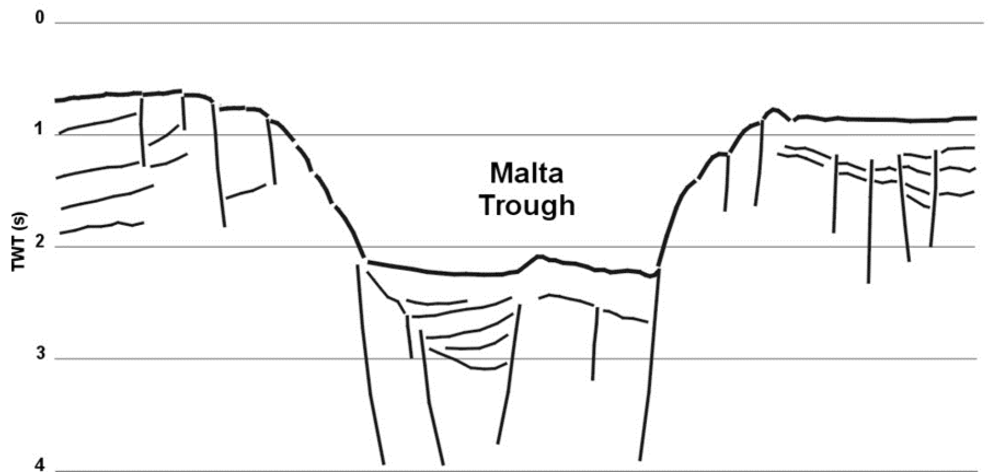




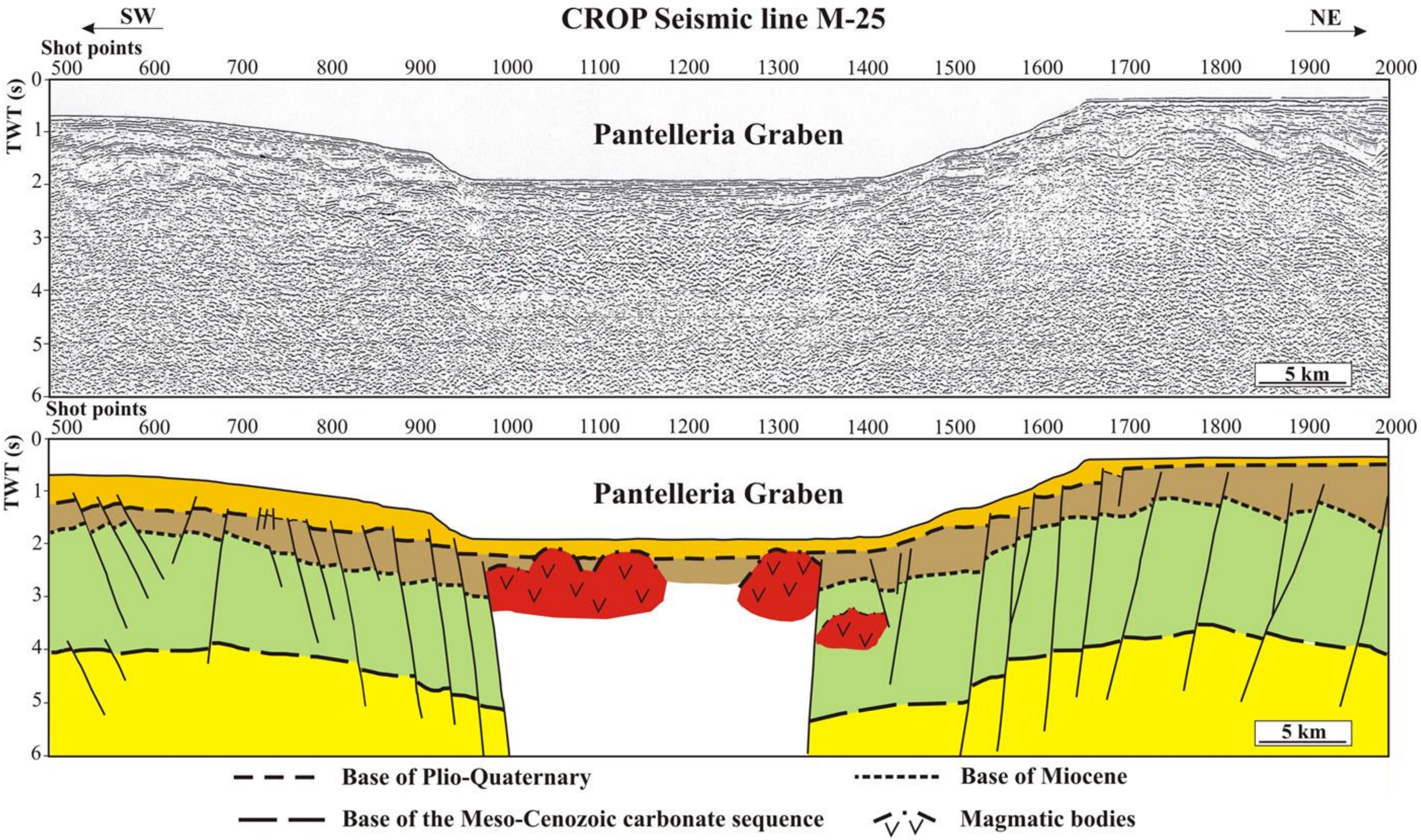
Malta graben



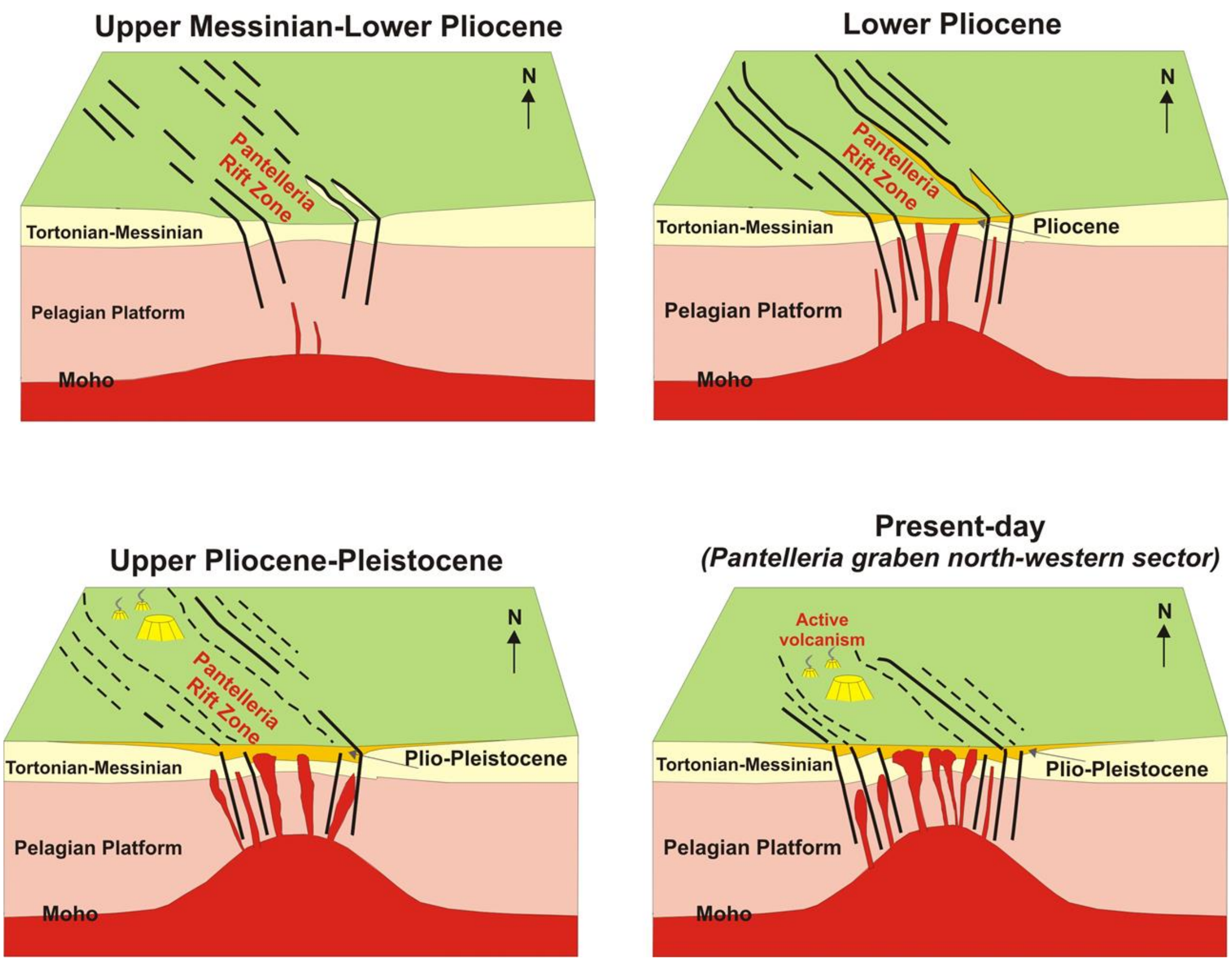




Pantelleria graben



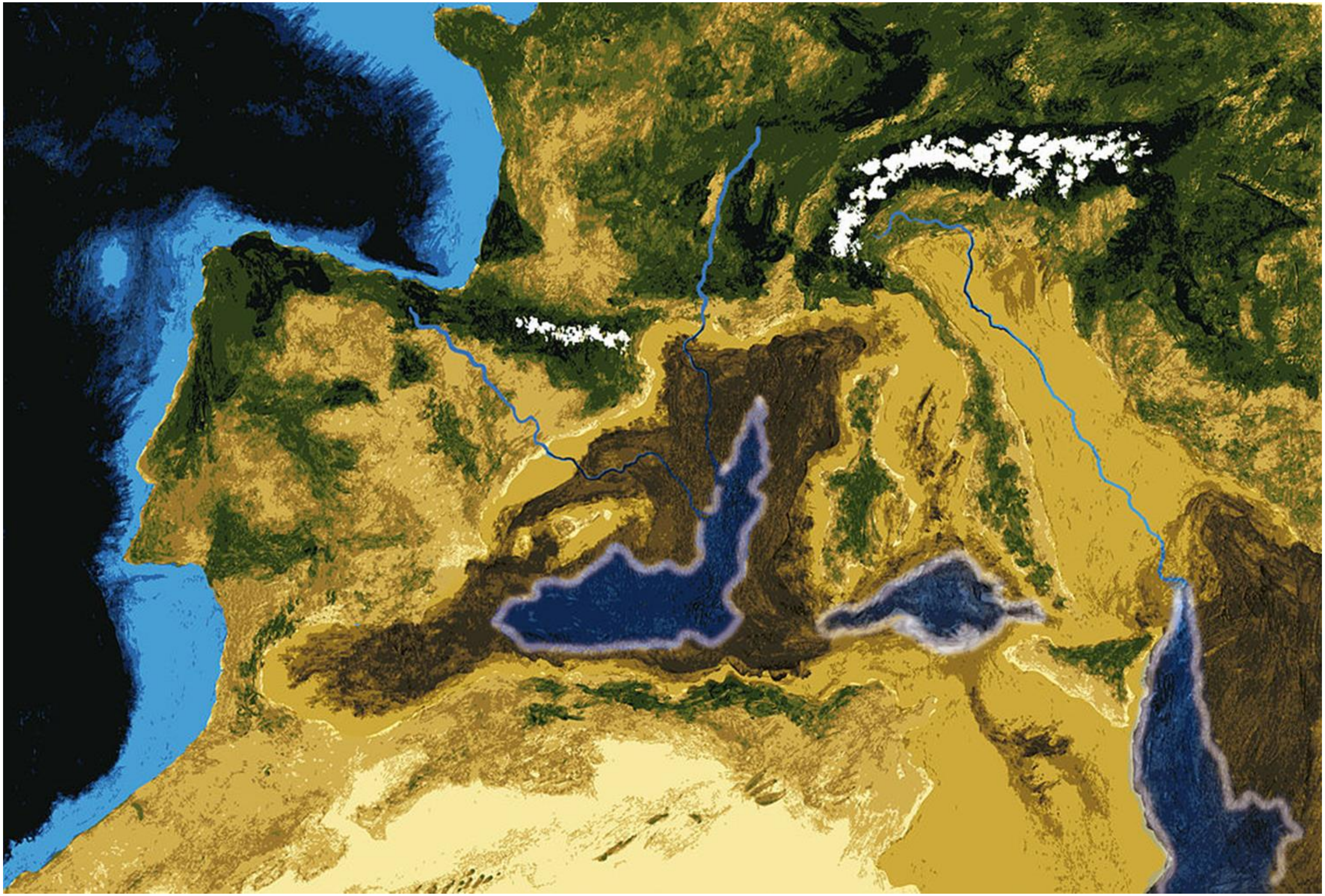
Pantelleria graben tectonic evolution



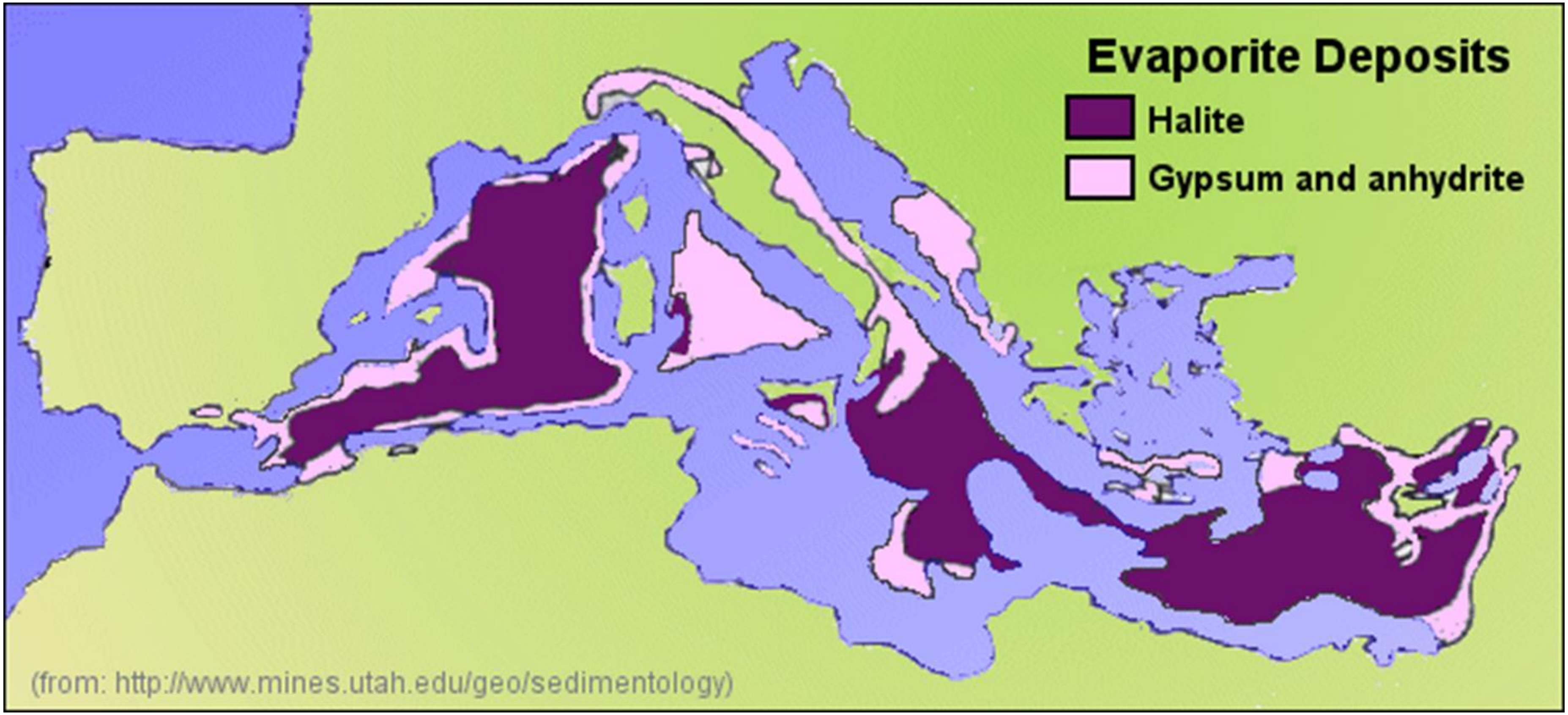
In rift basins, fill commonly consists of "continental" deposits (fluvial, lacustrine, alluvial fans). In some cases, evaporites may form if rift valley/basin is located in a hot, dry and closed area (e.g., the Messinian Salinity Crisis occurred in the Mediterranean Basin about 5 million years ago).

Volcanic rocks, and associated intrusions, may also be present in rift basins

Messinian palaeogeography



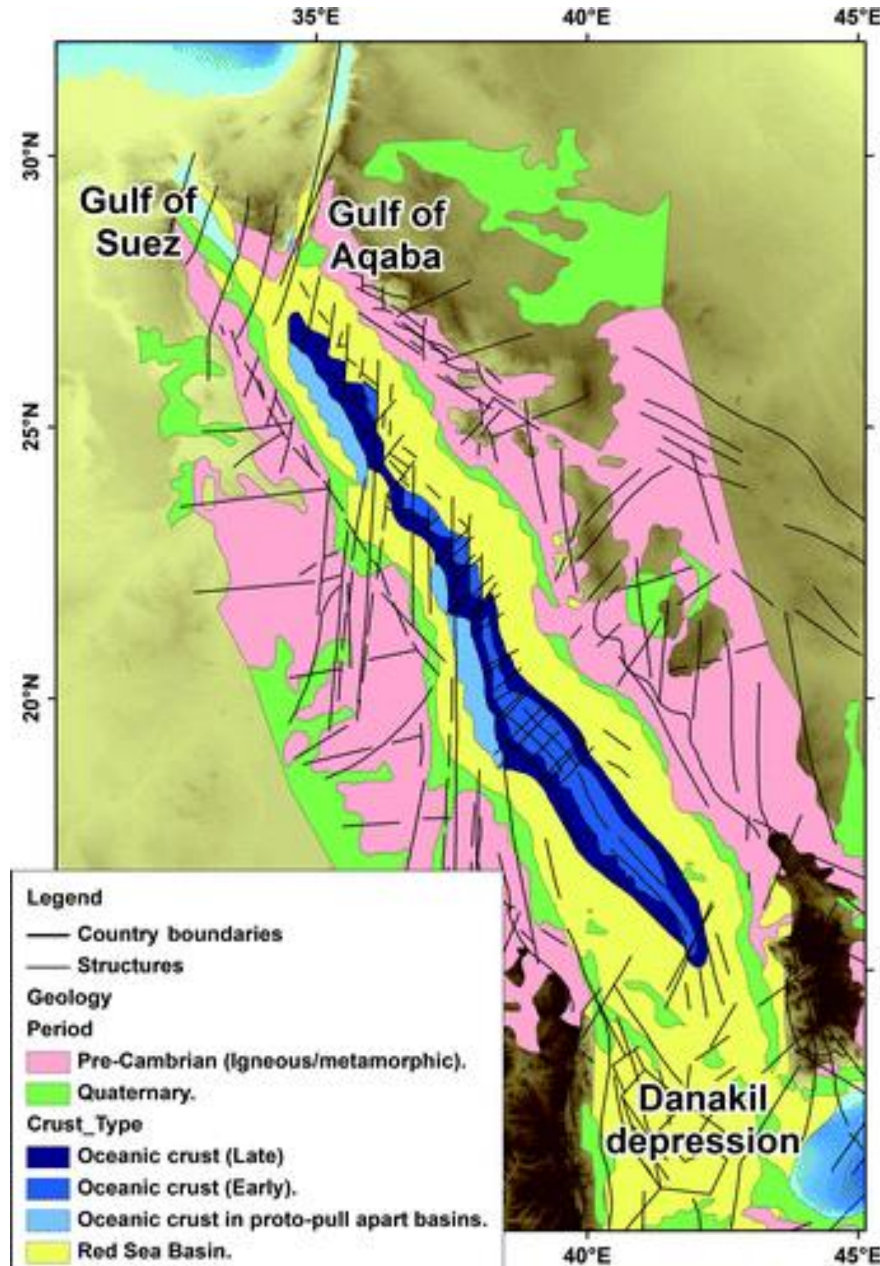
MIOCENE SALINITY CRISIS
Miocene Sup. (5.9 - 5.3 Ma)



Continued rifting can lead to formation of oceanic crust (i.e., opening of an ocean basin).

