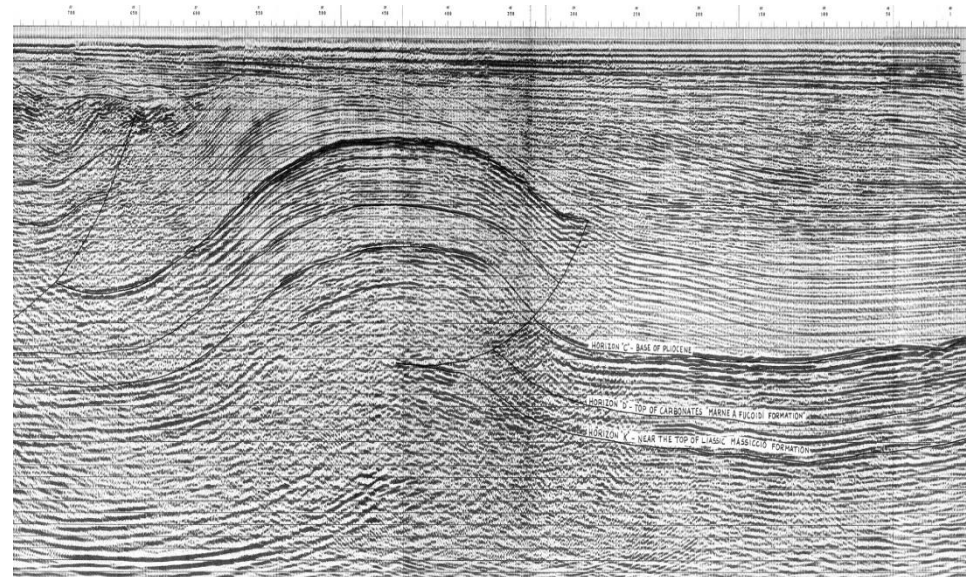
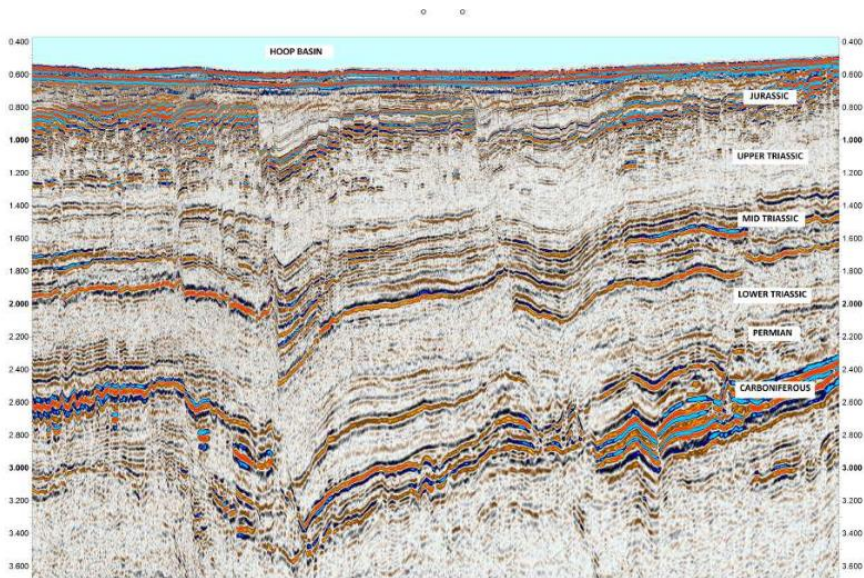


# Seismic Evidence of faults (systems)

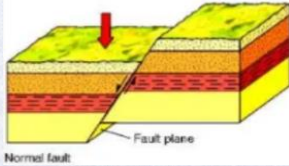
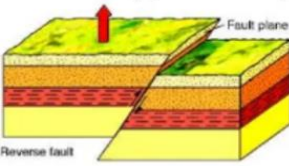
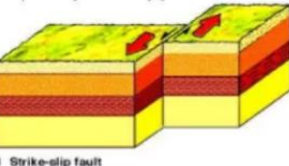

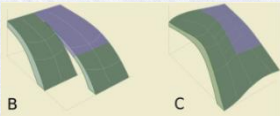
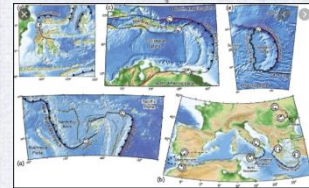
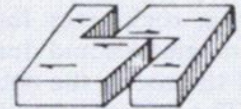
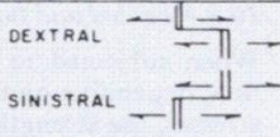
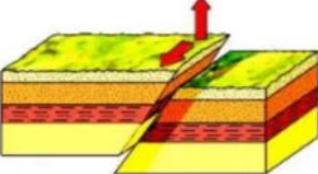
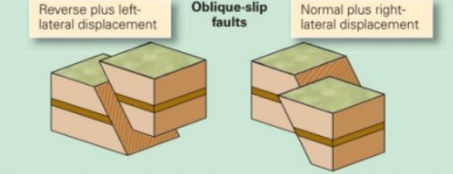
A tectonic regime is characterized by the presence of a more or less complex fracture system related to the brittle deformation of the sedimentary sequences, frequently, with a ductil component.



# Different types of faults

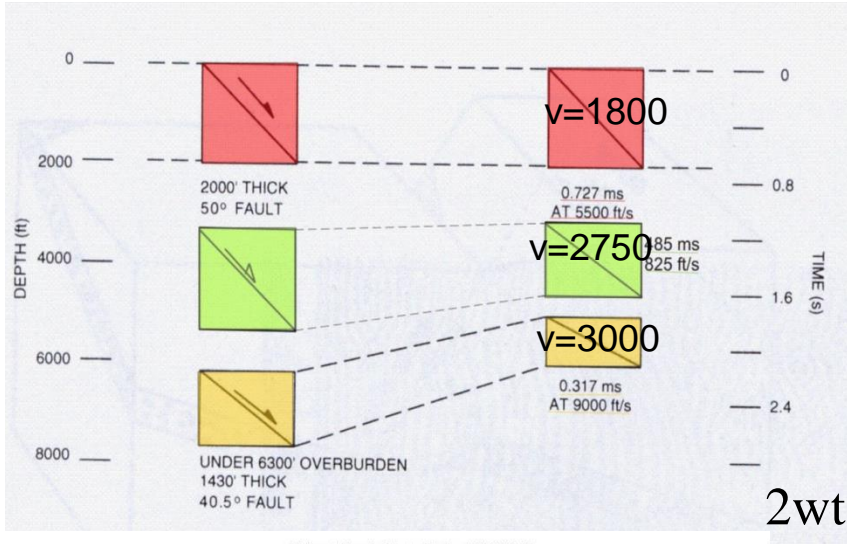
Faults can have very variable aspects along the seismic profiles: they can be seen as a reflecting surface or as a fracture system that interrupts the reflector continuity.

The inclination is apparent, depending on the P velocity and on the adopted scale (vertical exaggeration), on direction of profile respect on the one of the fault.