One typical example is the Red Sea

The rift-drift transition may be marked by a “breakup unconformity”, often visible on seismic profiles

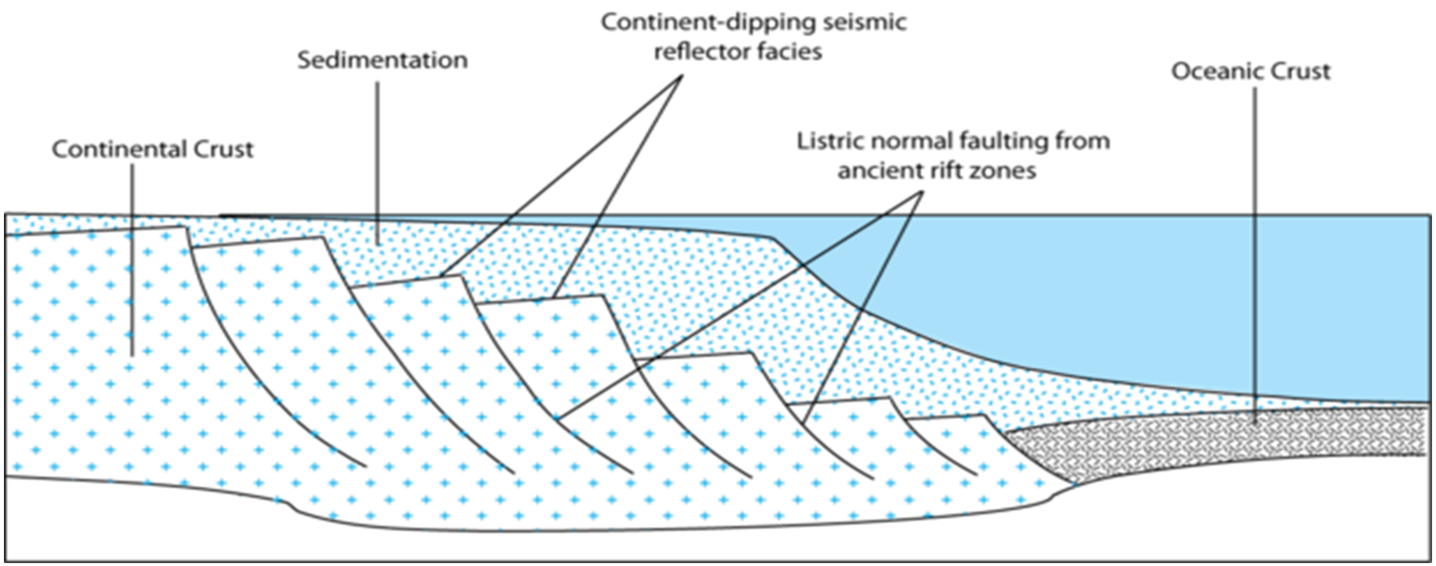


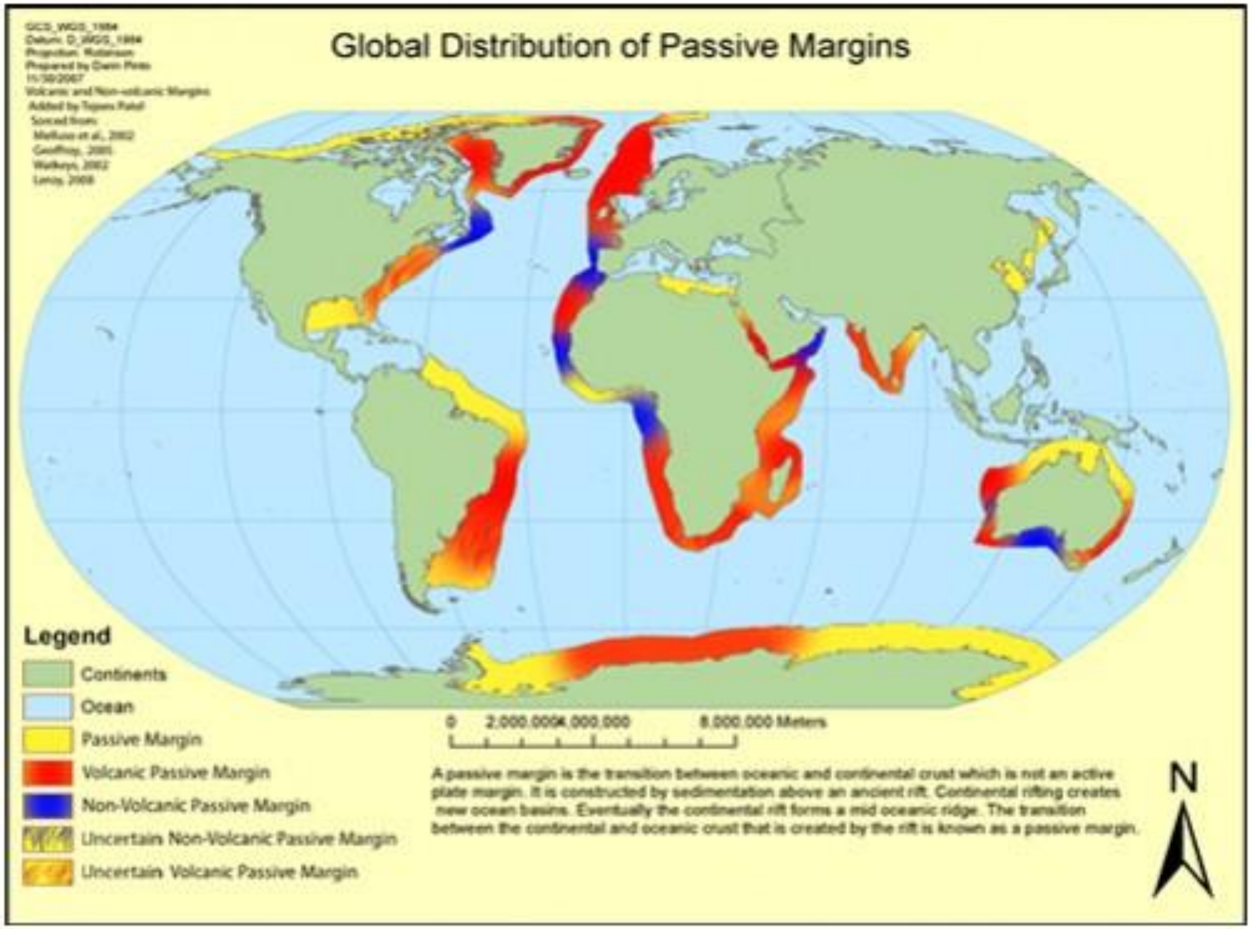
Passive margin sedimentary basins

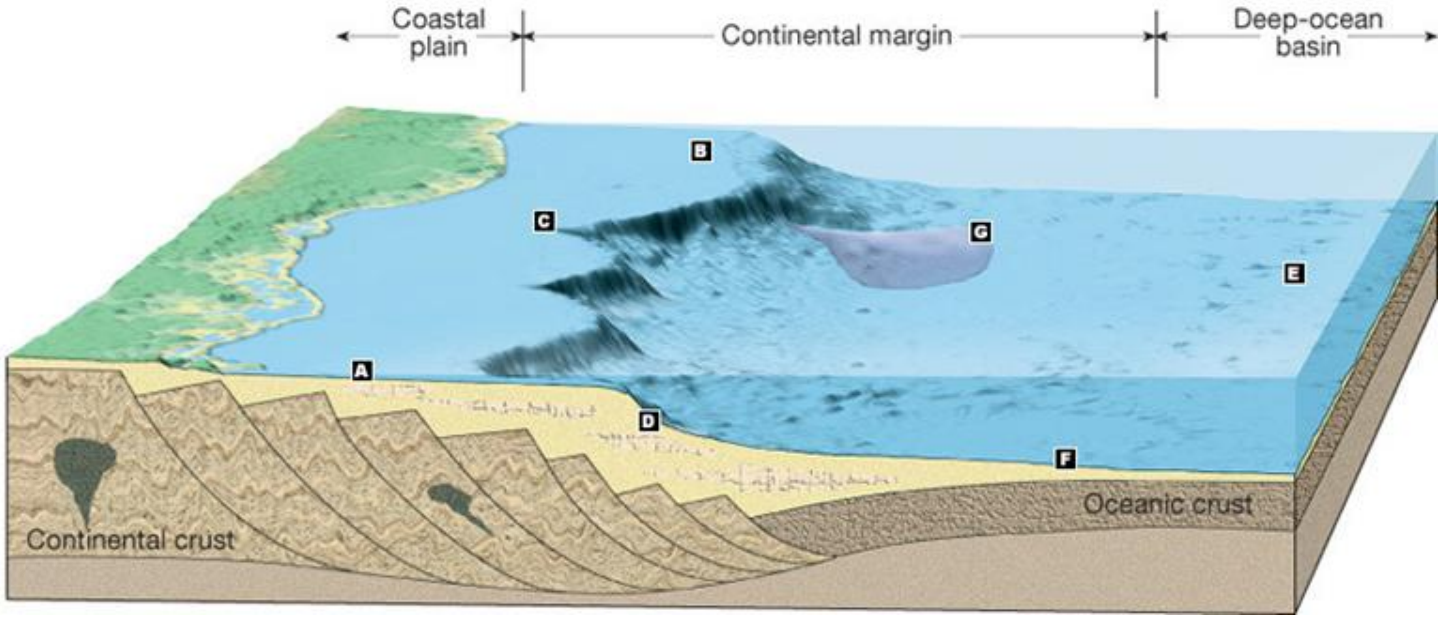
Strongly attenuated continental crust stretched over distances of 50-500 km
Overlain by seaward-thickening sediment prisms (shallow-marine deposits)
Sometimes referred to as "Atlantic-type margins"

Main mechanism for subsidence is the thermal contraction following lithospheric thinning
Subsidence is variable in space and time
Subsidence rate increases in offshore direction
Subsidence rate decreases with time for all parts of the profile

Rifted Passive Margin




GCS_WGS_1984
Datum: D_WGS_1984
Projection: Robinson
Volcanic and Non-volcanic Margins
Global Distribution of Passive Margins
Legend
Continents
Ocean
Passive Margin
Volcanic Passive Margin
Non-Volcanic Passive Margin
Uncertain Non-Volcanic Passive Margin
Uncertain Volcanic Passive Margin
0 2,000,000 4,000,000 8,000,000 Meters
A passive margin is the transition between oceanic and continental crust which is not an active plate margin. It is constructed by sedimentation above an ancient rift. Continental rifting creates new ocean basins. Eventually the continental rift forms a mid oceanic ridge. The transition between the continental and oceanic crust that is created by the rift is known as a passive margin.
N



Morphology of margin basins is characterized by shelf, slope and continental rise.

Shelf margin builds out with time.

Shelf sediments can be clastic or carbonate.

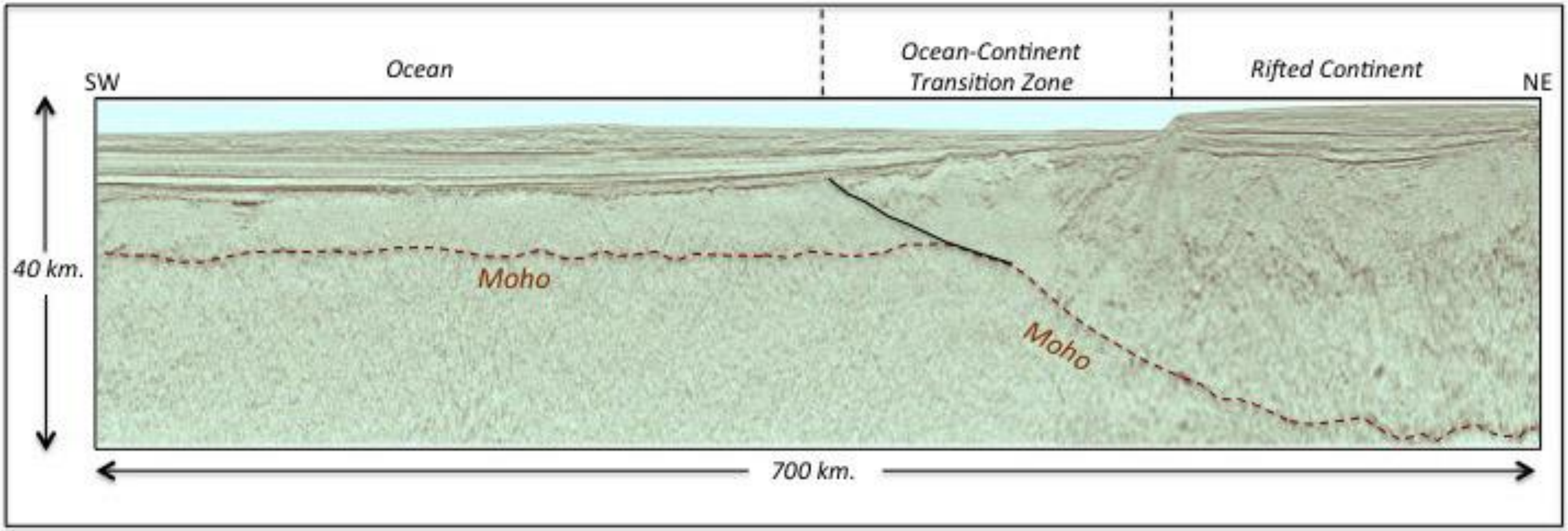
Slope/rise – material shed from continental shelf during lowstands (clastic systems)

Aprons/fans deposited along slope/rise as well as pelagic sediments, contourites, etc.

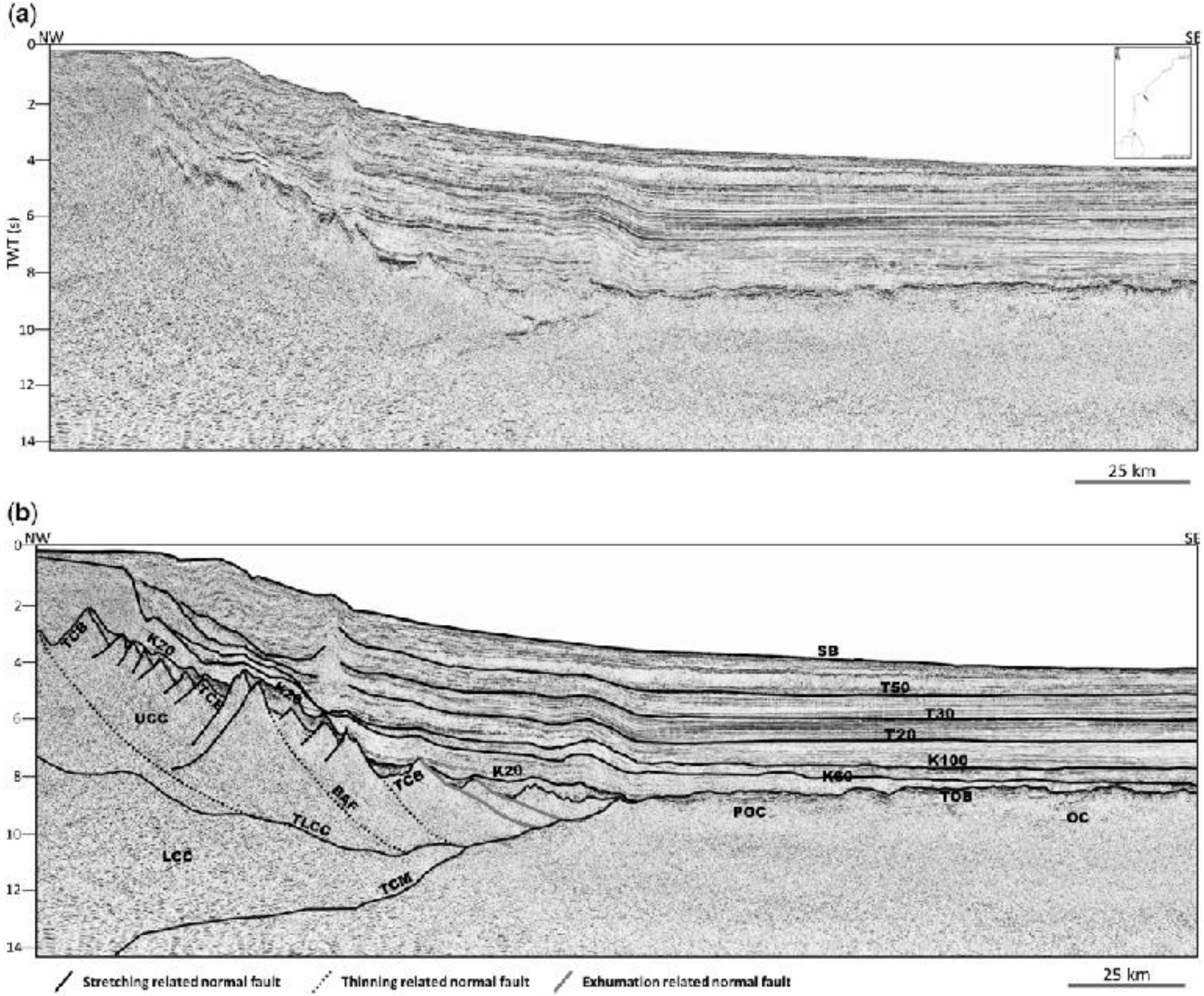
Gravity-driven deformation is common in drift-phase sediments.

Listric growth faults, salt tectonics, mud diapirs, etc.

Crustal architecture of a passive margin as seen on seismic profiles



East India Margin

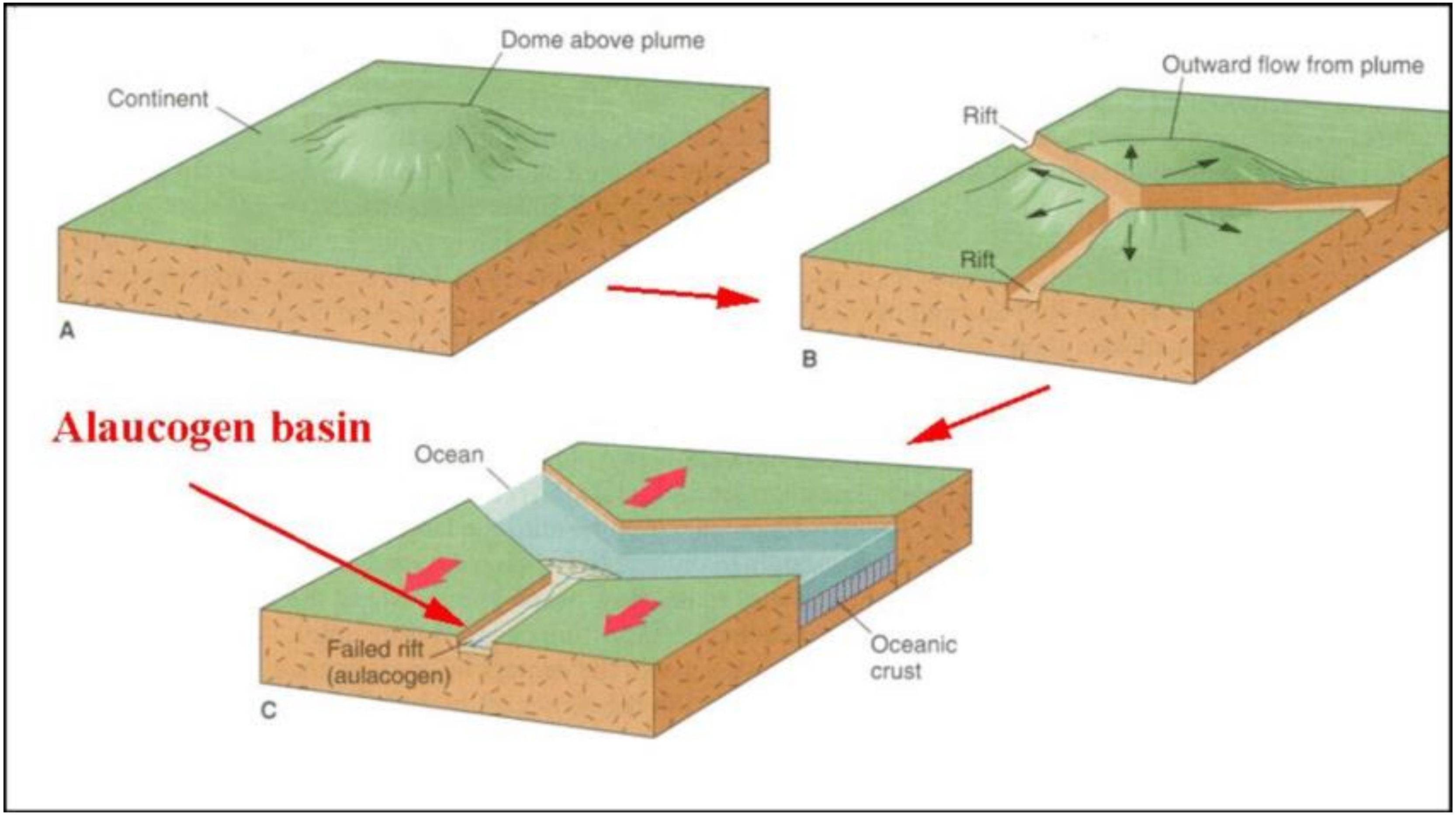


AULACOGENS

“Failed rifts” which occur at high angle to continental margin

Fill: non-marine to deep marine

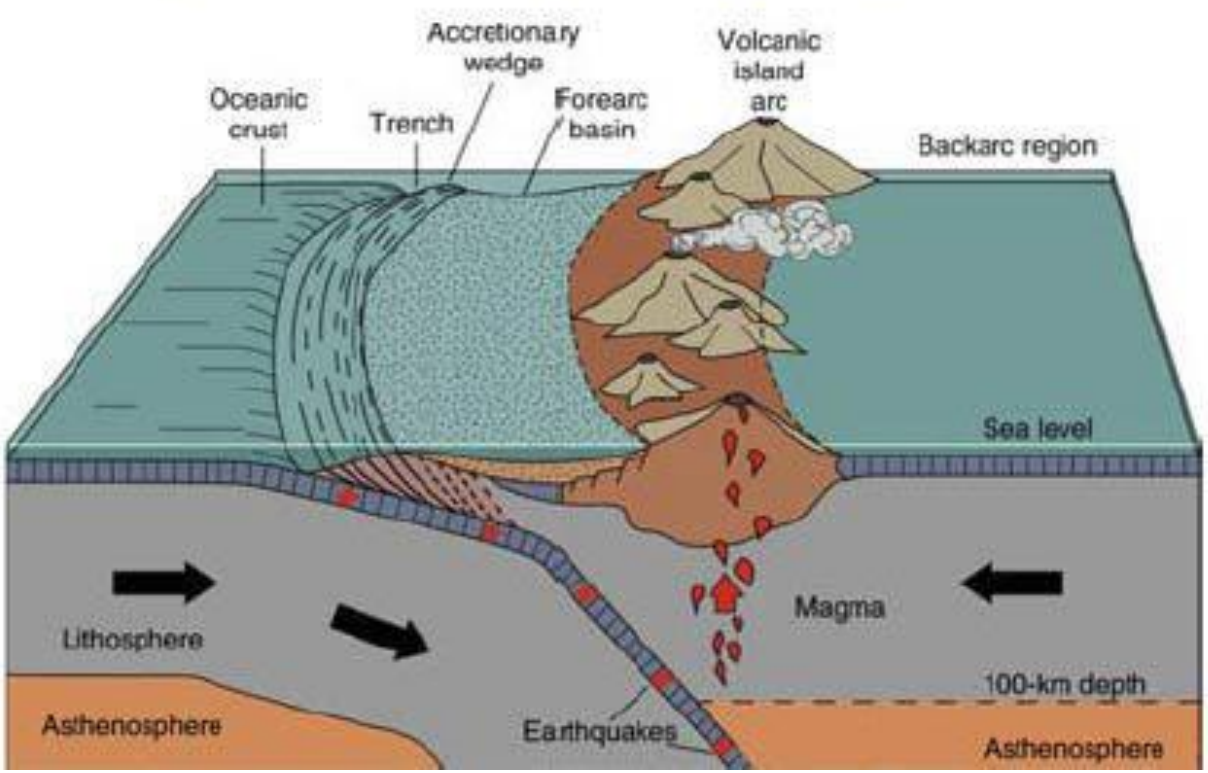
Example: Reelfoot Rift (Mississippi Valley)



Basins on Convergent Plate Boundaries

(Subduction of oceanic plate may lead to closing of ocean basin and ultimately to continental collision)

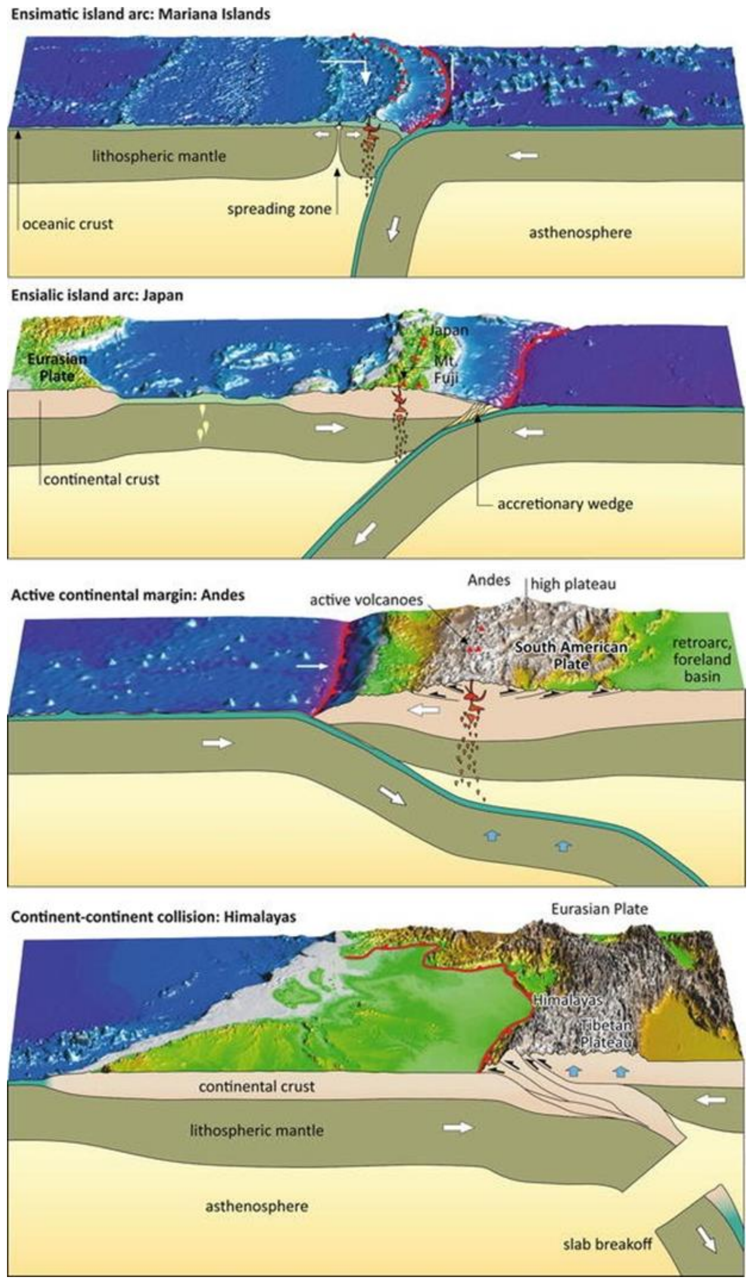
Cooler oceanic plate subducts underneath island arcs (also oceanic crust), creating a deep sea trench



Age of oceanic crust affects angle at which it is subducted

Young crust – shallow angle subduction, compression behind arc

Old crust – steep angle subduction, “roll-back”, extension behind arc

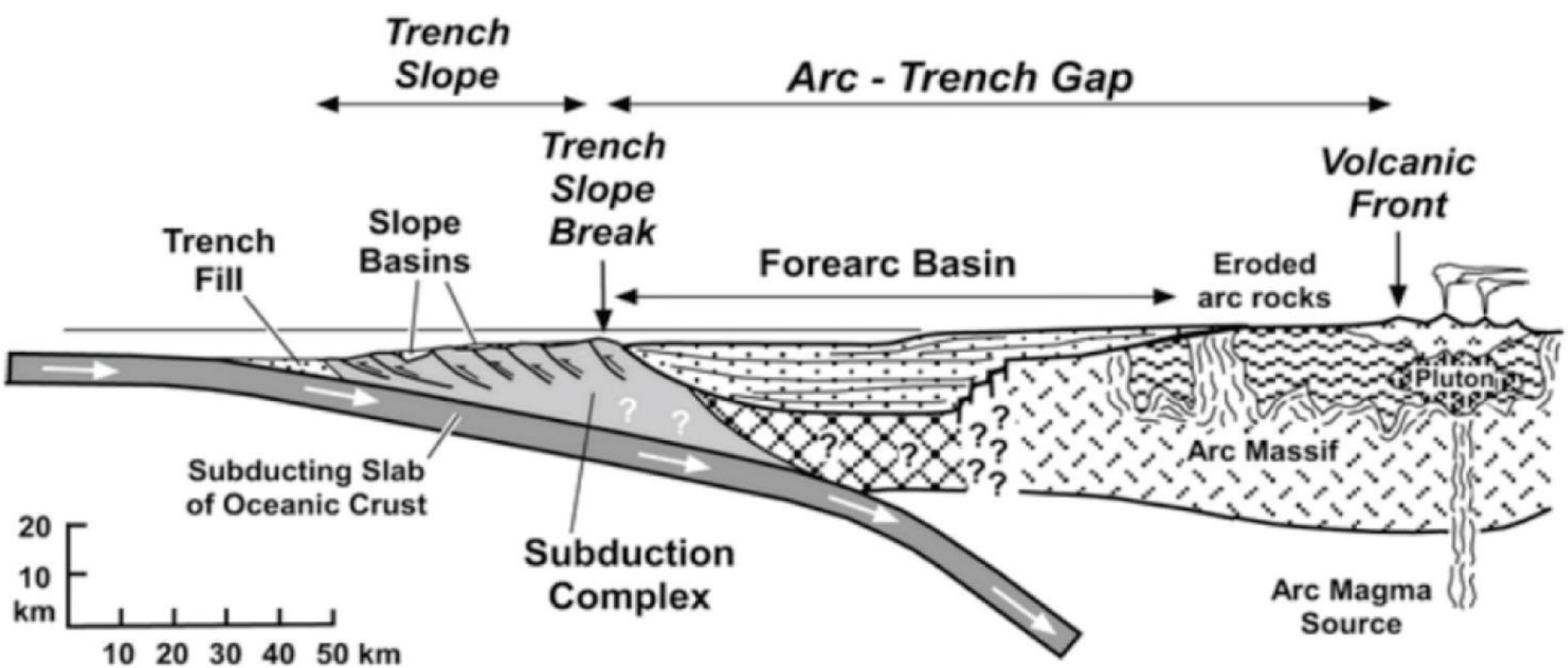


Forearc basin is the area between the accretionary wedge and the magmatic arc

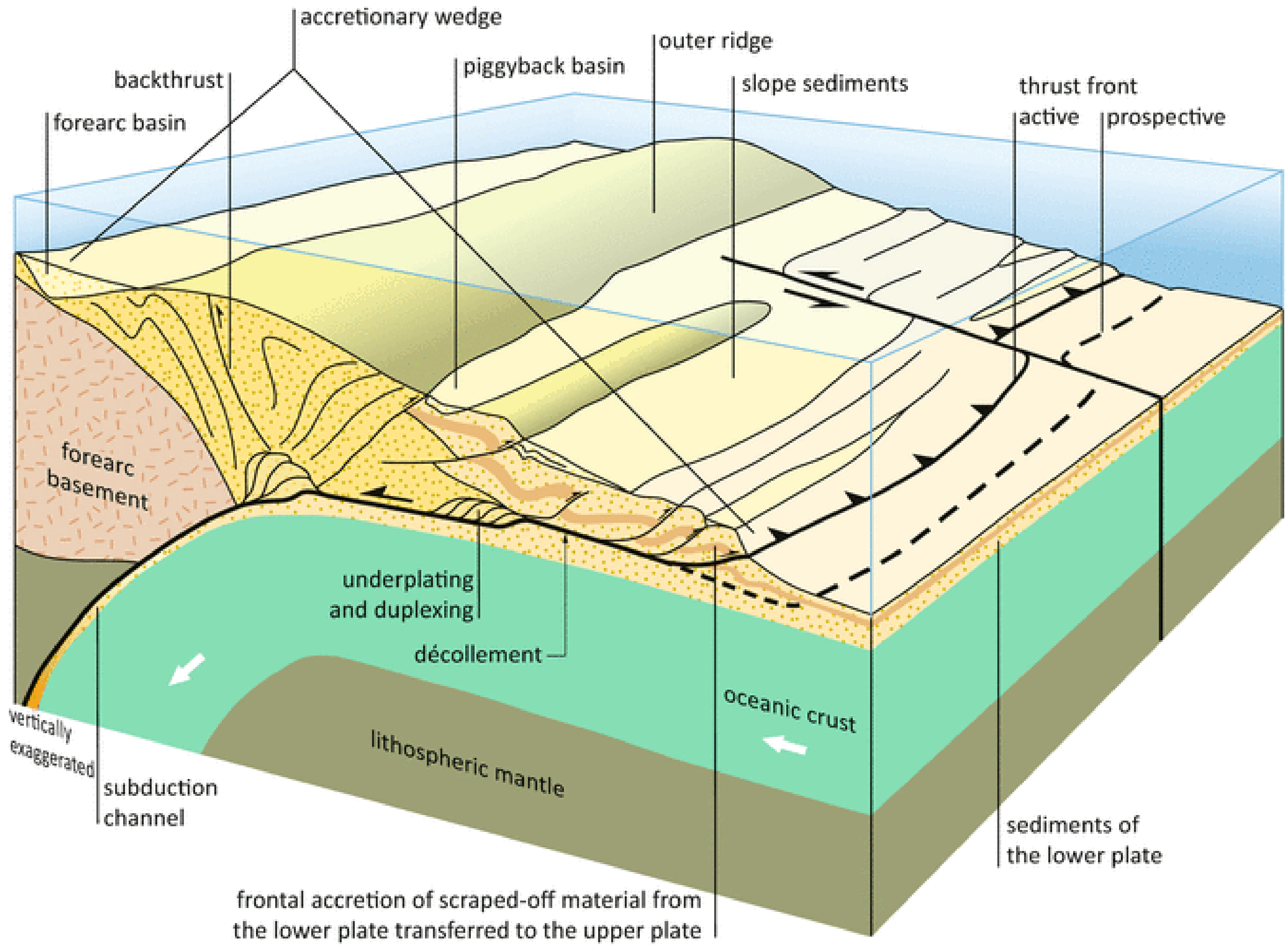
Forearc and back-arc basins are dominated by sediment derived from arc

Back-arc basin may also have component derived from continent

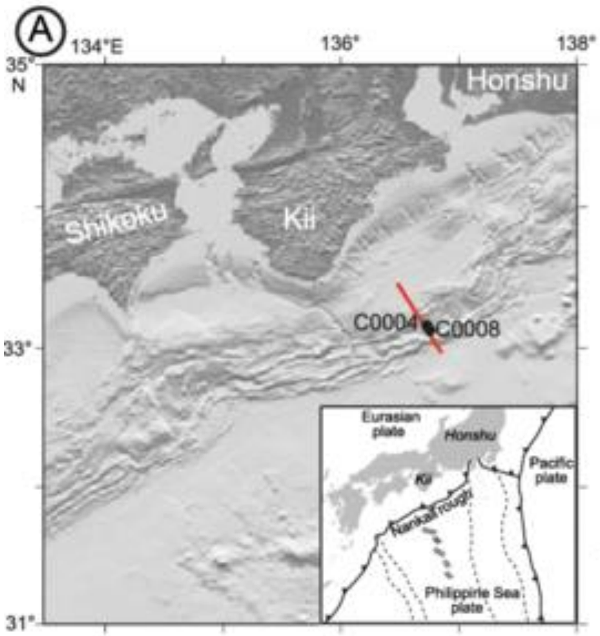
Deep-sea trench has sediments derived from arc and sediments scraped off subducting oceanic crust (melange)