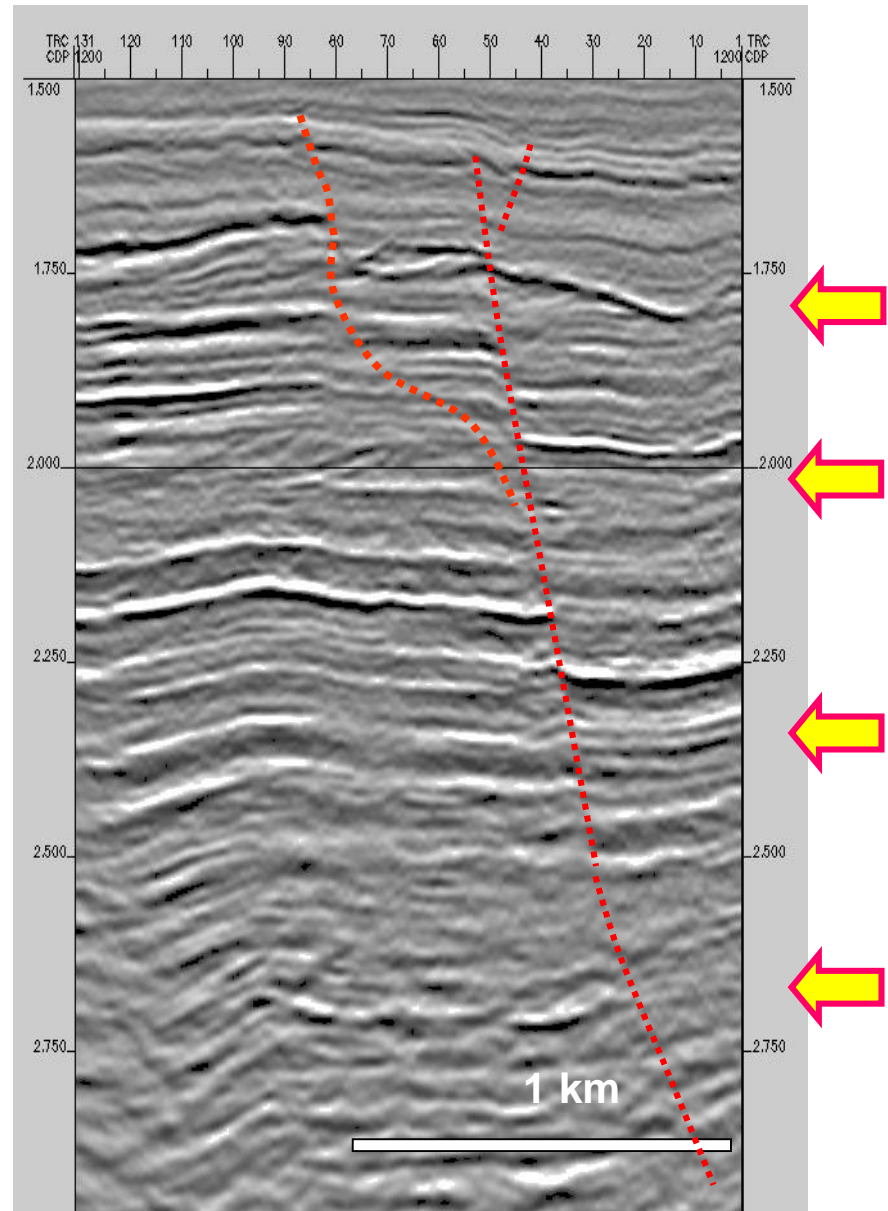
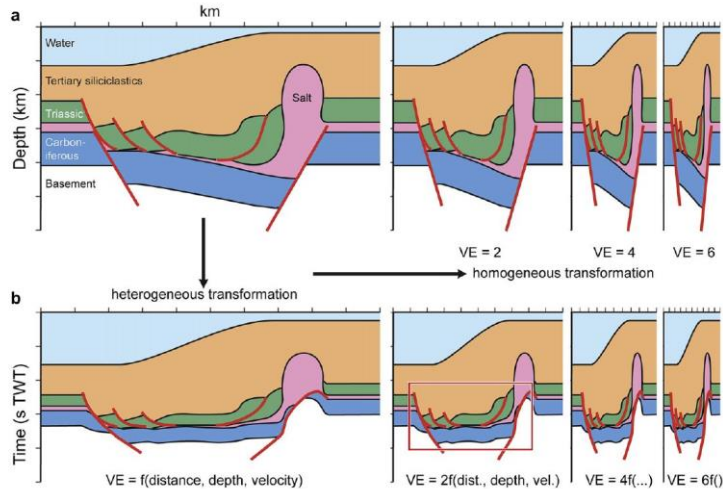
FAULT TYPE	RELATED TERMS	STRESS DIRECTION		CHARACTERISTICS
		MINIMUM	MAXIMUM	
 <p>Normal fault</p>	TENSION FAULT GRAVITY FAULT SLIP FAULT LISTRIC FAULT (CURVED FAULT PLANE)	HORIZONTAL (Tension)	VERTICAL (Gravity)	Dip usually 75° to 40°
 <p>Reverse fault</p>	THRUST FAULT LOW ANGLE (dip < 45°) HIGH ANGLE (dip > 45°)	VERTICAL	HORIZONTAL (Compression)	Fault plane may disappear along bedding thrust fault → faglie listriche
 <p>B Strike-slip fault</p>	TRANSCURRENT FAULT TEAR FAULT WRENCH FAULT RIGHT LATERAL (Dextral) LEFT LATERAL (Sinistral)	HORIZONTAL	HORIZONTAL	Fault trace often 30° to maximum stress
ROTATIONAL Tear fault 	SCISSORS FAULT HINGE FAULT 			Throw varies along fault strike; may vary from normal throw to reverse.
TRANSFORM 	DEXTRAL SINISTRAL 	HORIZONTAL		Associated with separation or collision of plates New material fills rifts between separating plates or one plate rides up on another if plates collide.
 <p>C Oblique-slip fault</p>	Reverse plus left-lateral displacement Oblique-slip faults Normal plus right-lateral displacement 			(c) Displacement on an oblique-slip fault combines dip-slip and strike-slip displacement. One block moves diagonally relative to the other.

**STEP: Subduction-Transform Edge Propagator**

# Rate between the real deepening faults and their deepening on the twt seismic profiles



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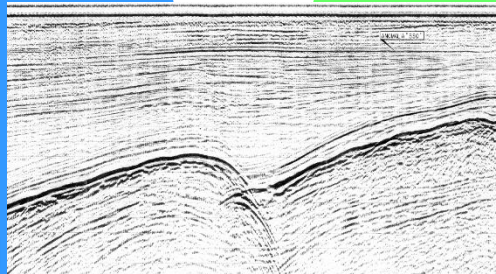


# Interpreting Faults



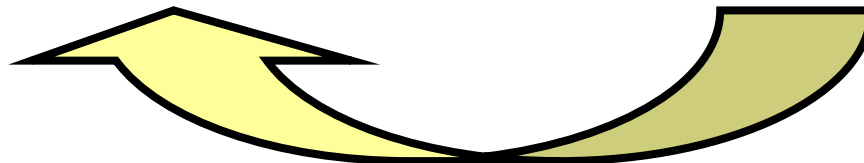
## *Structural Observations*

- Fault segments on seismic lines
- Fault plane orientation
  - Sense of motion
- Magnitude of offset
  - Range of depths
  - Relative timing
    - when faults moved
    - when structures grew



## *Structural Concepts*

- Tectonic Setting
  - Divergent zones
  - Convergent zones
  - Strike-slip zones
  - Mobile substrate
- How Structures Evolve
  - Fault-bend folds
  - Fault-propagation folds
  - Salt movement
  - etc.



# Fault recognition

Faults are recognized along the seismic profiles on the base of:

- 1 - *Fault cutoffs*: abrupt reflection termination or marked seismic attribute variation
- 2 - *Kink bands*: “piega a gomito” of strata
- 3 - Direct reflection from the fault plane.

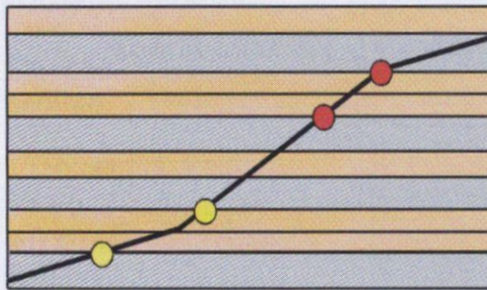
The 1 and 3 criteria give us directly the fault position;

All the 3 criteria, if recognized, are useful to identify and correctly interpret a fault.

## Fault cutoffs and kink-band terminations

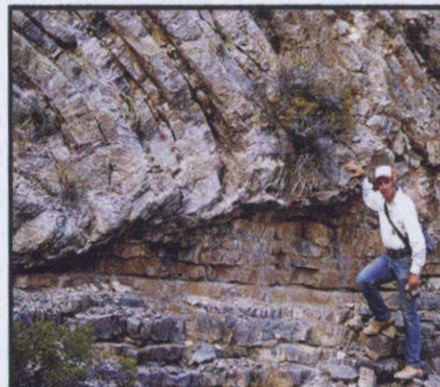
### *balanced model*

Incipient fault with markers along fault surface.

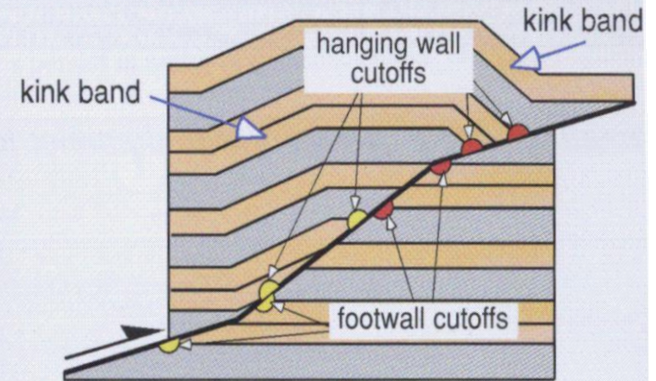


### *in outcrop*

Fault cutoffs in outcrop, Mississippian Joana limestone, Nevada, U.S.A.

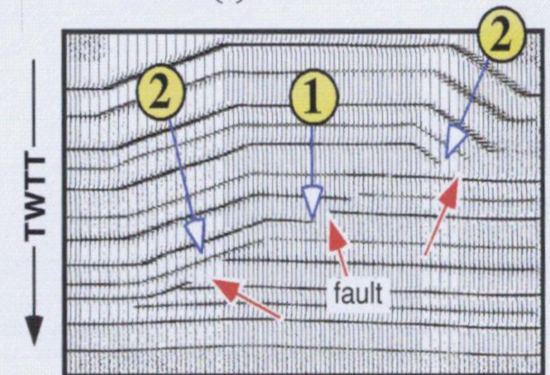


Fault with offset markers and cutoffs. Note that hanging wall kink bands terminate downward into the fault surface.



### *in synthetic seismic*

Seismic forward model showing fault cutoffs (1) and downward terminating kink-bands (2).



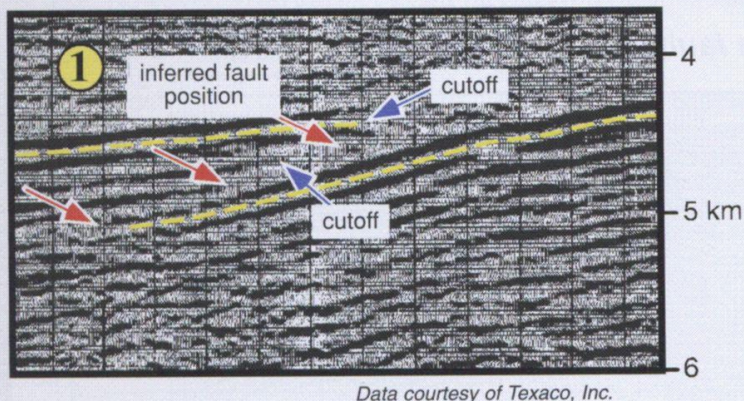
## Recognizing and interpreting faults in seismic section

Example of seismic profiles where we can recognize:

1 - *Fault cutoffs:*

2 - *Kink bands:*

3 - Reflection from fault plane

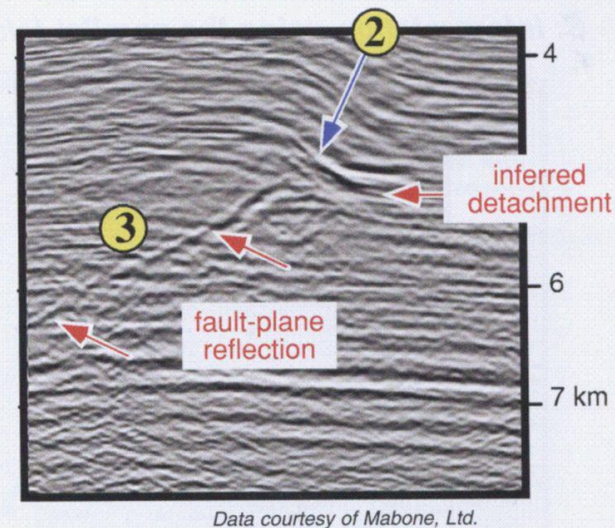
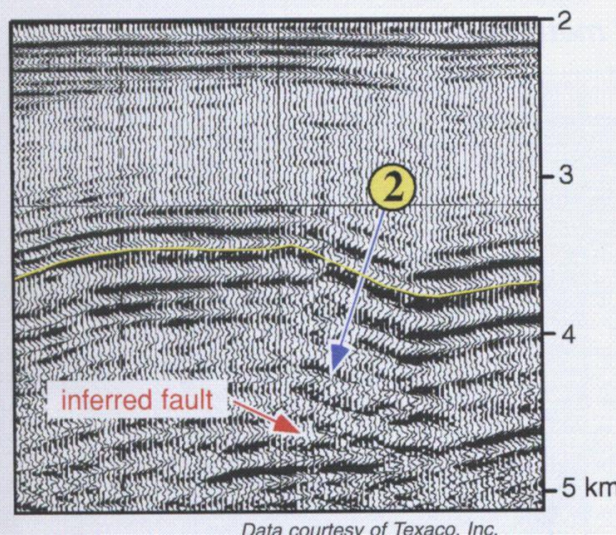


### ***fault cutoffs***

Abrupt terminations (cutoffs) and duplications of prominent reflections constrain the position of a gently dipping thrust fault. (2-D seismic data, Permian basin, Texas, U.S.A.)

### ***kink-band terminations***

Thrust faults and bed-parallel detachments can be identified by the abrupt, downward terminations of kink bands. Terminations are generally marked by regions of dipping reflections above horizontal or more gently dipping reflections, and may contain fault cutoffs. Dipping reflections in kink bands represent strata folded in the hanging wall of a thrust/reverse fault or detachment; whereas, horizontal or more gently dipping reflections represent footwall strata below the fault or detachment. Thus faults and/or detachments should be interpreted at the transition between these two dip domains.

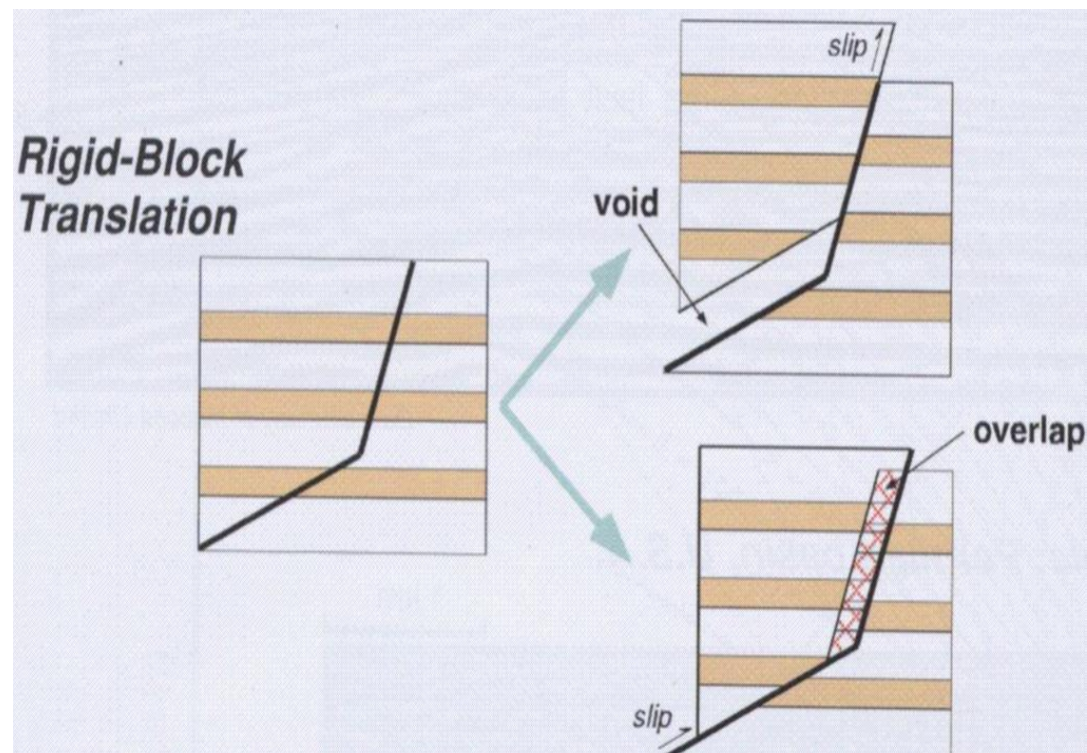


# Fault-bend folds

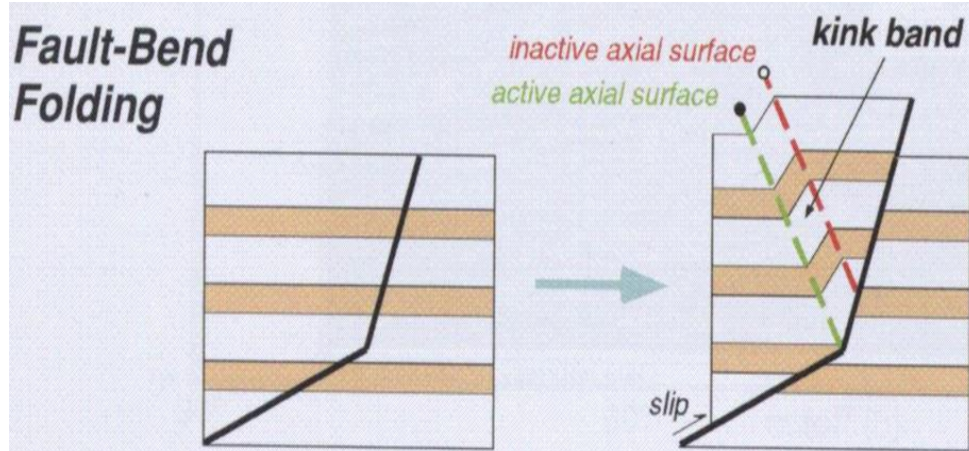
(bending of fault blocks as they ride over non planar fault surfaces)

These folds origin when the *hanging wall* moves above a fault kink.