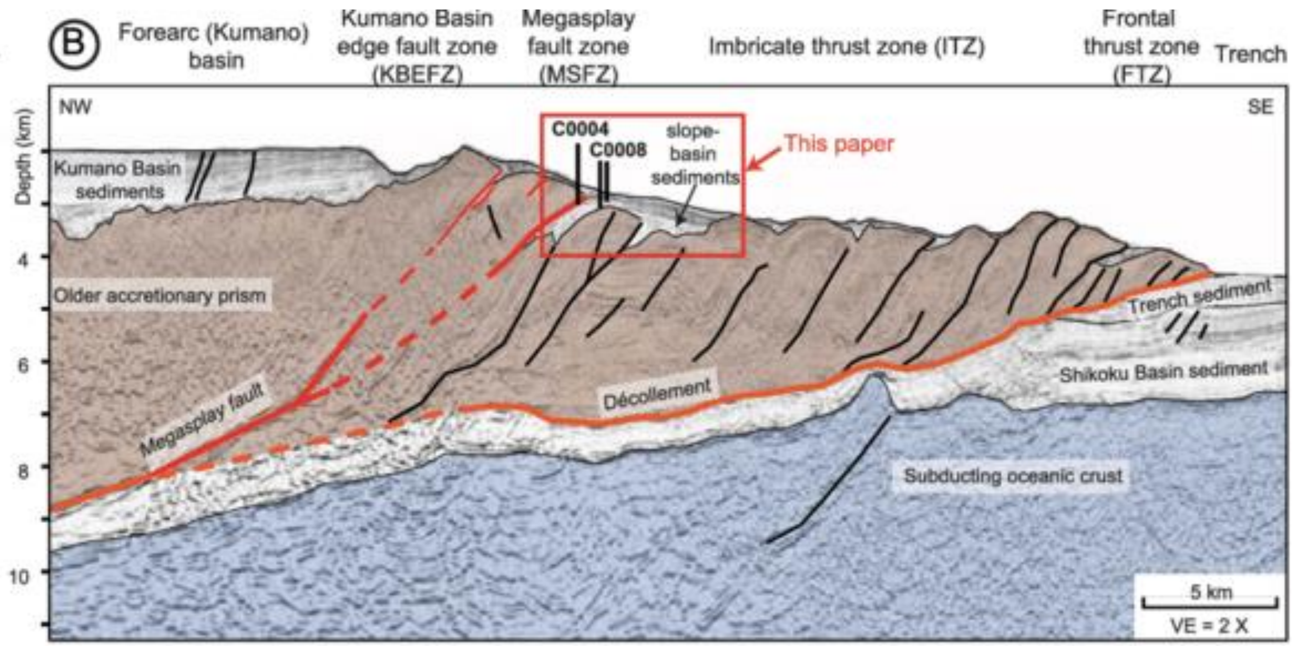


Accretionary (or subduction) complex

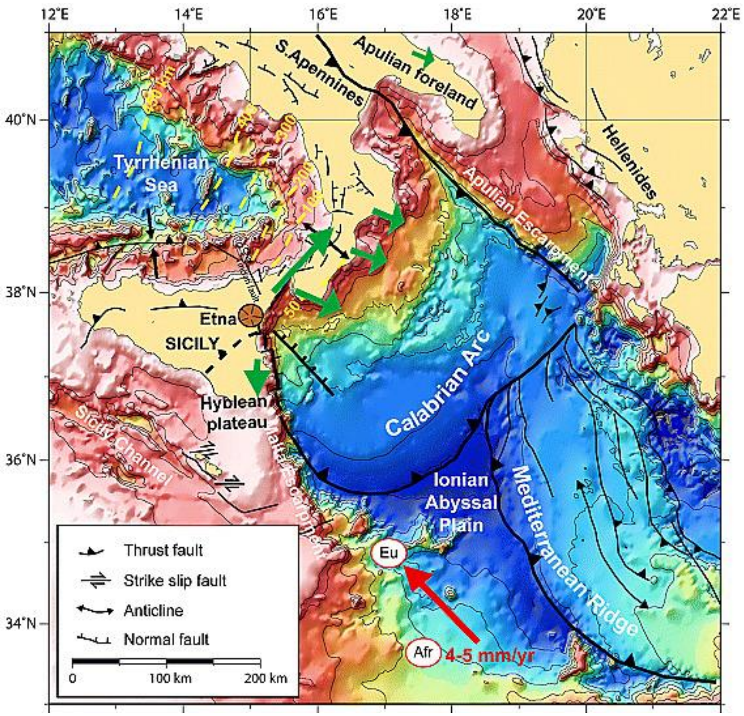


Subduction complex off Japan

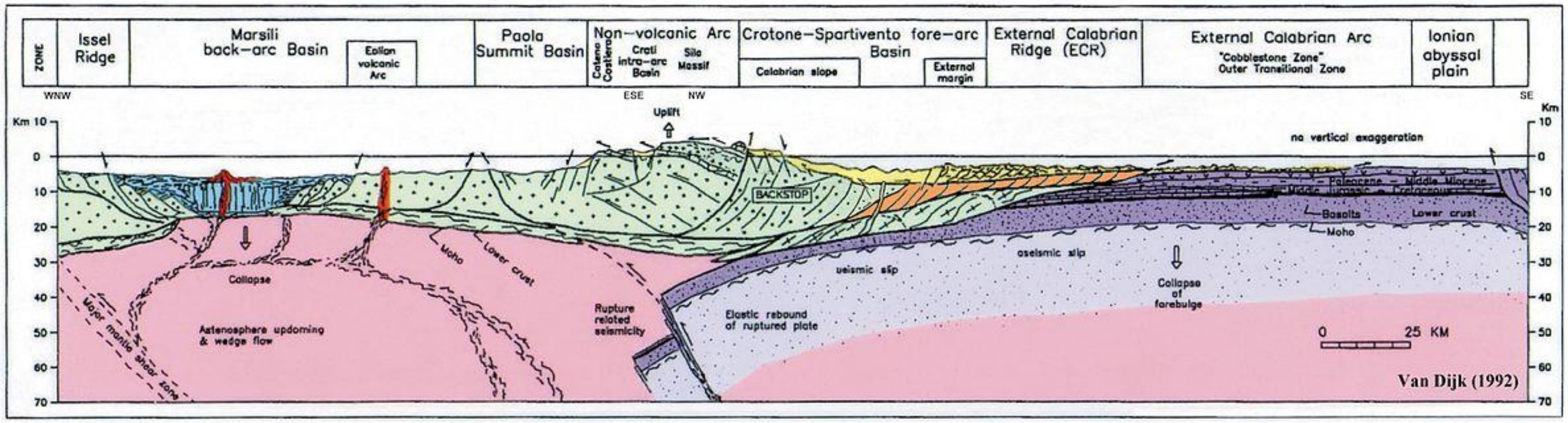




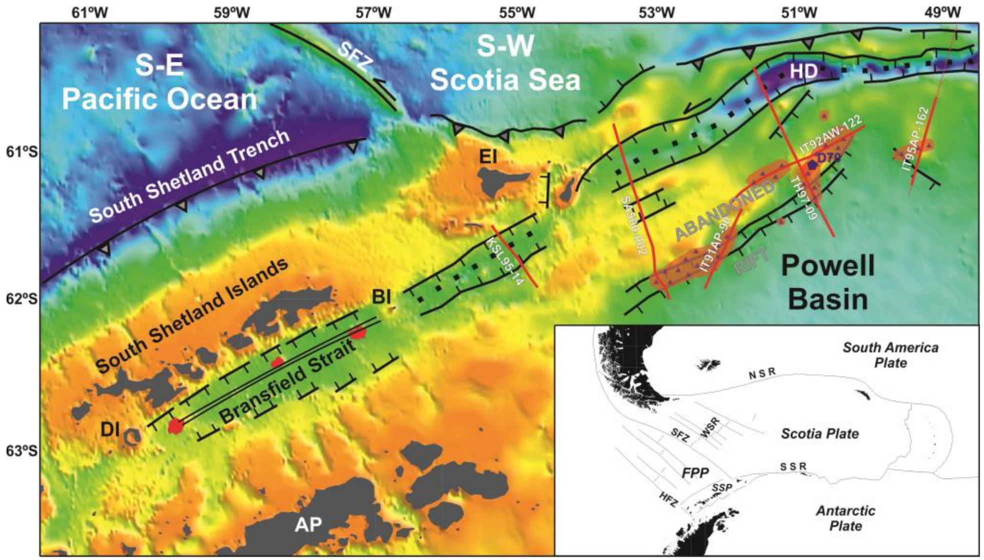
Calabrian Arc

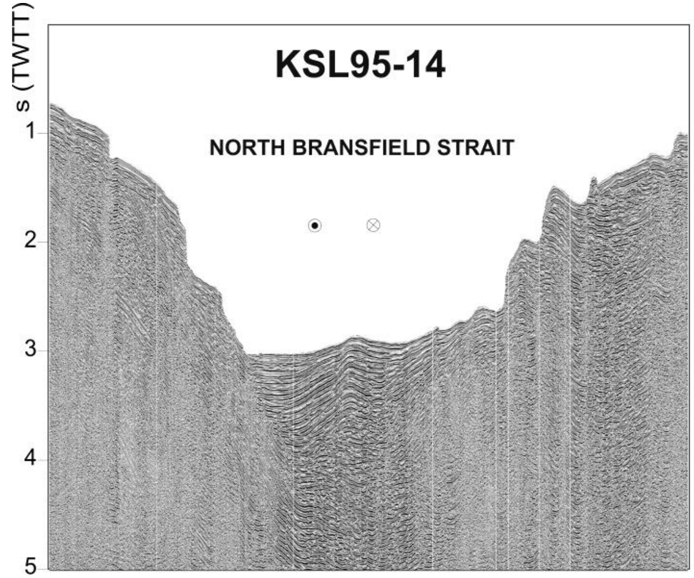


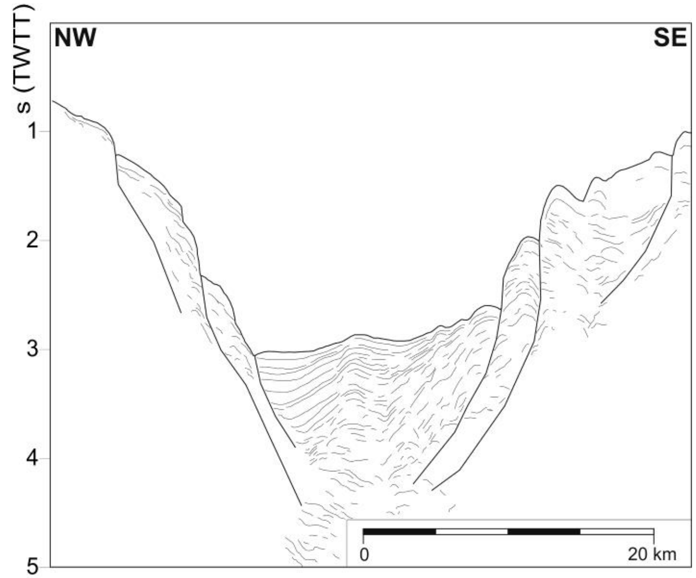
Deformation is related to an imbricate fan within the post-Messinian salt-bearing accretionary wedge, out-of-sequence thrust faults in the pre-Messinian wedge and normal faults in the inner plateau.



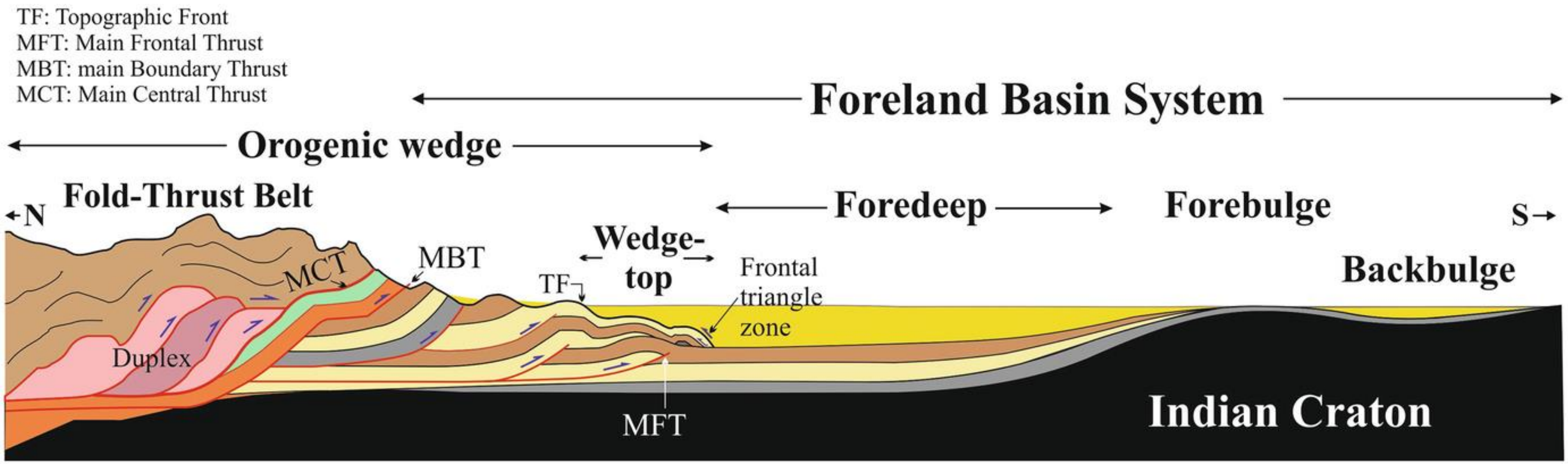
Bransfield Strait back-arc basin



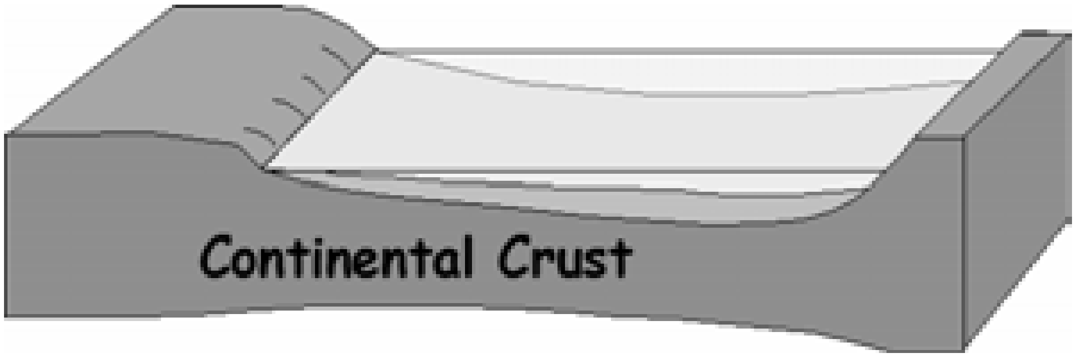




Himalayan peripheral foreland basin

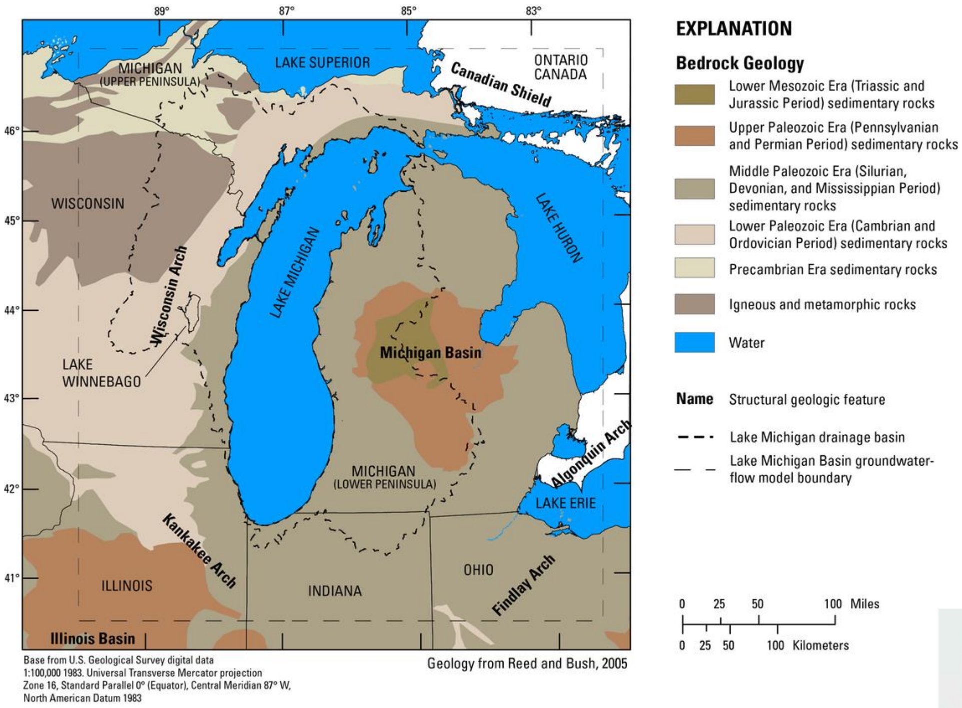


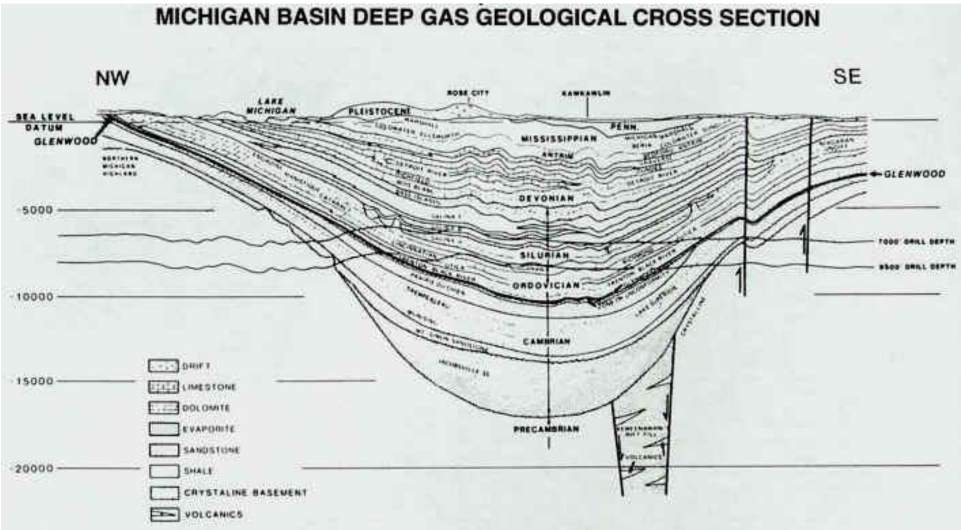
Intracontinental basins



Form within continental interiors (stable cratonic areas) and have in general semi-circular to ovate downwarps
They develop away from plate boundaries
Causes of subsidence are: presence of underlying rifts, large-scale fault blocks, cooling after intrusion of dense material
Subsidence is greatest towards center of basin
Sedimentary fill terrestrial or marine (carbonates, clastics, evaporites)

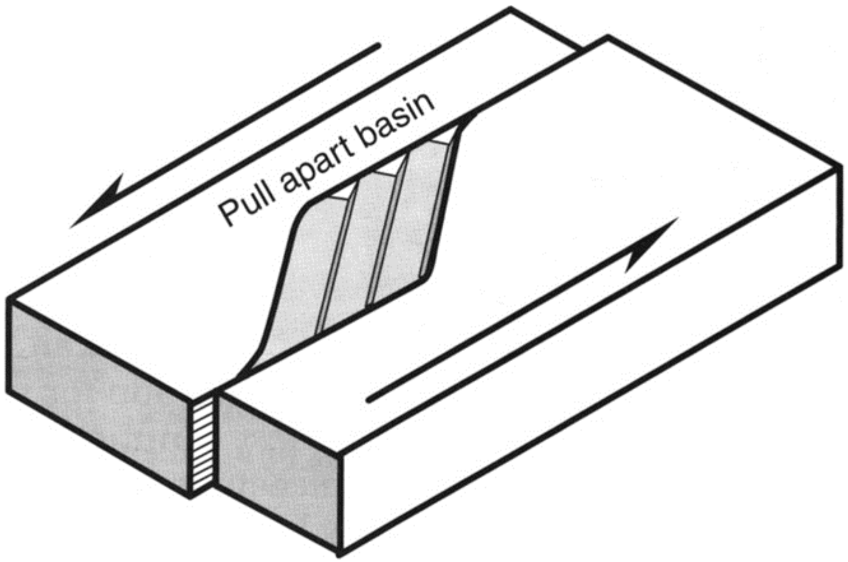
Michigan Basin



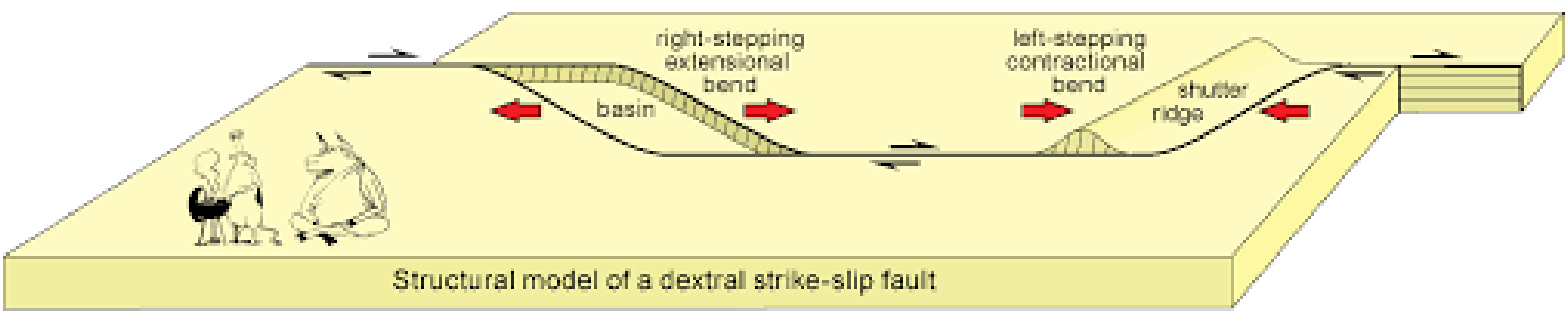


2° PART

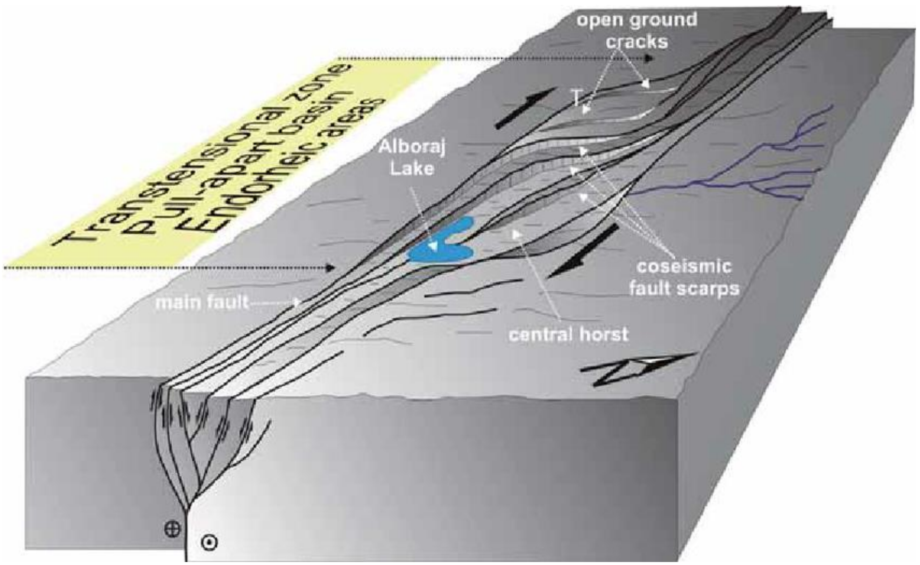
Strike-slip related basins

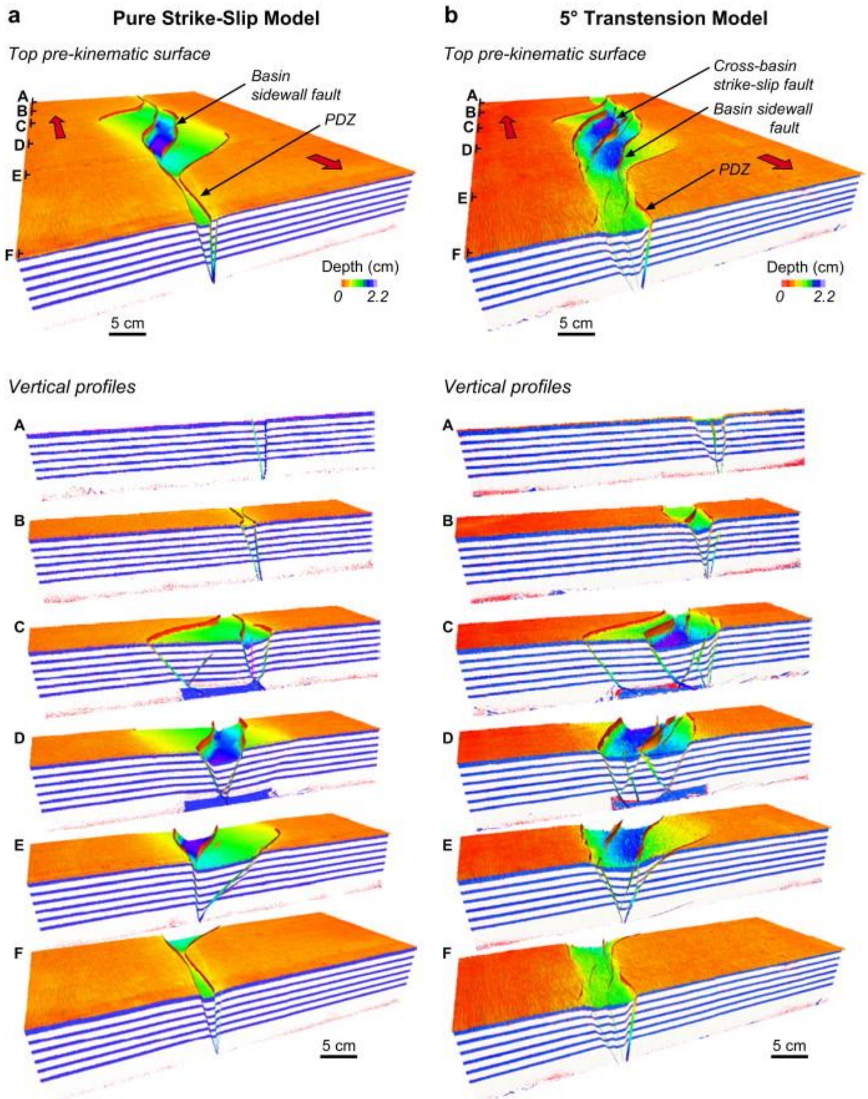


Pull apart or fault overstep basins associated with strike-slip fault systems.
Strike-slip basins often have extremely rapid lateral facies variations
May be sediment-starved (marine or lacustrine) in center