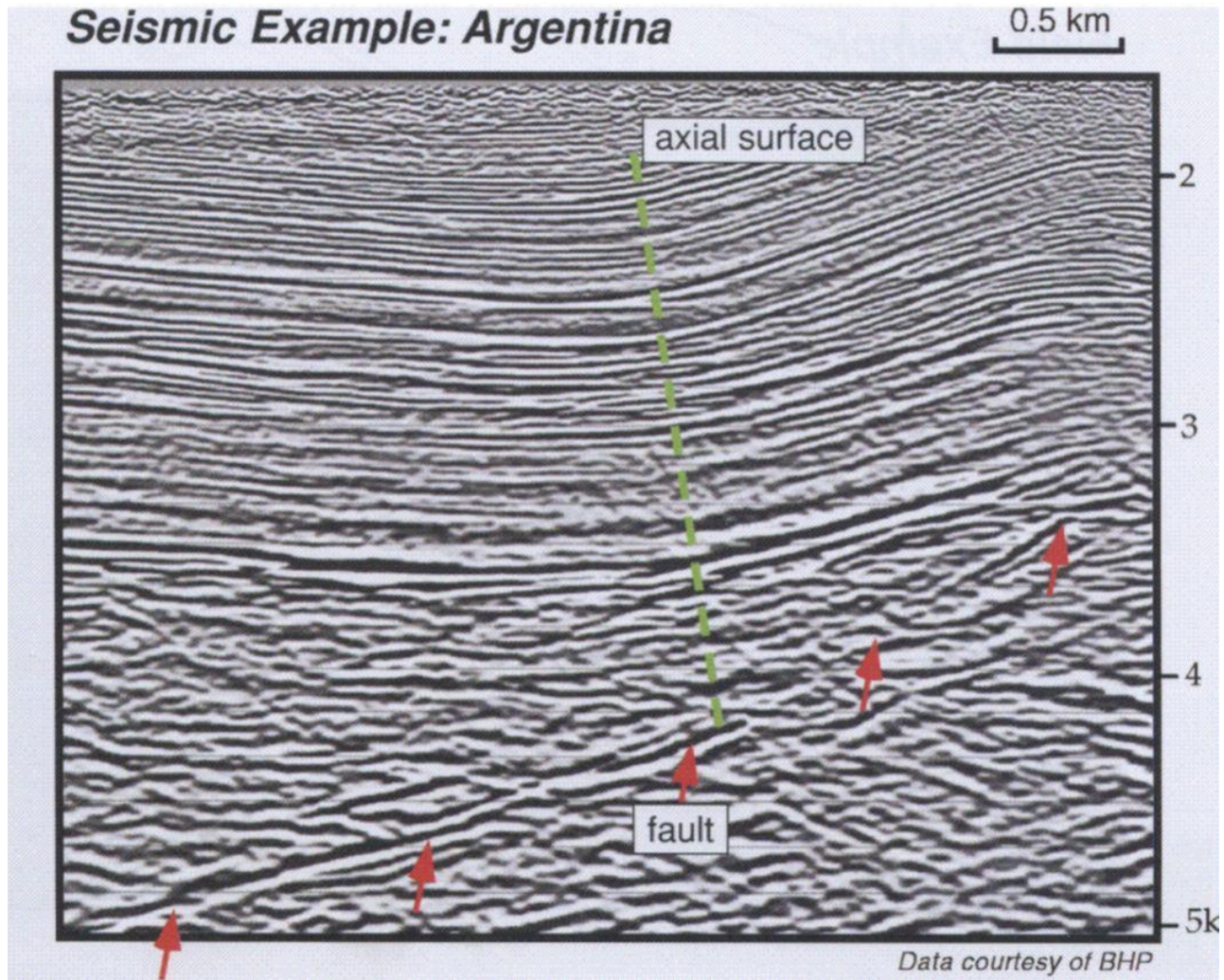
Sliding along different segments of fault, the translation of a rigid block would produce a gap or an overlap between the two blocks separated by the fault. Both of these situations are not feasible in reality.



Accommodation is achieved by forming a fold in the *hanging wall block*, located along an **active axial surface**, while the **inactive axial surface** identifies the active surface during the first phase.



# *Fault-bend folds – example*



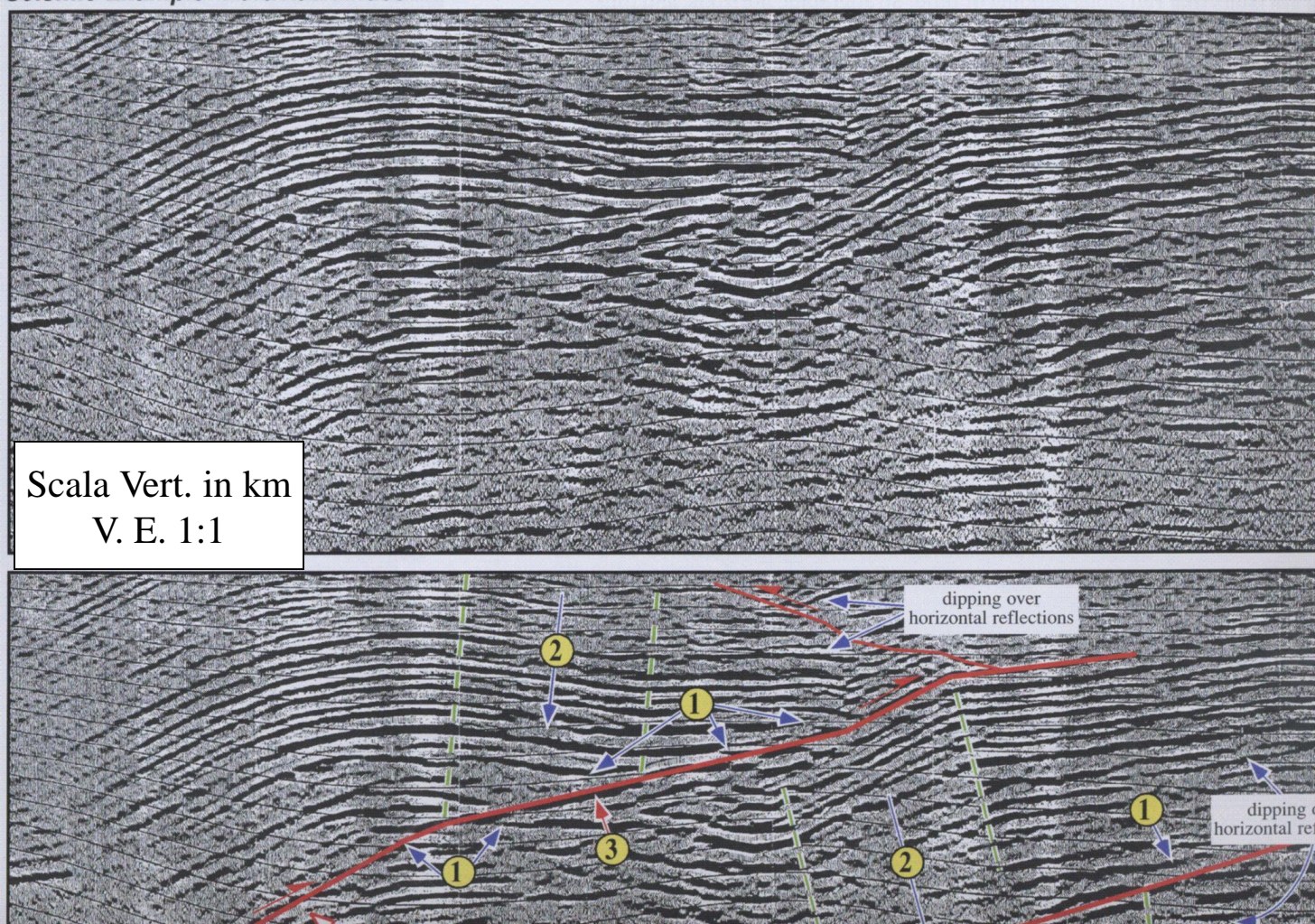


Example of interpretation of an inverse fault, based on recognition of:

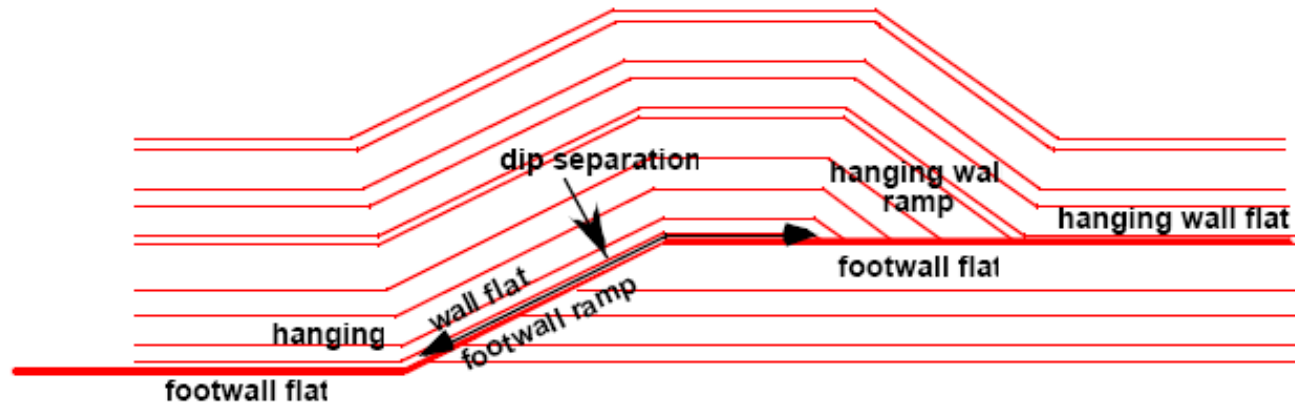
1 - *Fault cutoffs*

2 - *Kink bands*

3 - Reflection from the fault plane



## “flat & ramp” geometry



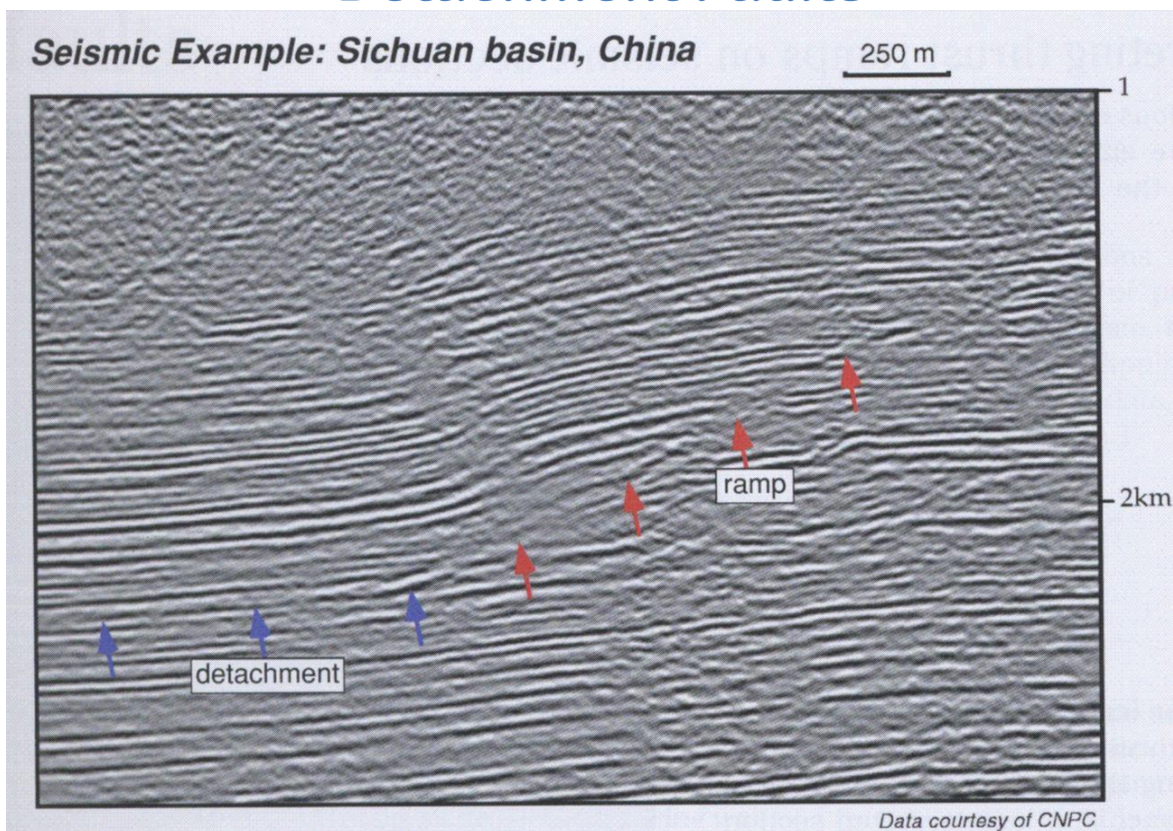
The thrust planes generally tend to be arranged:

- parallel to stratification (flat) in less resistant sediments, such as evaporites or clays

- cutting the stratification (ramp) in the most resistant sediments, such as limestone, sandstone, etc.

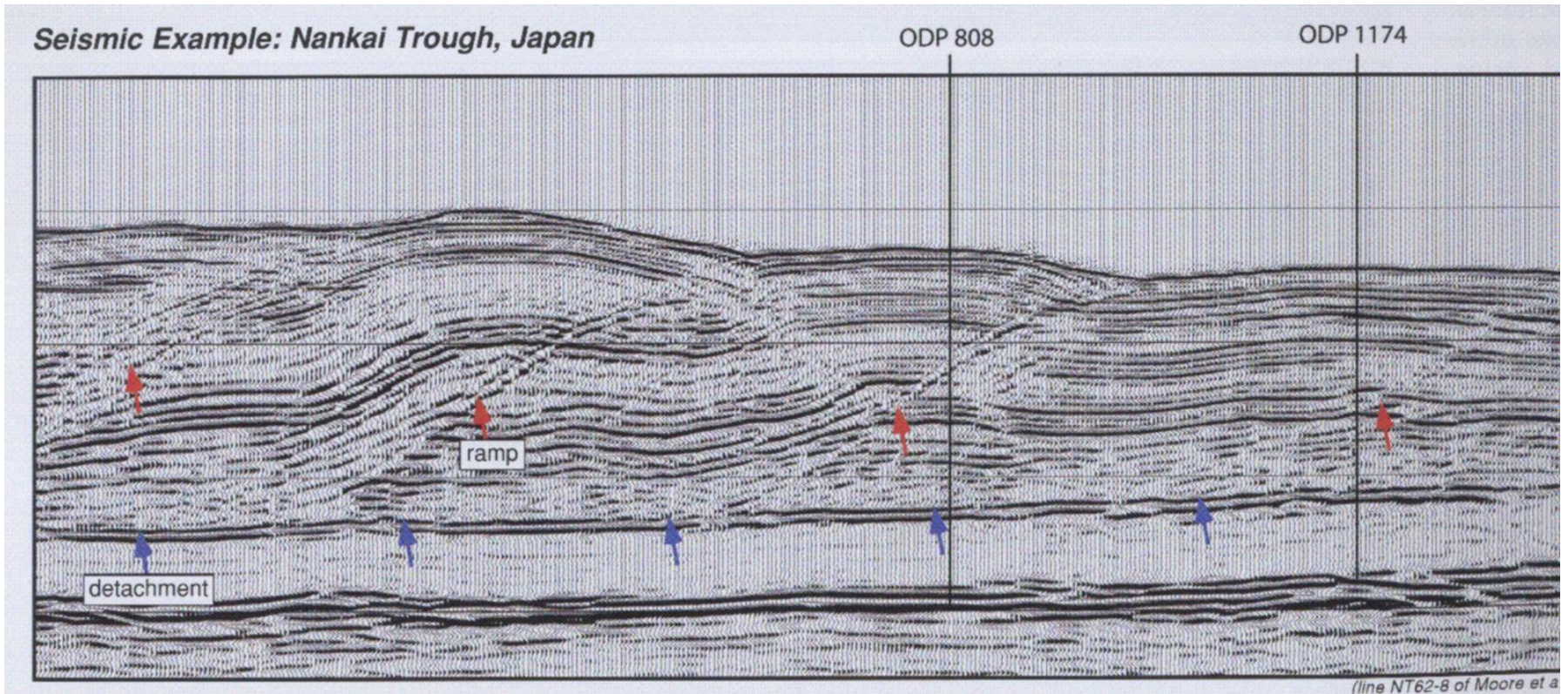
This often determines an alternation of sub-horizontal and inclined sections of fault, for variable lengths.

## *Detachment Faults*



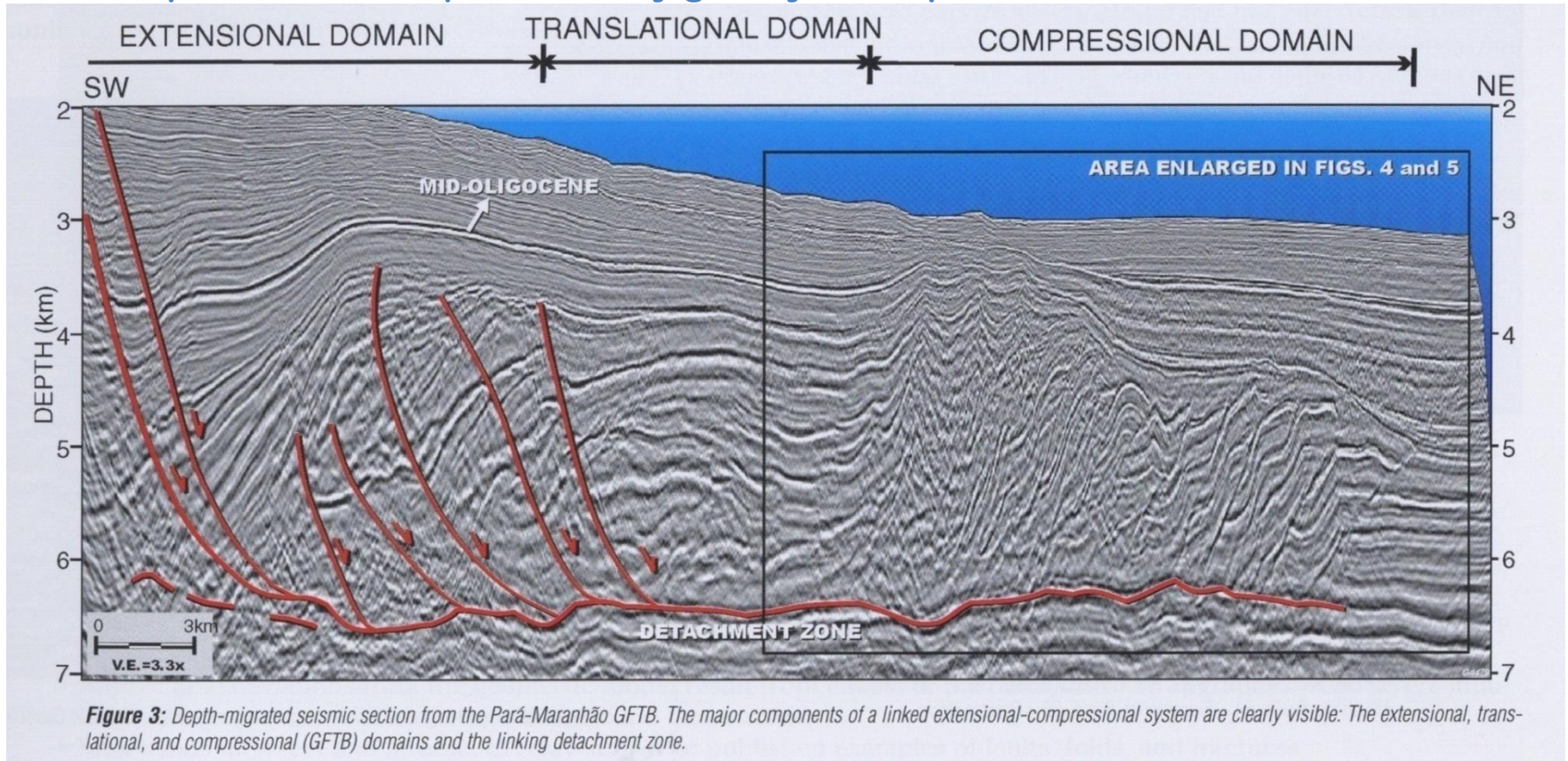
Detachment faults lie along one or more stratigraphic horizons, therefore with a horizontal or slightly inclined setting. In fold and thrust chains, they are also referred to as "decollement". They are not always directly interpretable along seismic profiles (they coincide with a lithological discontinuity), but they can be deduced at the base and/or at the top of the thrust ramps.