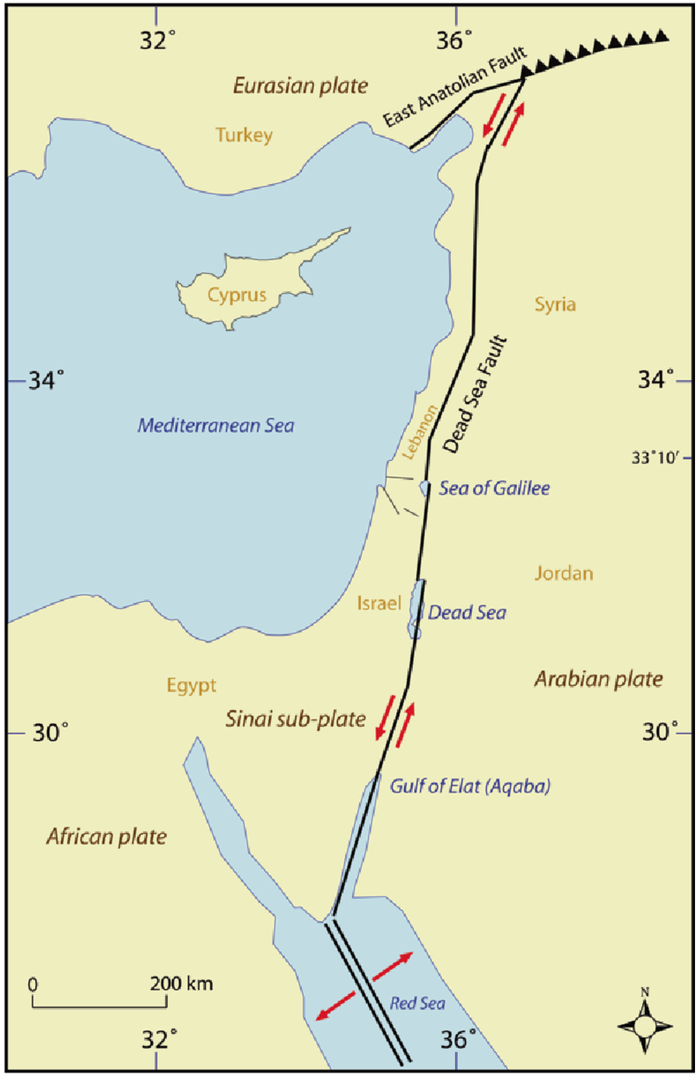


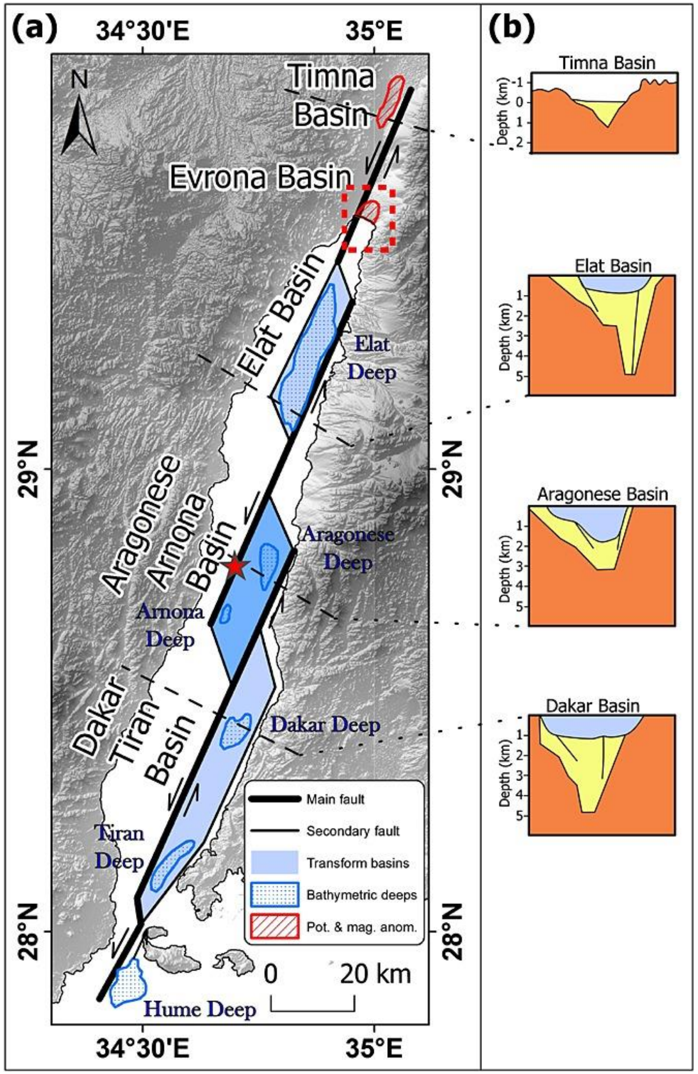
Analogue modelling of transtensional pull-apart basins



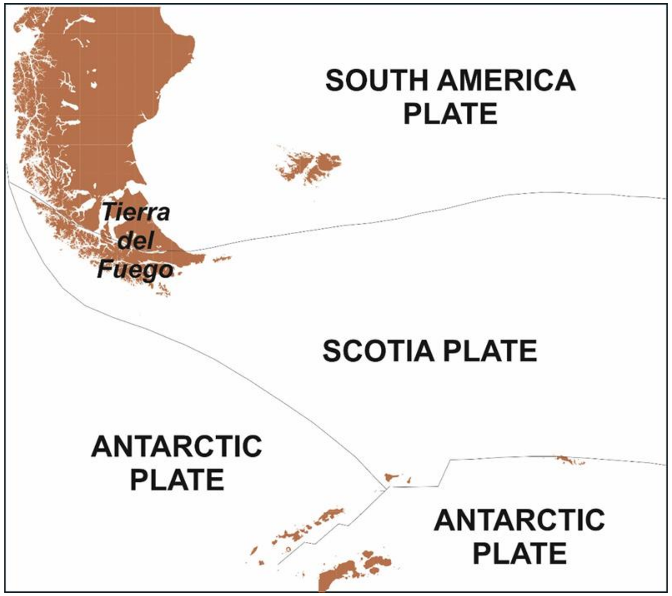


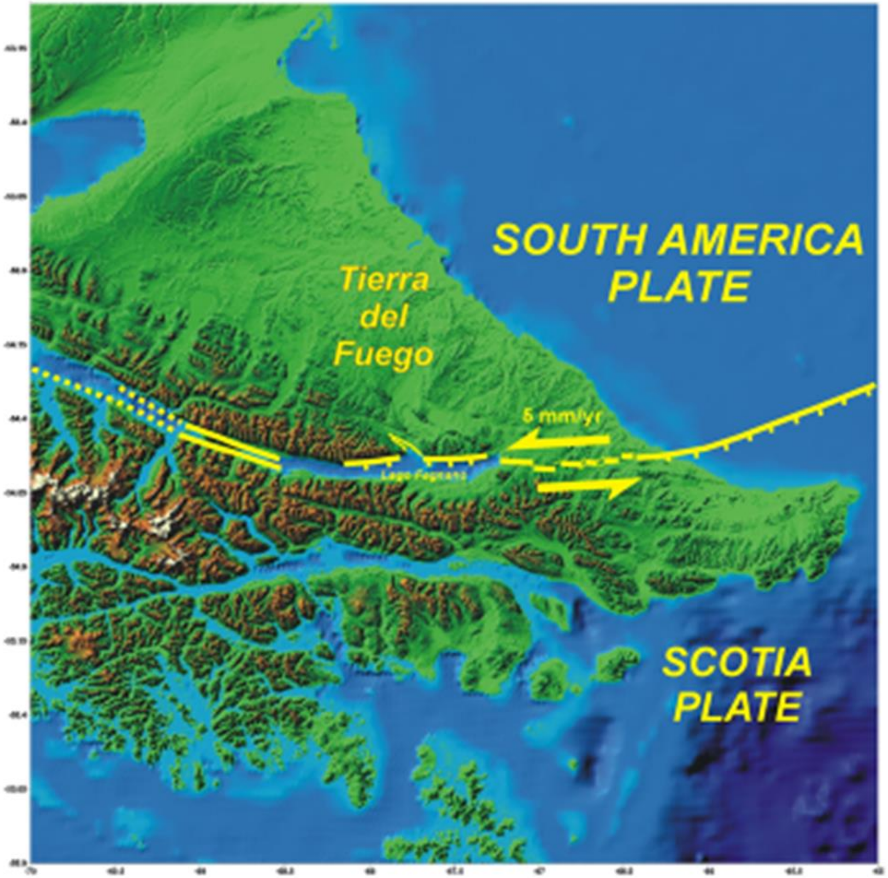
Dead Sea Transform Fault System



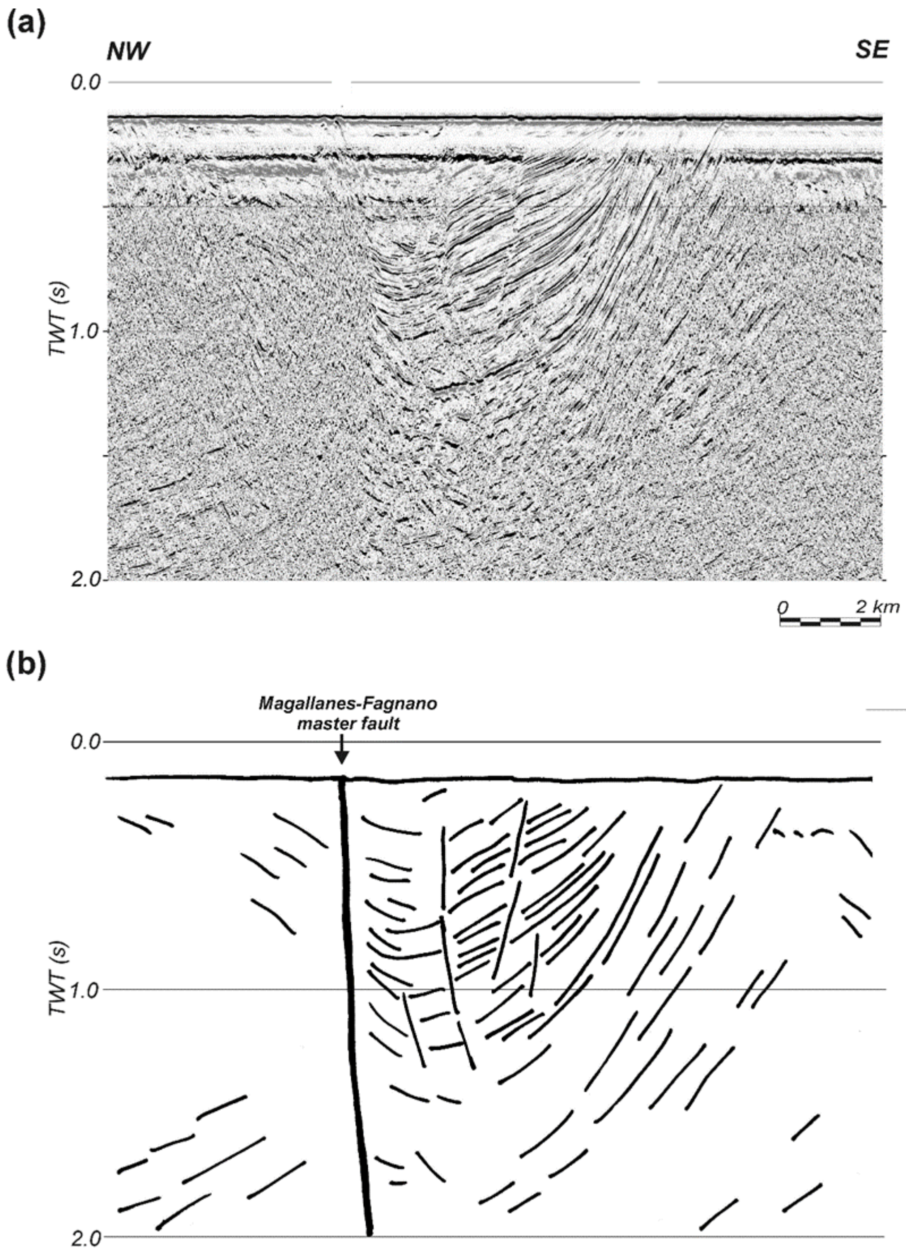


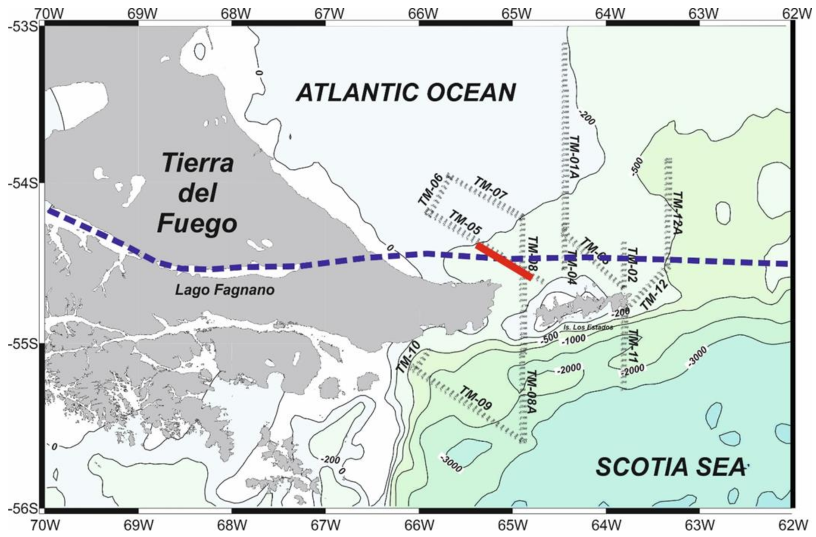
Tierra del Fuego
(South America-Scotia plate boundary)



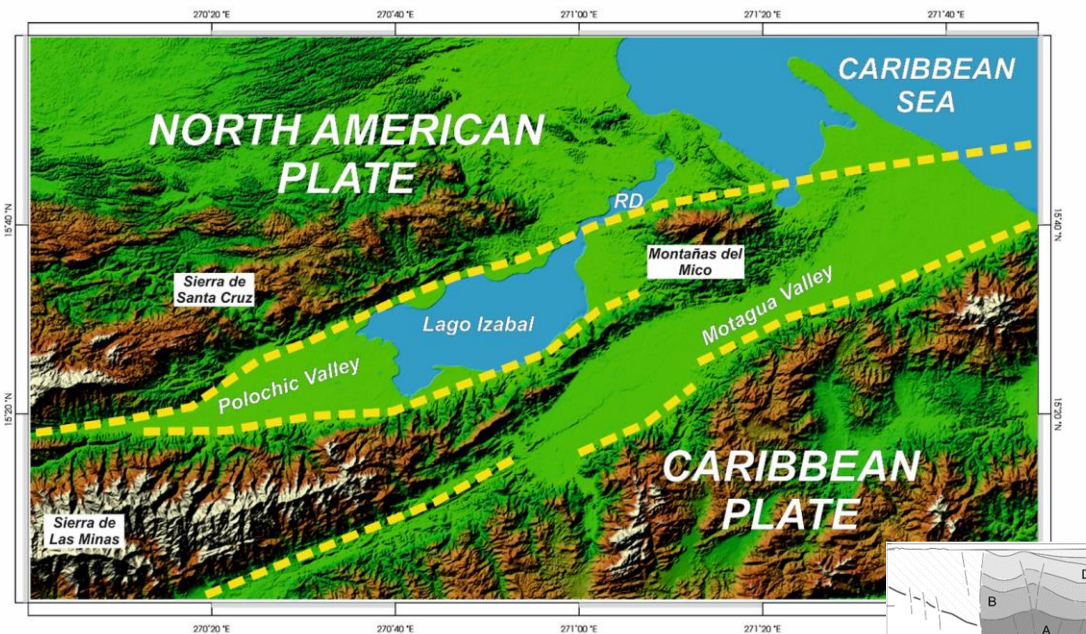


Magallanes-Fagnano transform fault



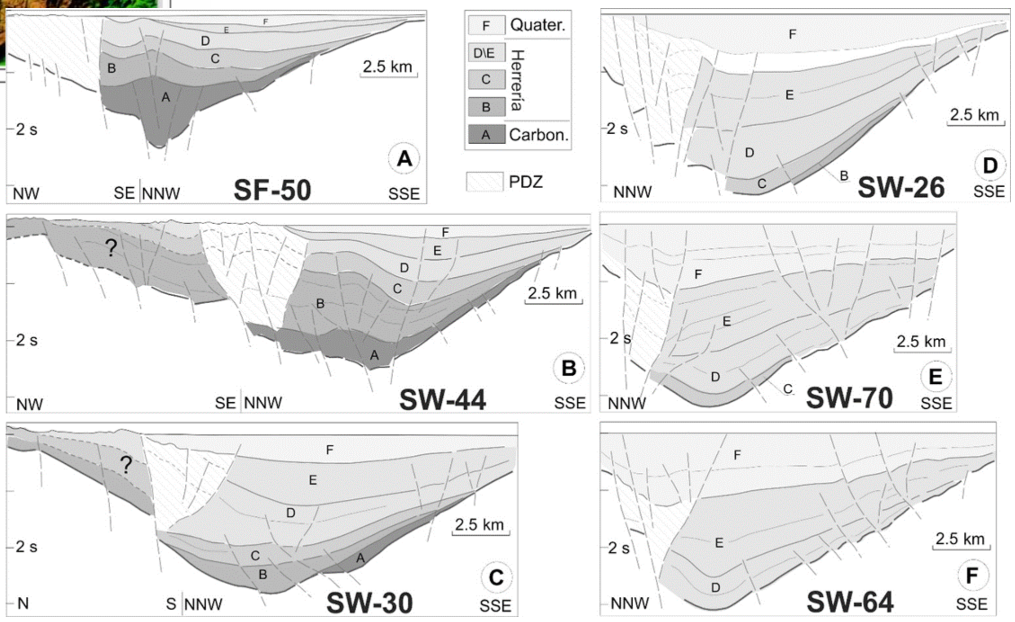


Lago de Izabal (eastern Guatemala)