## Example of *detachment* along a seismic profile (reflector evidenced by the blue arrows)

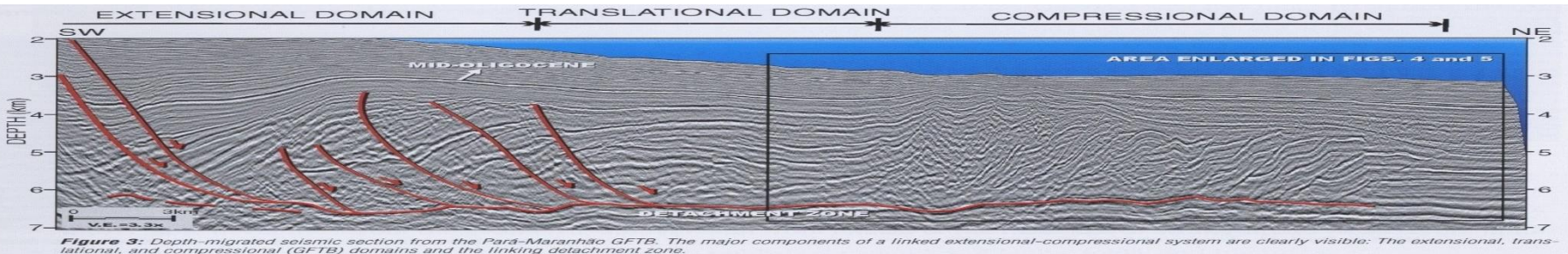


The red arrows evidence the “*ramps*”

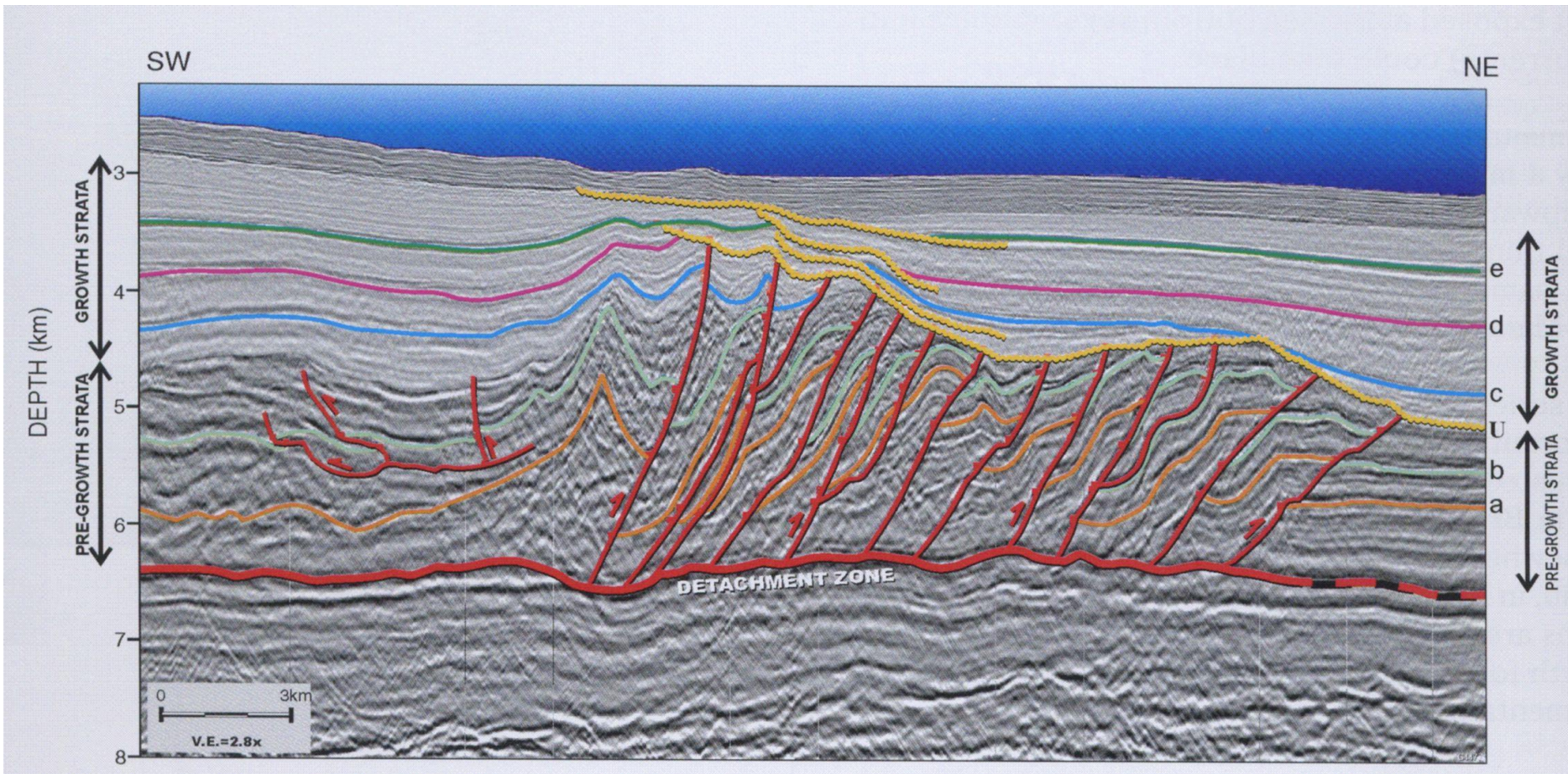
# Compressive faults produced by gravity: example from the Brazilian offshore



The *detachment* represent the decollement surface related to the extensional/gravitation tectonics (on the left) and compressive tectonics (on the right). Below is the same profile without vertical exaggeration.

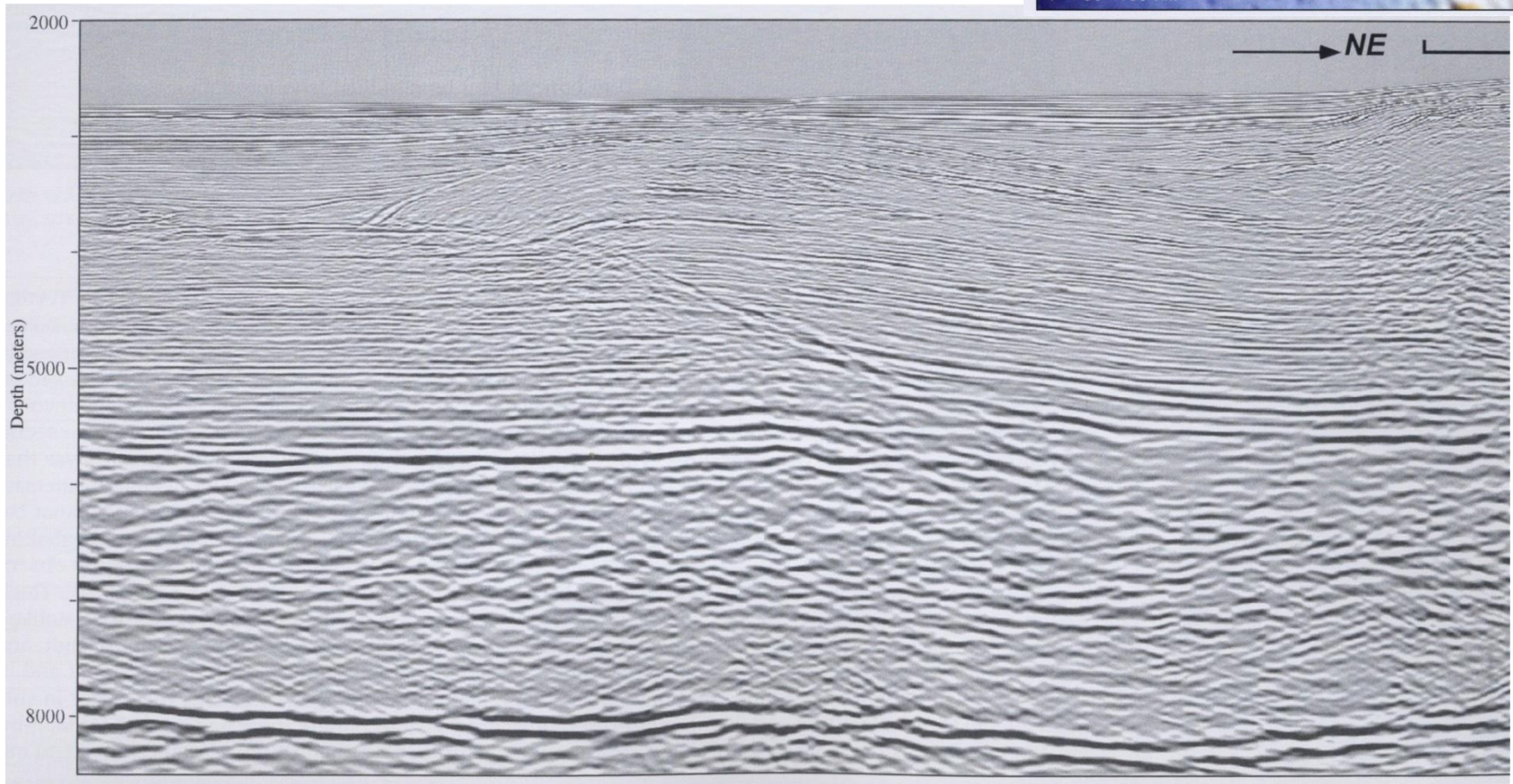
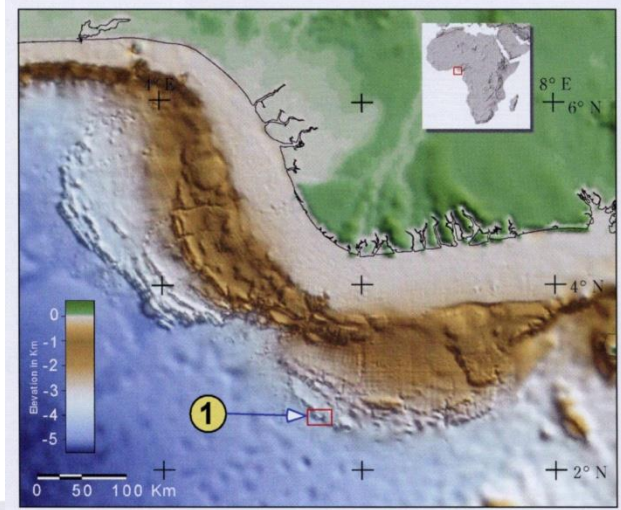


# Detail of the previous slide: compressive domain



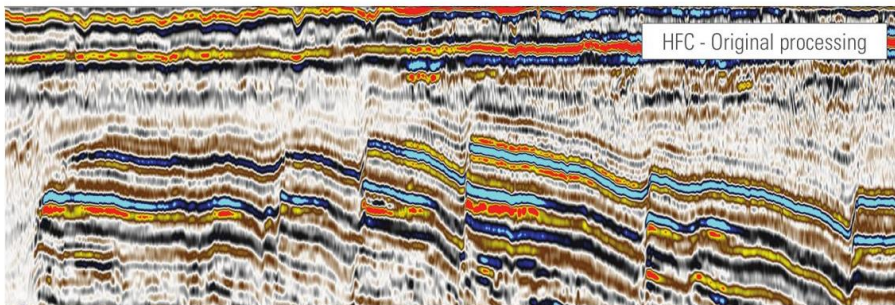
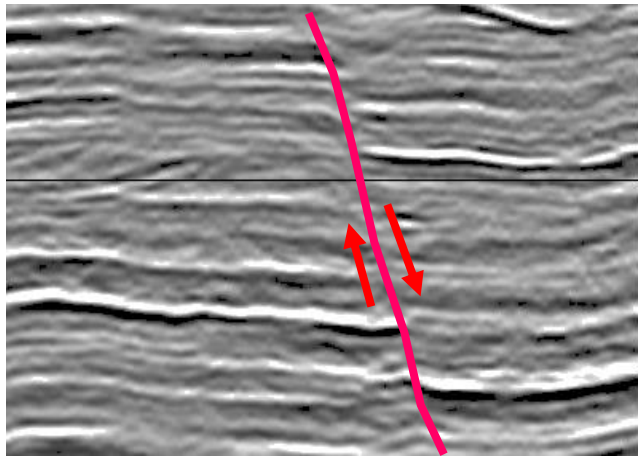
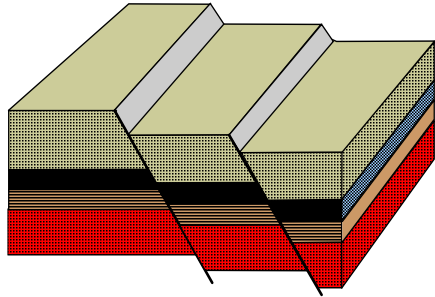
Compressive faults produced by gravity, example in the Niger delta:

the marine clastic deposits, of Cretaceous-Present age, lay above oceanic crust or above blocks of thinned continental crust. The compressive structures are due to gravitative collapse, that is active upstream, along the continental slope.

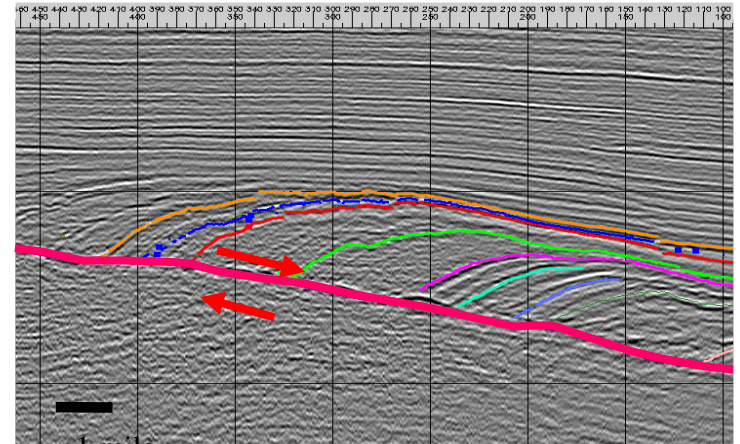
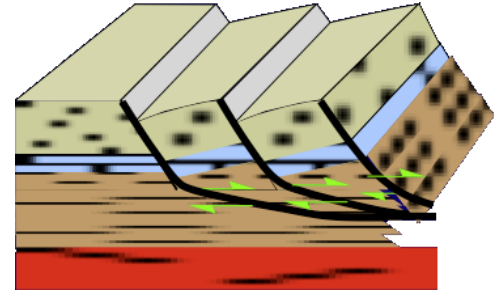