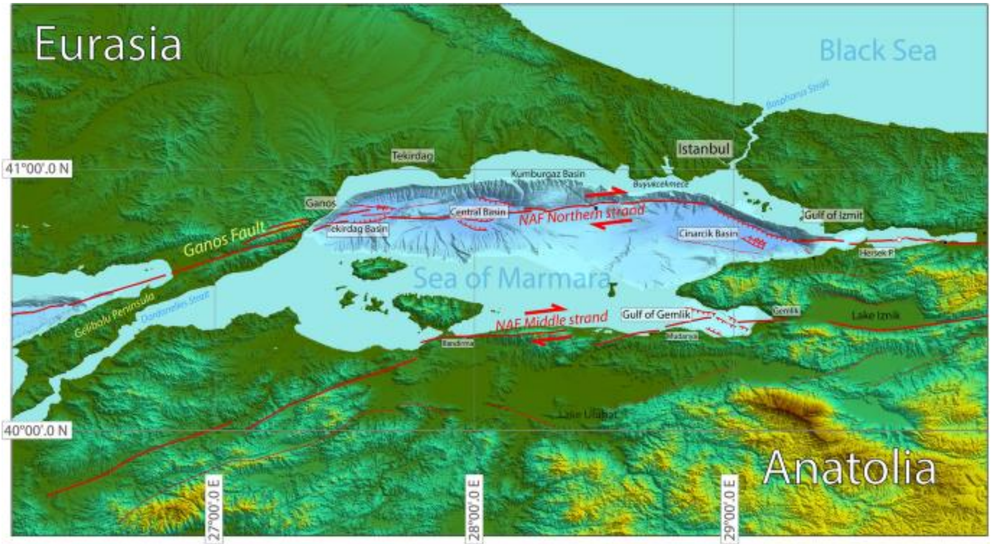


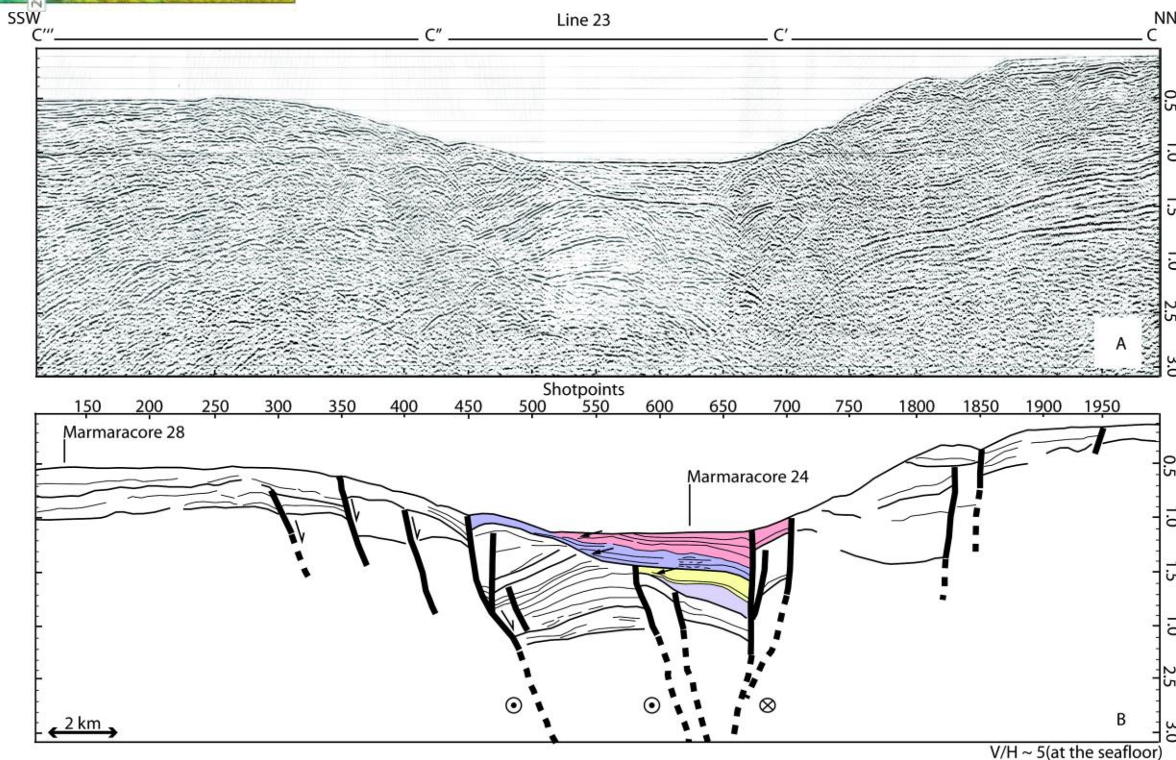
Studies show that basin asymmetry is toward the transform fault, suggesting that subsidence was mostly governed by extension in a direction normal to the strike of the transform, at the same time that strike-slip motion is taking place.

The occurrence of many asymmetric basins along transform environments testify that this specific geometry is the rule, rather than the exception.



Pull-apart basins along the North Anatolian Fault system in the Sea of Marmara





GEOPHYSICAL AND GEOLOGICAL METHODS FOR BASIN STUDIES

Data needed for large-scale surveys:

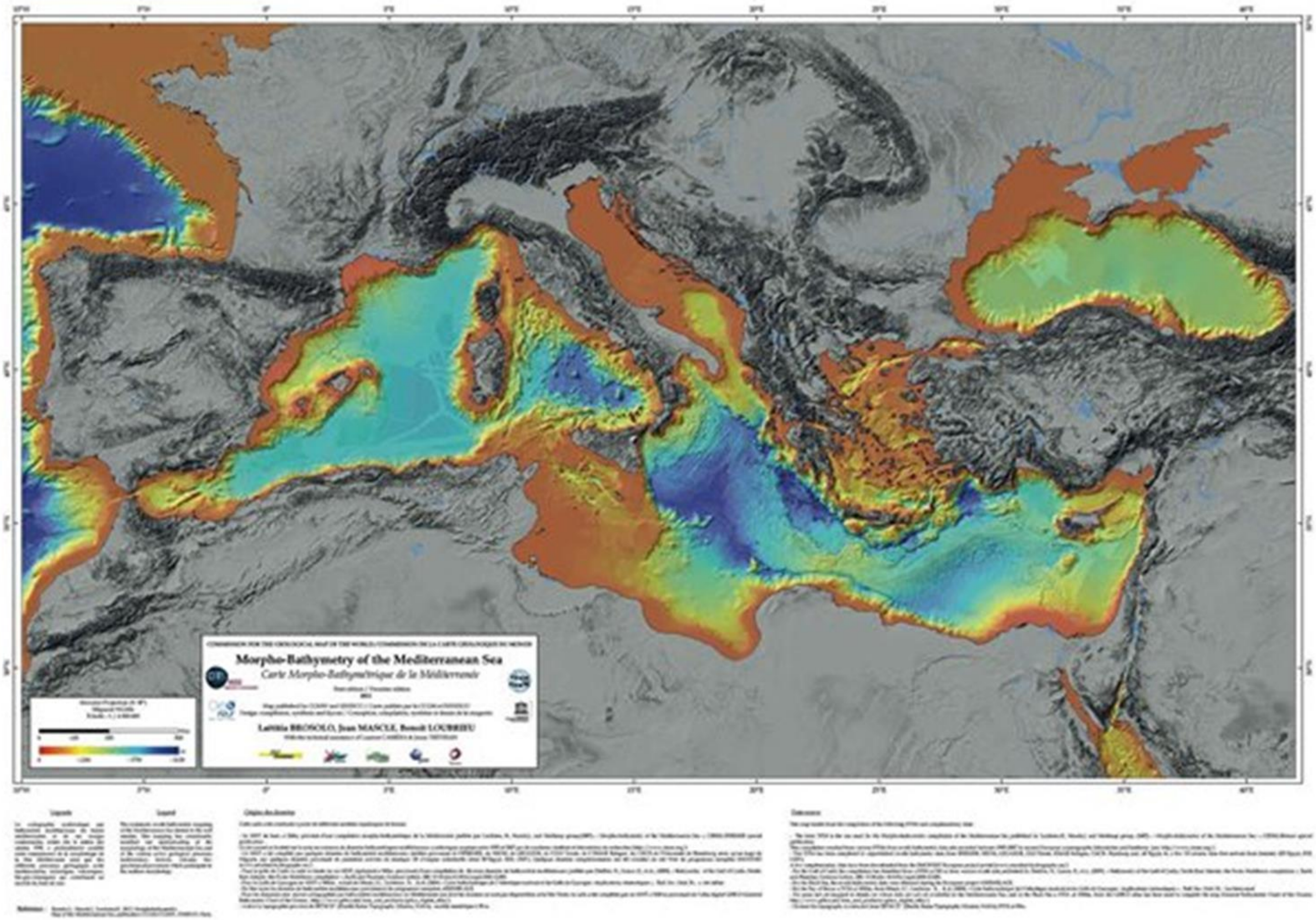
- **Satellite-derived images**
- **Airborne surveys (magnetic, gravity) and drones**
- **Multichannel seismic reflection surveys (both onshore and onland)**
- **Gravity surveys (both onshore and onland)**
- **Magnetic surveys (both onshore and onland)**

Data needed for small-scale surveys:

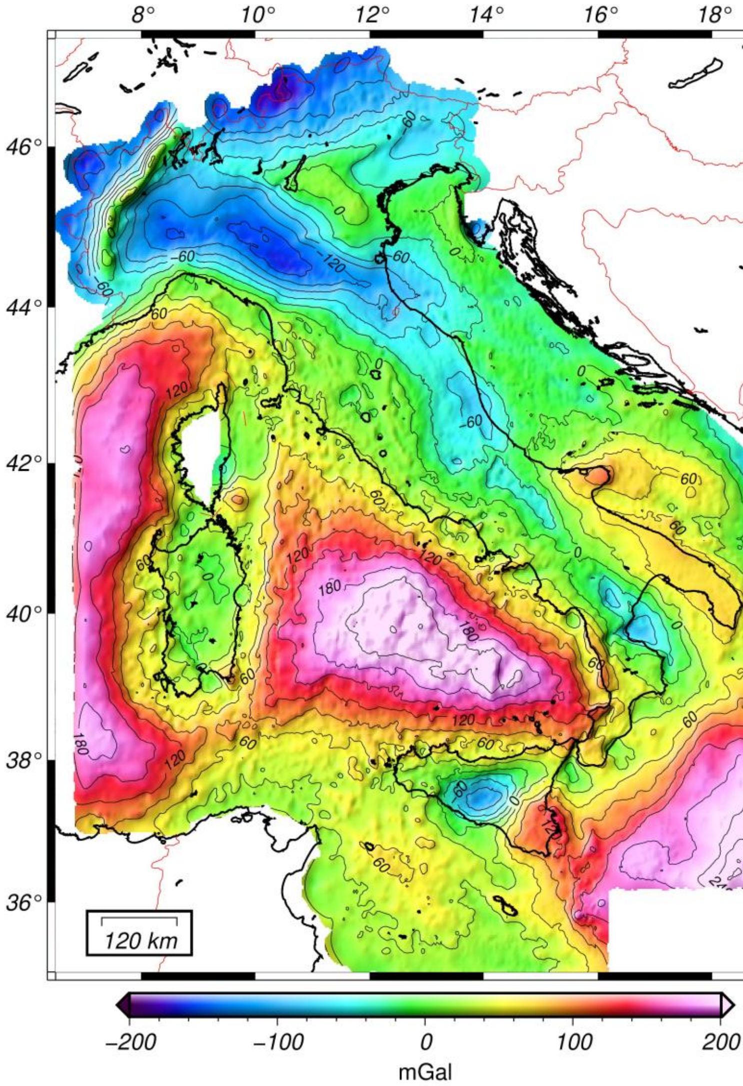
- **High-resolution seismic profiles**
- **Geoelectrical soundings**
- **Georadar**
- **Sedimentary cores**

Modeling, tomography, 3-D reconstructions, etc.

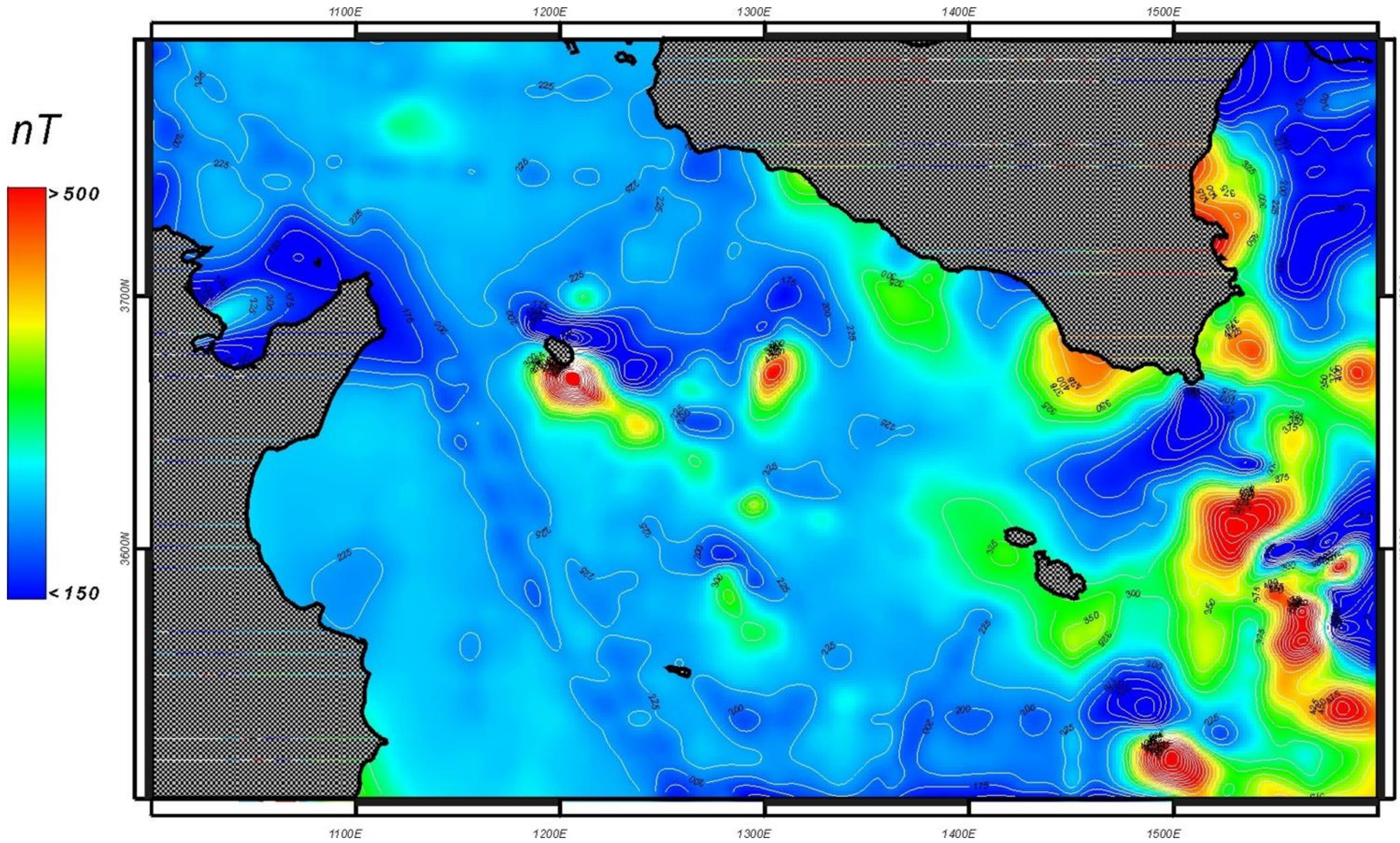
Bathymetry



Bouguer gravity map



Magnetic anomaly map



SCIENTIFIC DRILLING

HISTORY

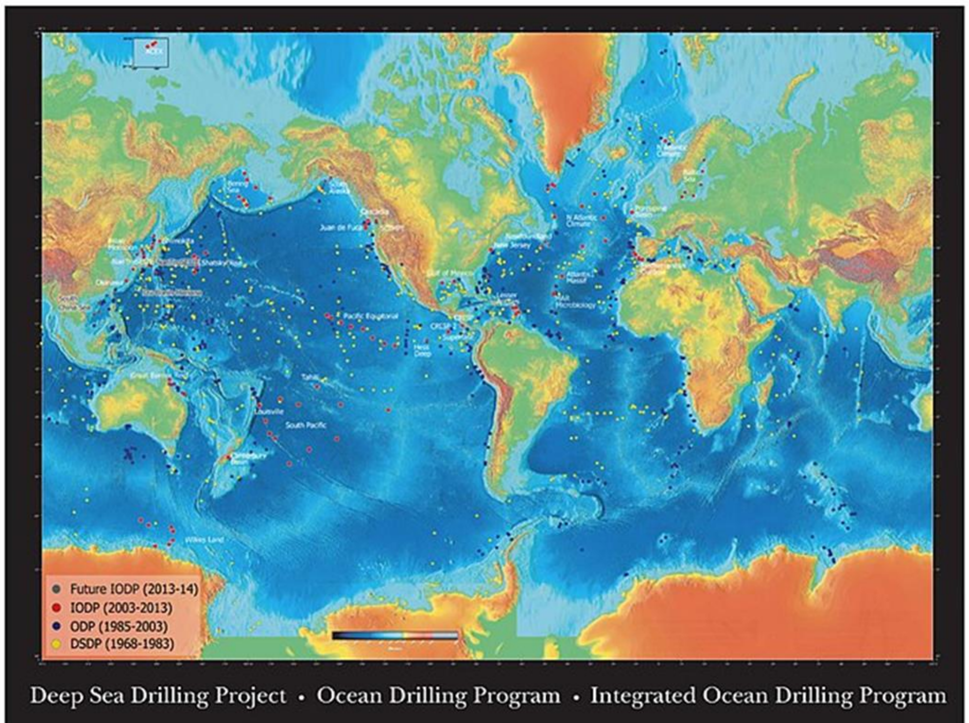
1961: Project MoHole

1966-1983: Deep Sea Drilling Project (DSDP)
Drilling Vessel *Glomar Challenger*

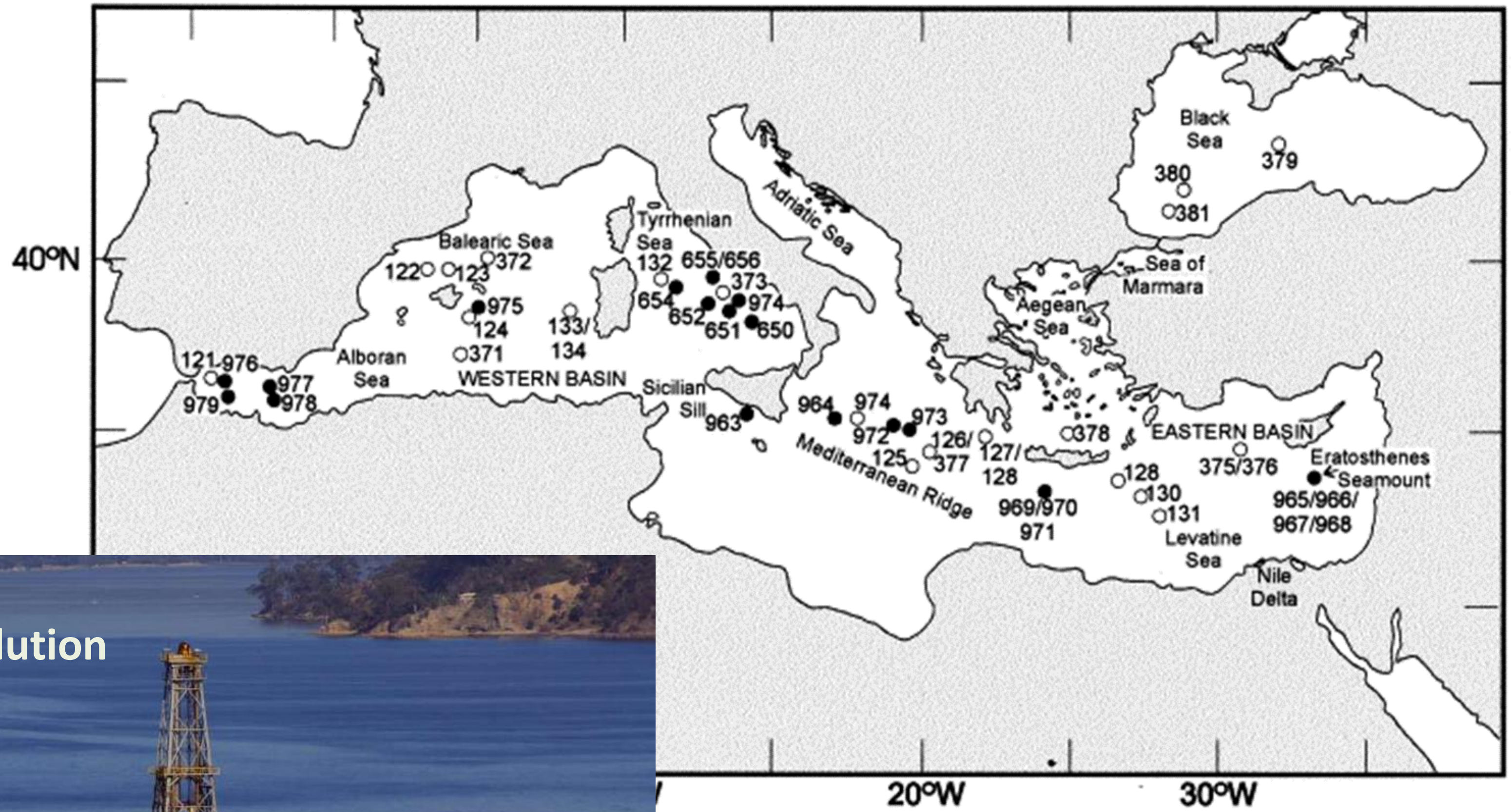
1983-2003: Ocean Drilling Program (ODP)
JOIDES Resolution replaced the *Glomar Challenger*

2003-2013: Integrated Ocean Drilling Program (IODP)
JOIDES Resolution, the new marine-riser equipped Japanese Vessel *Chikyu*, and specialized Mission-Specific-Platforms

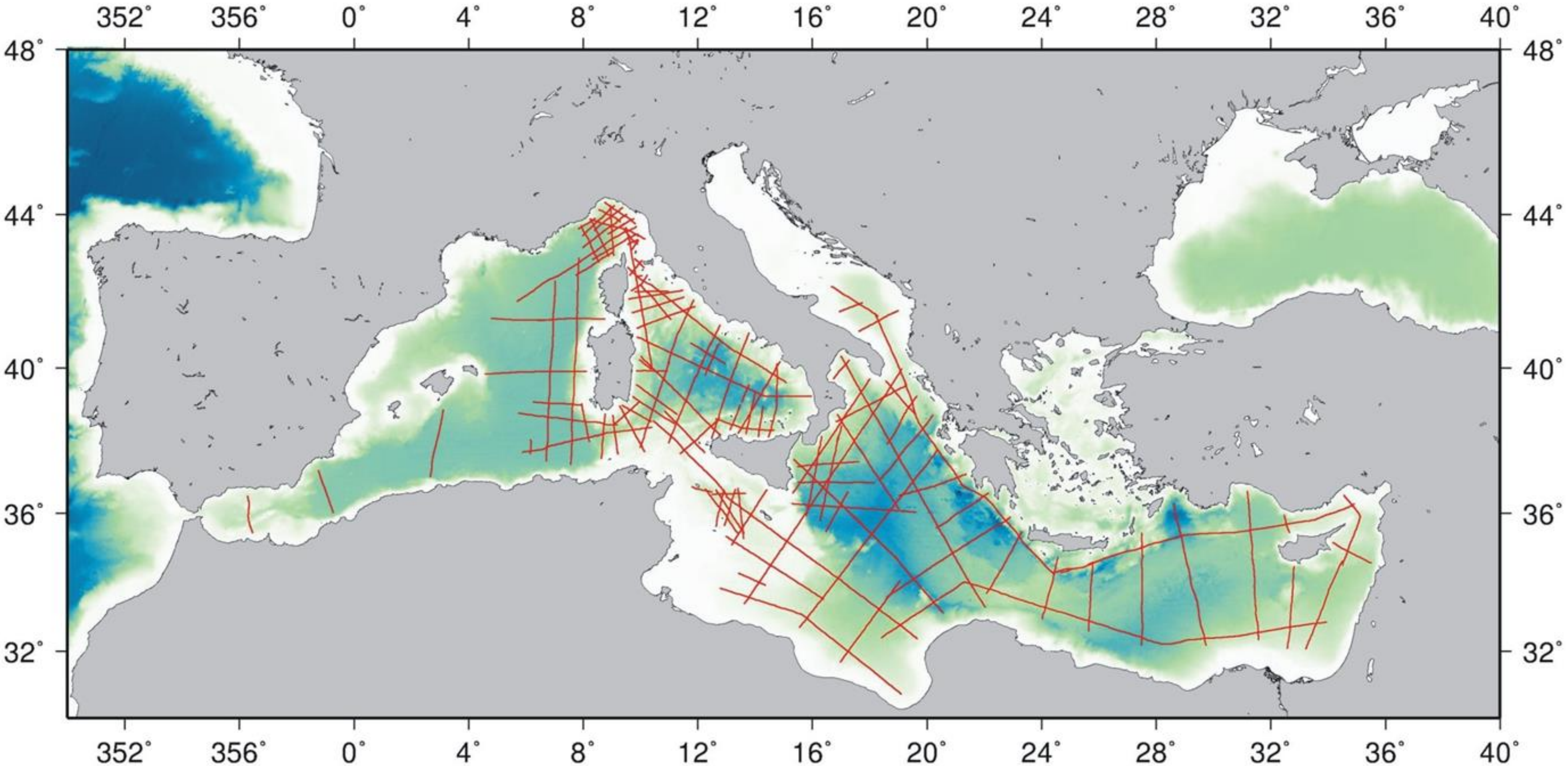
2013-Present: International Ocean Discovery Program (IODP)



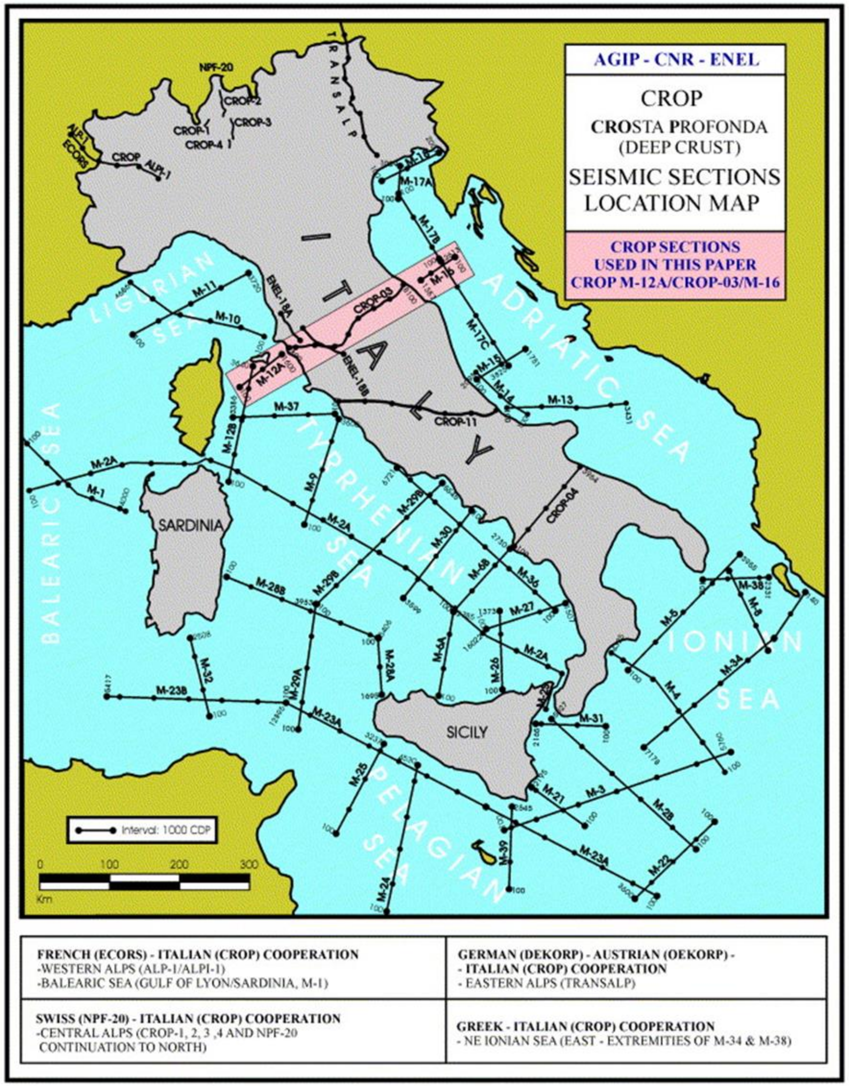
DSDP and IODP sites in the Mediterranean Sea



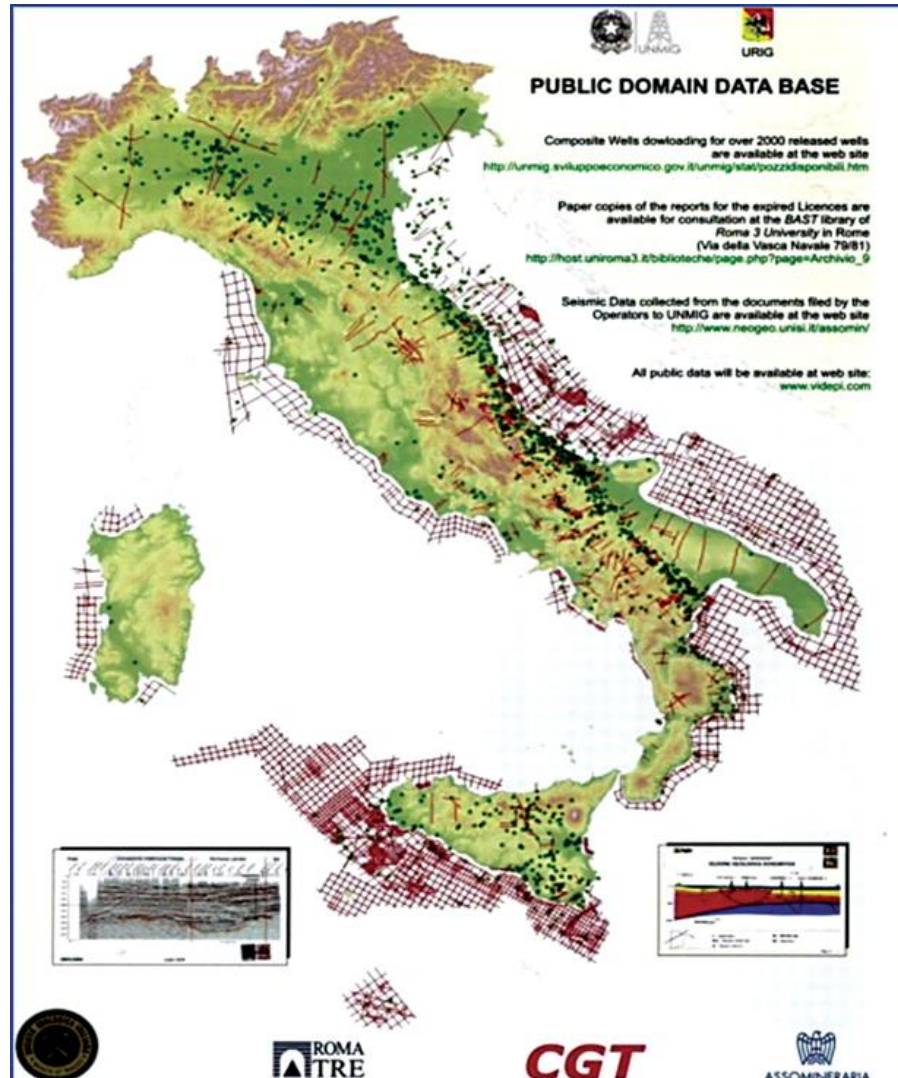
MS seismic profiles
(collected from 1968 to 1982)



CROP Crustal Project (Seismic profiles collected both onshore and offshore)

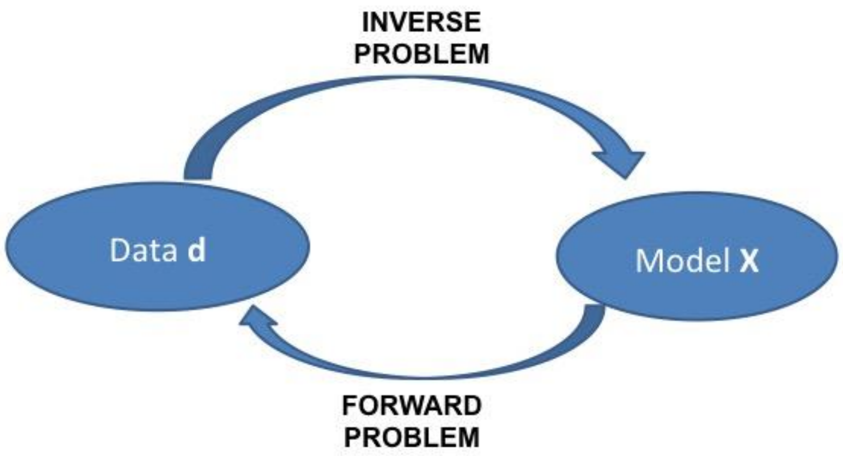


ViDEPI
http://unmig.sviluppoeconomico.gov.it/videpi/

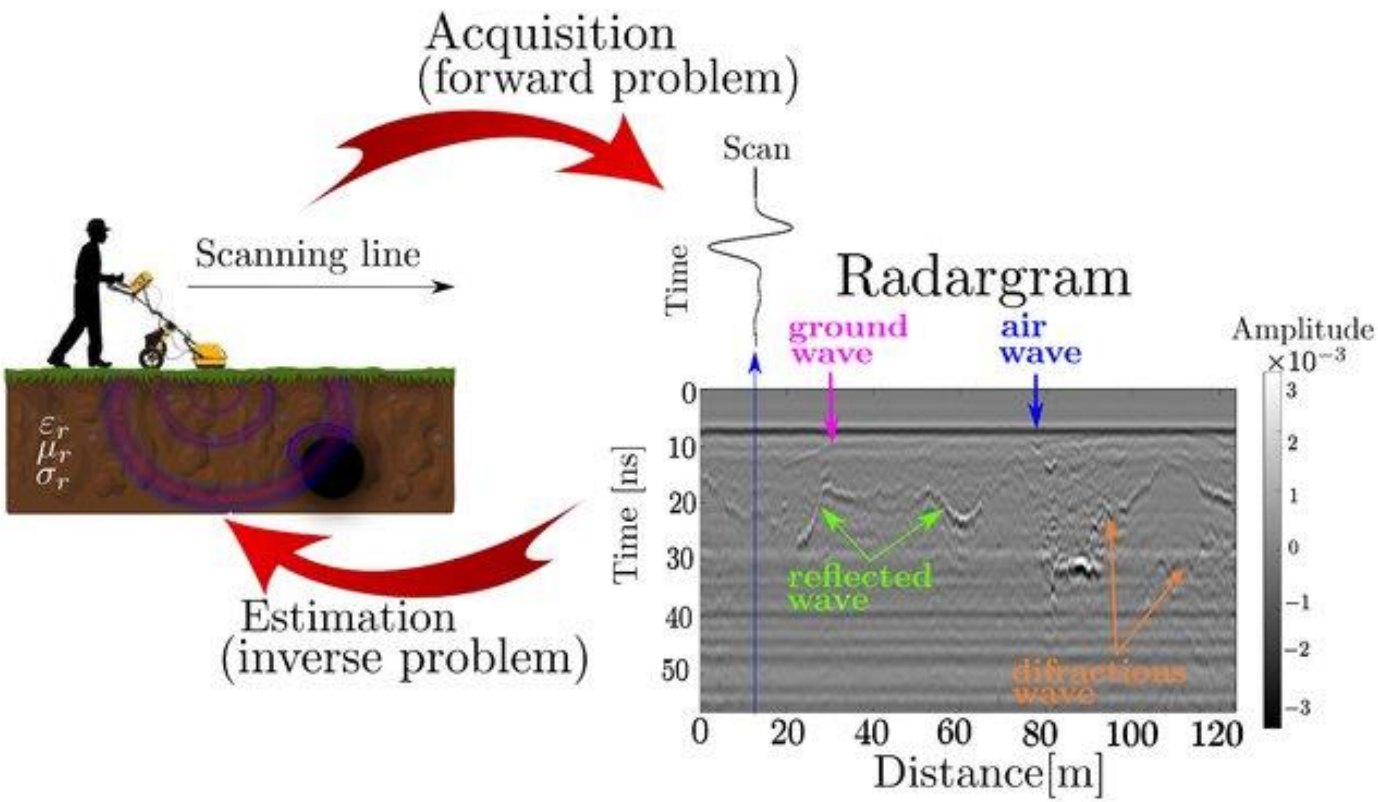


GEOPHYSICAL MODELLING AND INVERSION
(computerized representation of the Earth based on geophysical and geological observations)

Inversion procedure: Recording data “d” and predicting model “X”

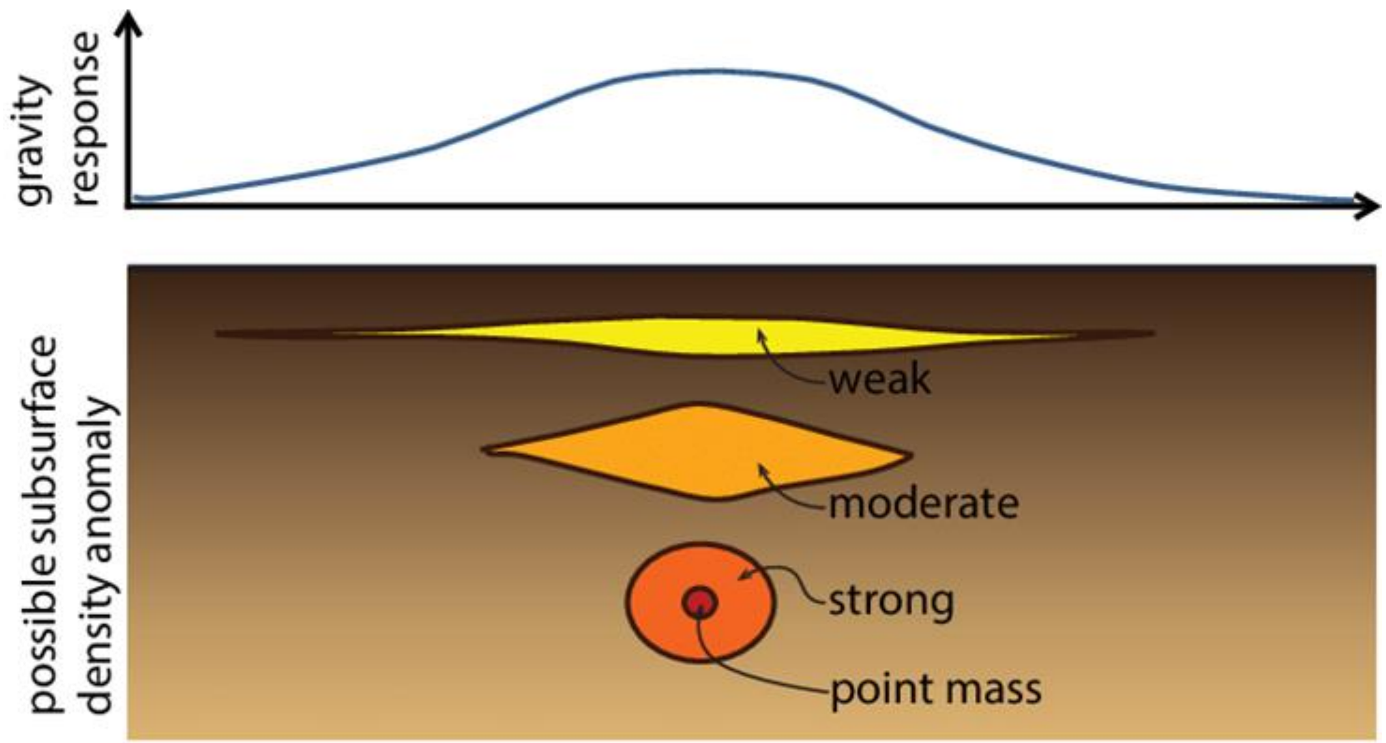


Forward modelling: Given a model “X” and predicting data “d”

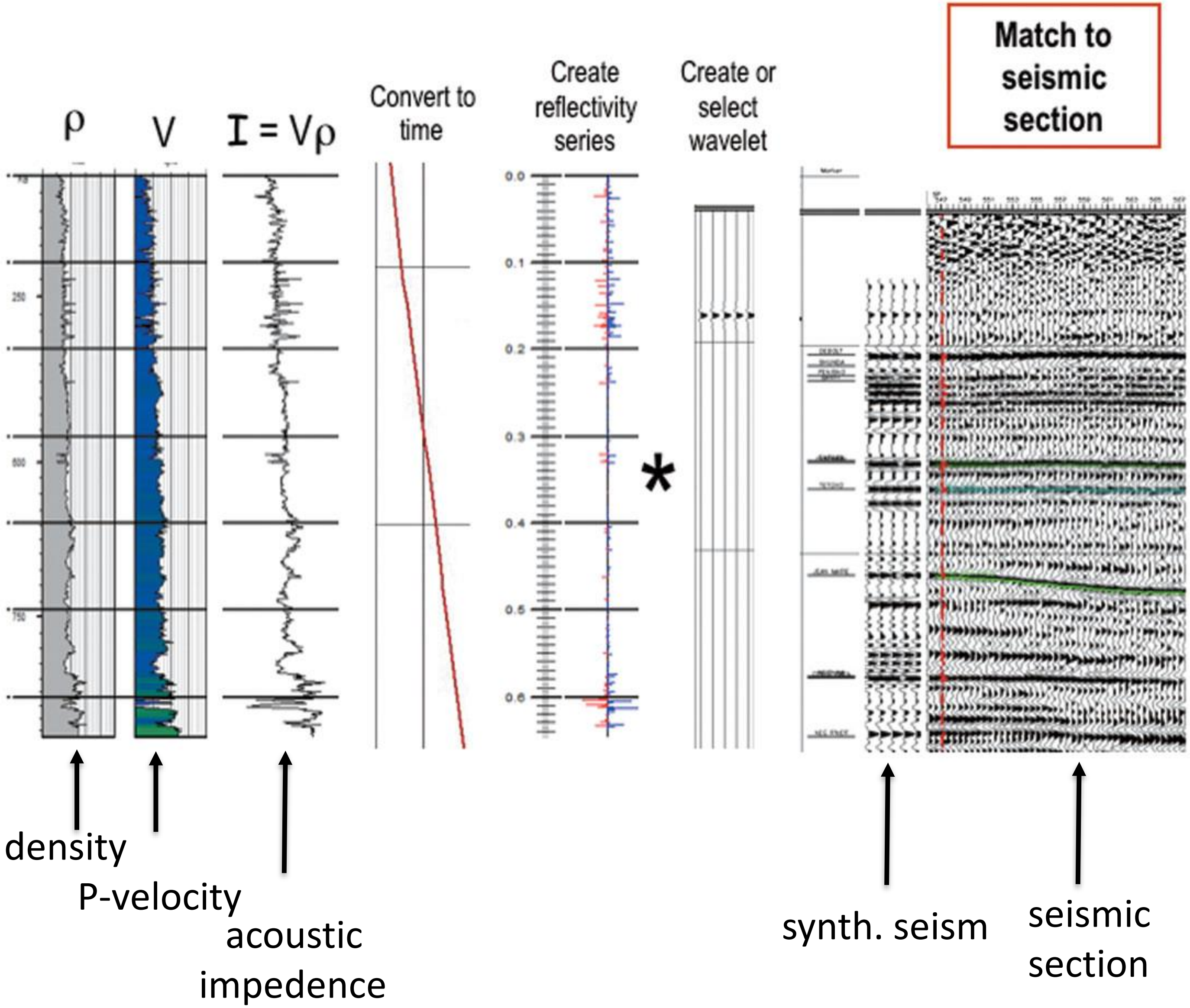


Geophysical inversion refers to the mathematical and statistical techniques for recovering information on subsurface physical properties from observed geophysical data

All geophysical (and geological) models are non-unique.
As an example, given only the gravity anomaly, the causative source is non-unique.
Additional information (e.g., seismostratigraphy from wells, geologic context, other geophysical data) are needed to narrow the solution space (constraints).



Example of forward modelling

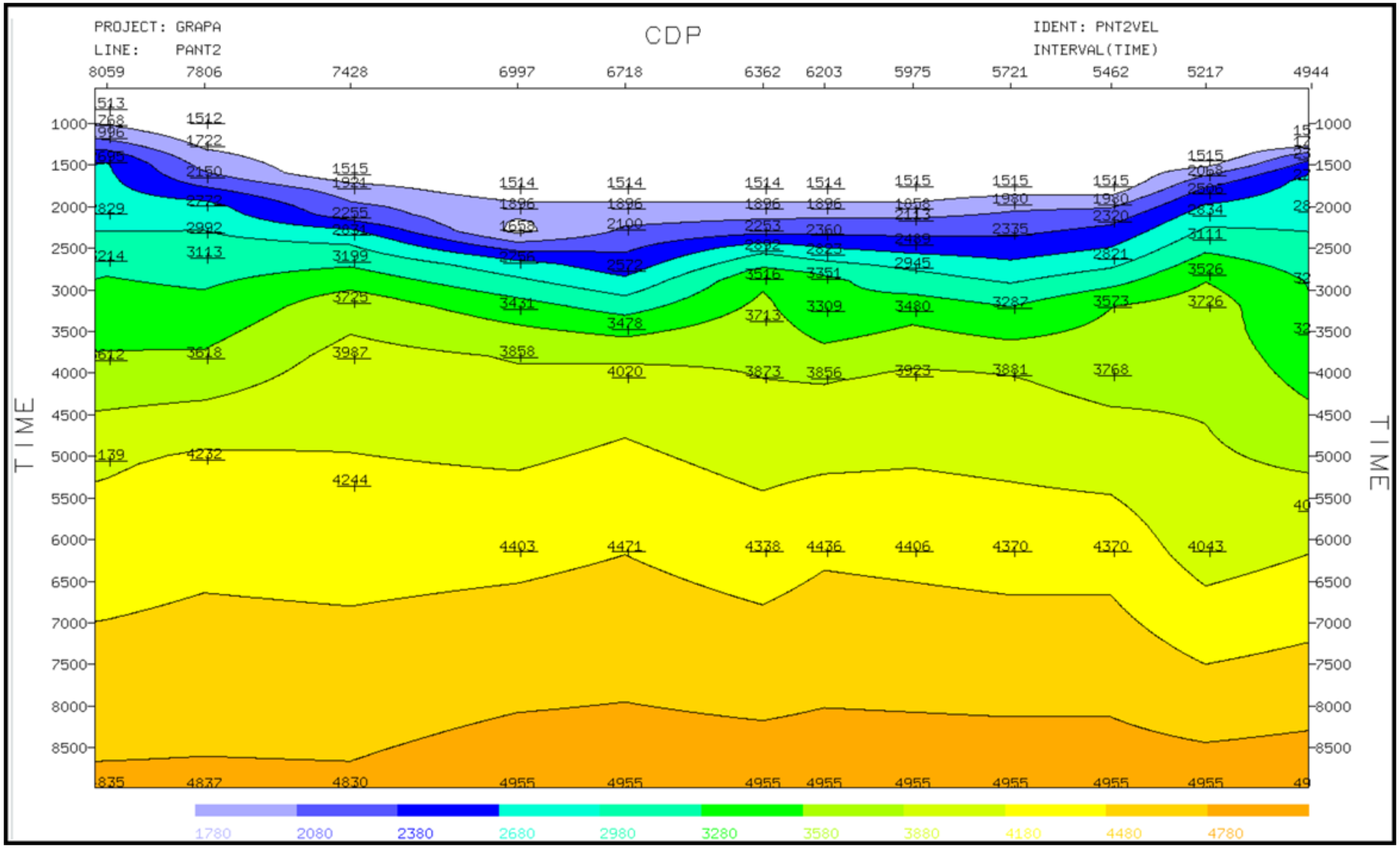


Synthetic seismogram

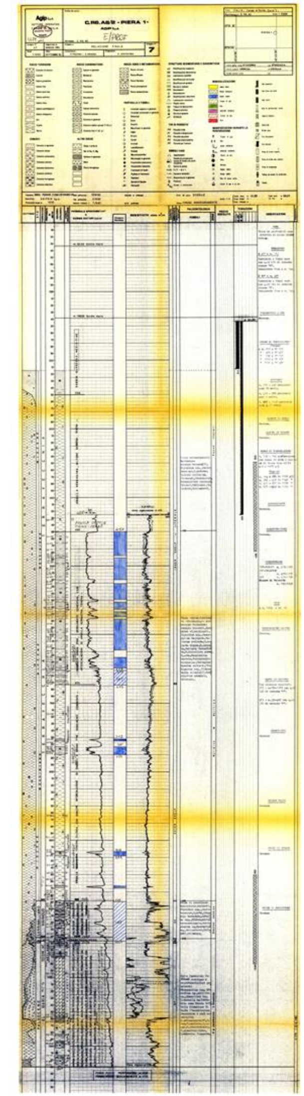
Modelling the seismic response of an input earth model (variations in physical properties).

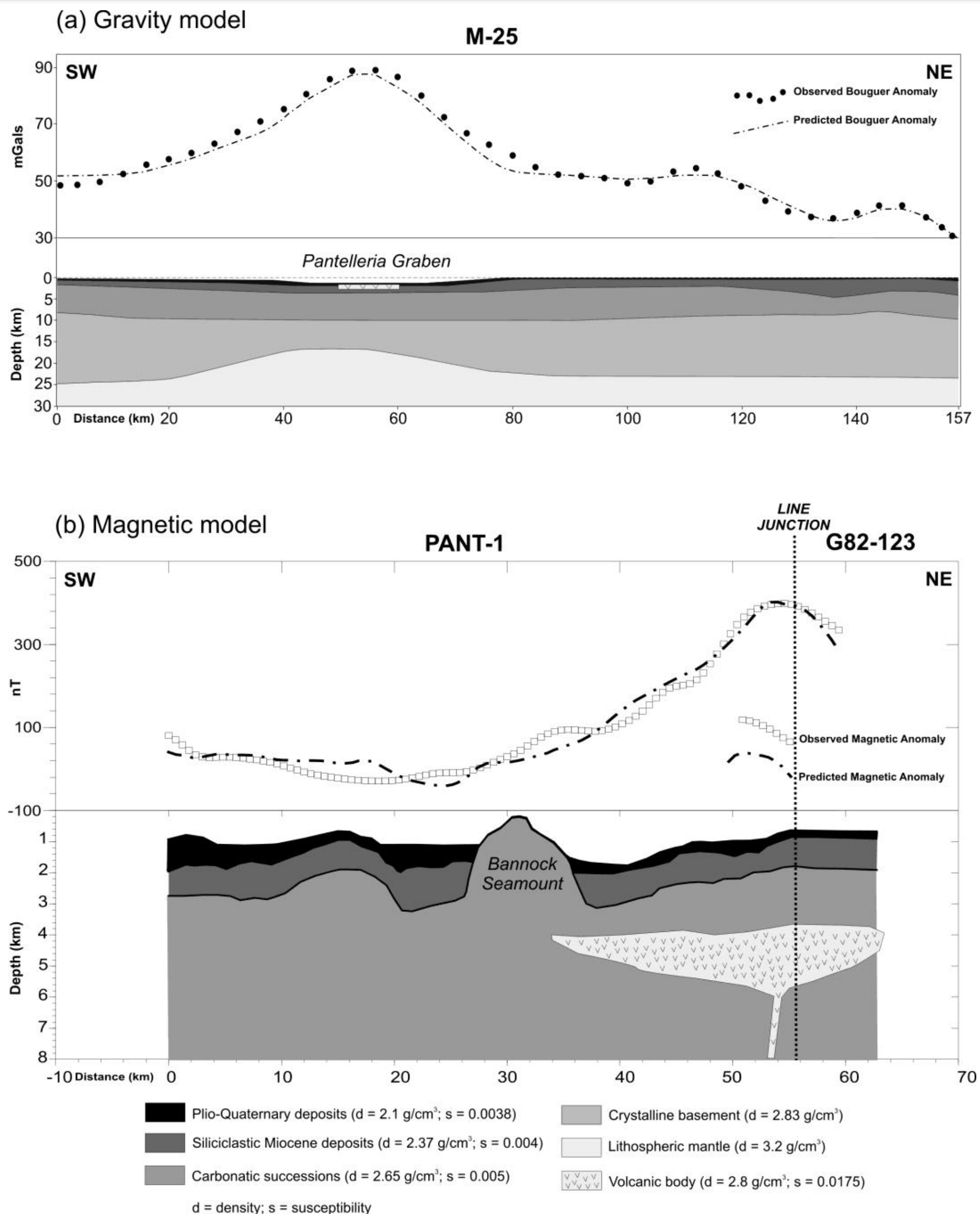
Widely used in hydrocarbon exploration to provide a 'tie' between changes in rock properties in a borehole and seismic reflection data at the same location.

Interval acoustic velocities



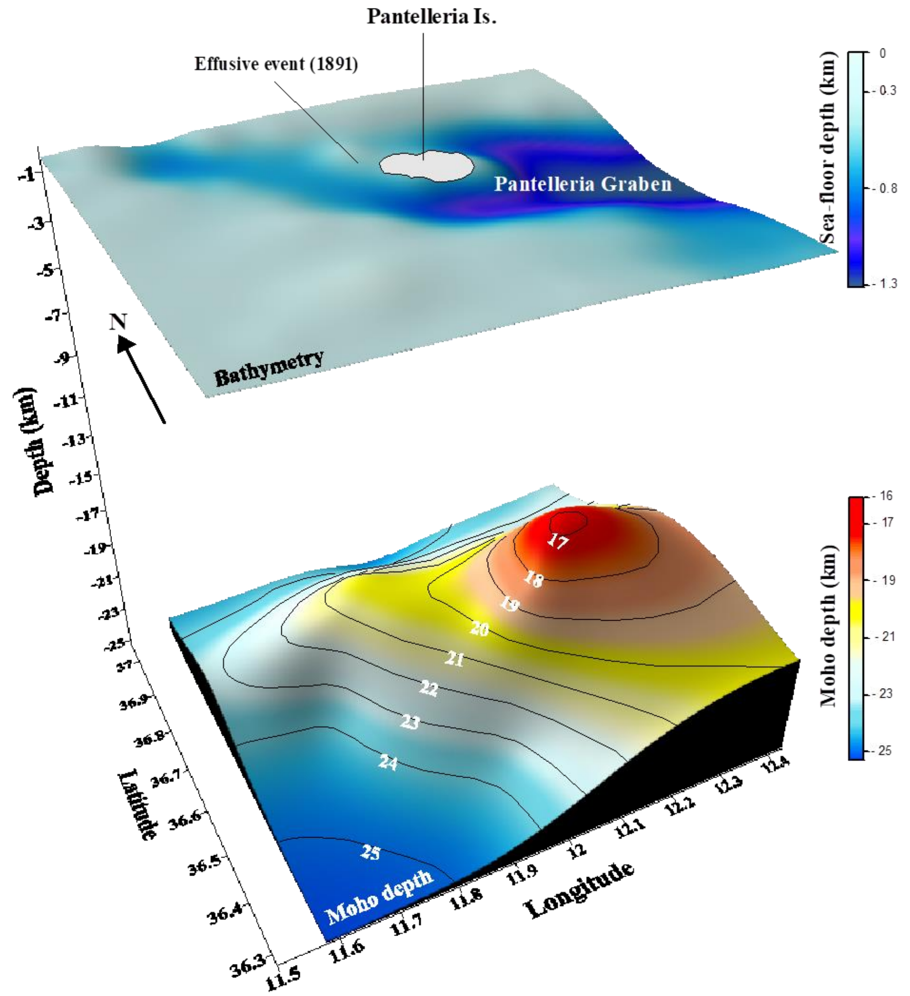
Piera 1 well



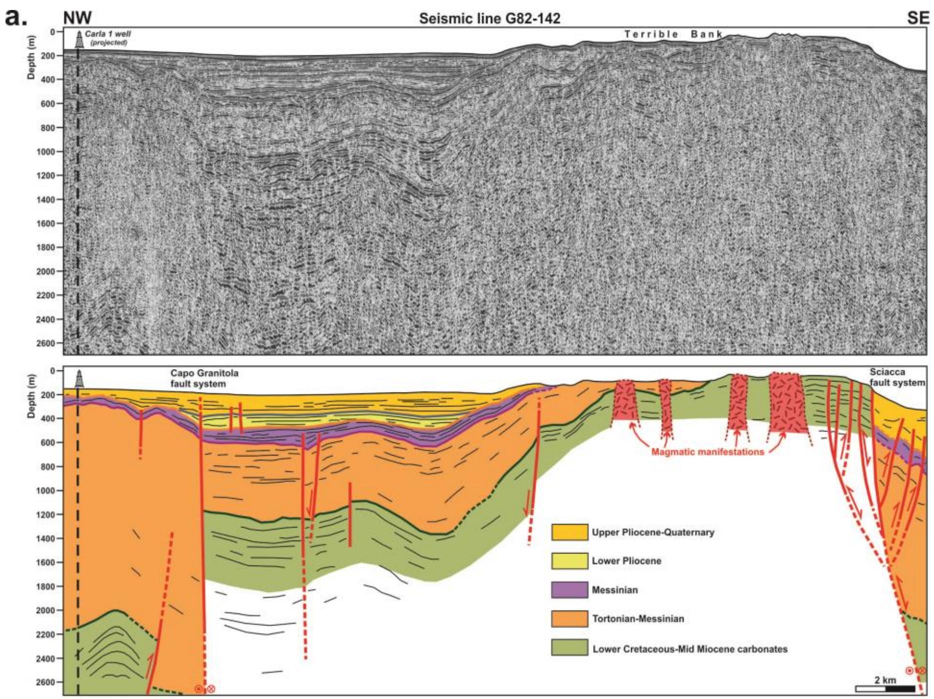


Gravity and magnetic modelling

3-D Moho depth geometry beneath the Pantelleria Island

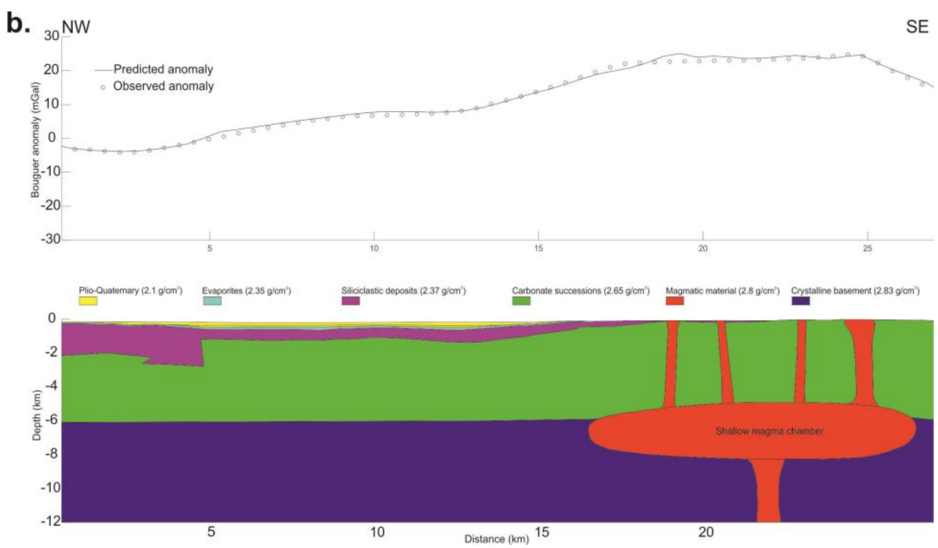


Schematic example of how to generate a crustal geological model from experimental geophysical information (seismic profile + gravimetric profile)



Acquired seismic data

Stratigraphic interpretation from well data (after seismic data depth conversion) – shallow model



Crustal geological model from inversion of observed gravity data - deep model

SUMMARY

- Sedimentary basins are repositories for sediment that are formed by crustal subsidence relative to surrounding areas
- Several different mechanisms can produce subsidence, but they can be grouped into two main categories: (1) Isostasy and (2) Loading

Sedimentary basins are found in many different tectonic settings:

- Divergent plate boundaries – rift/drift transitions (not all rifts lead to the opening of ocean basins)
- Passive margins, which have highest subsidence (primarily due to cooling) that increases seawards
- Strike-slip margins along which pull-apart basins develop
- Convergent environments (i.e., subduction zones)

- Geophysical and geological data needed for basin studies
- Inverse and forward modelling

SUGGESTED READINGS