# Normal faults

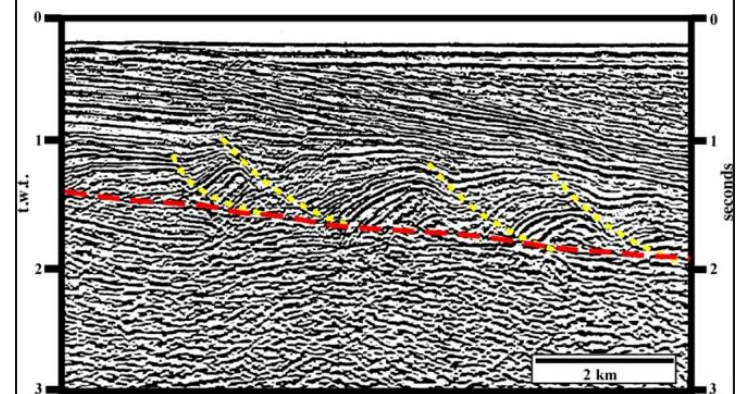
## Planar



## Listric



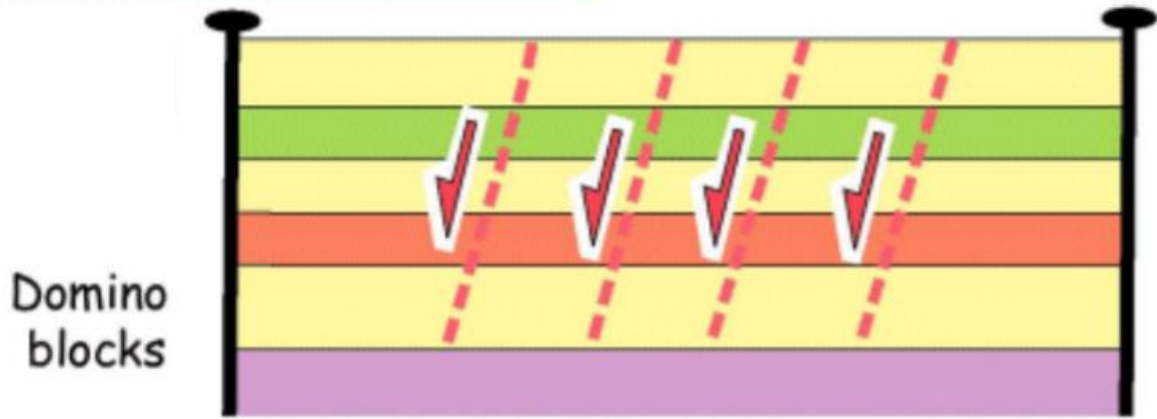
### Detachment Surface



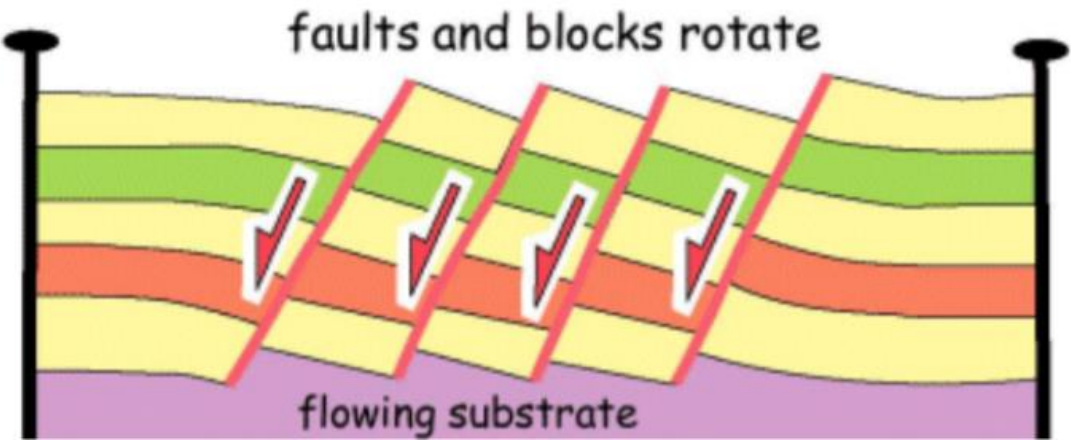


# domino system

## Planar Normal Faults



example

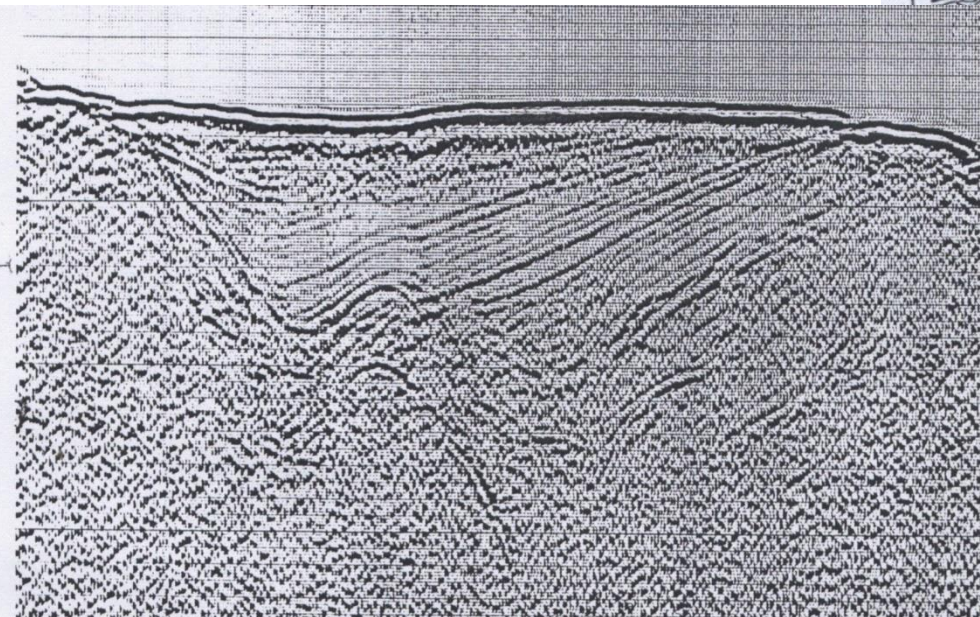
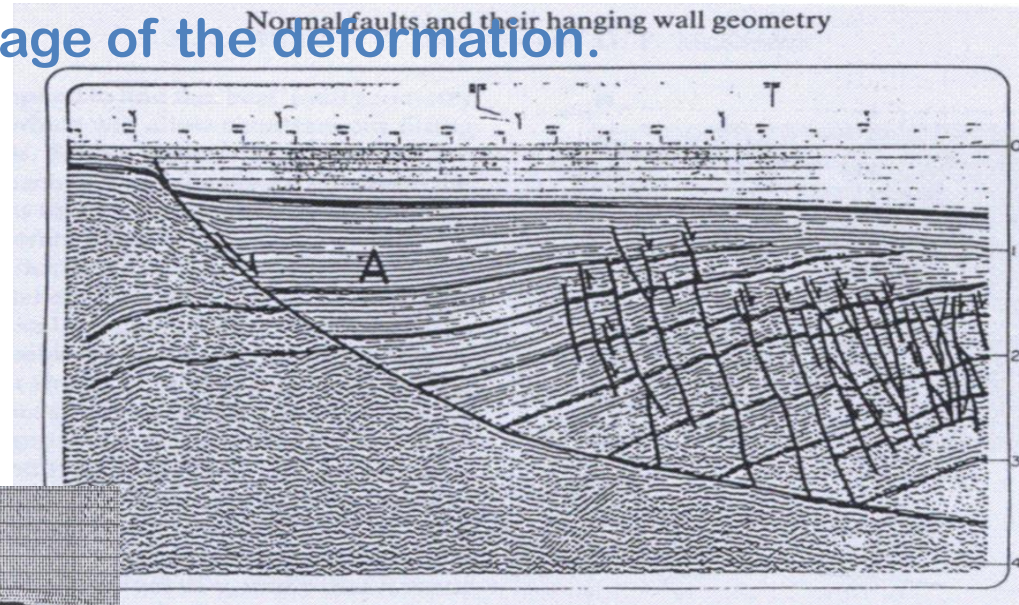


# *GROWTH (o SYNTECTONIC) STRATA*

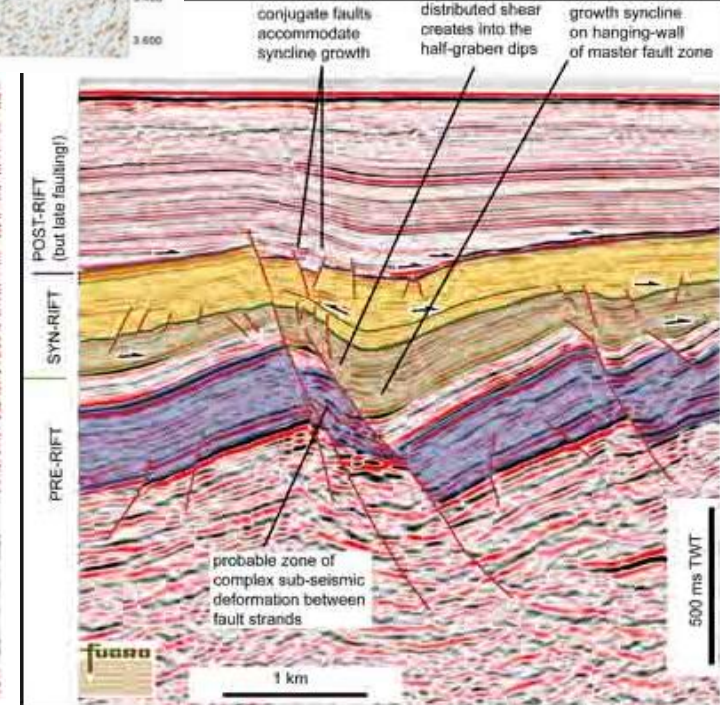
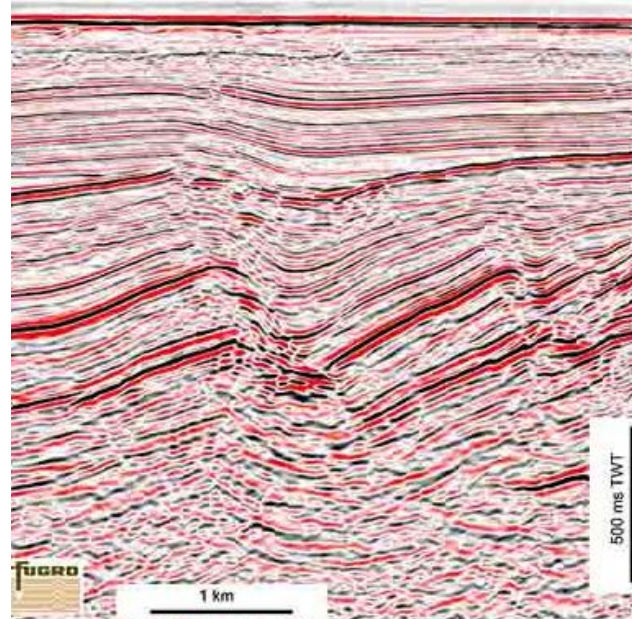
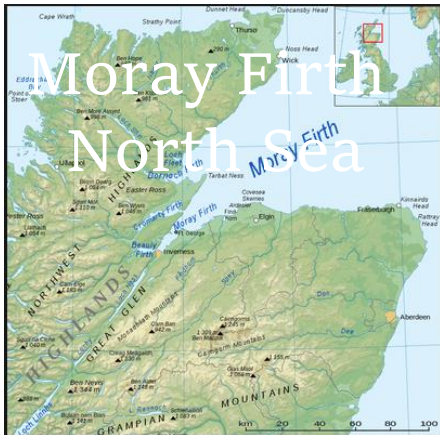
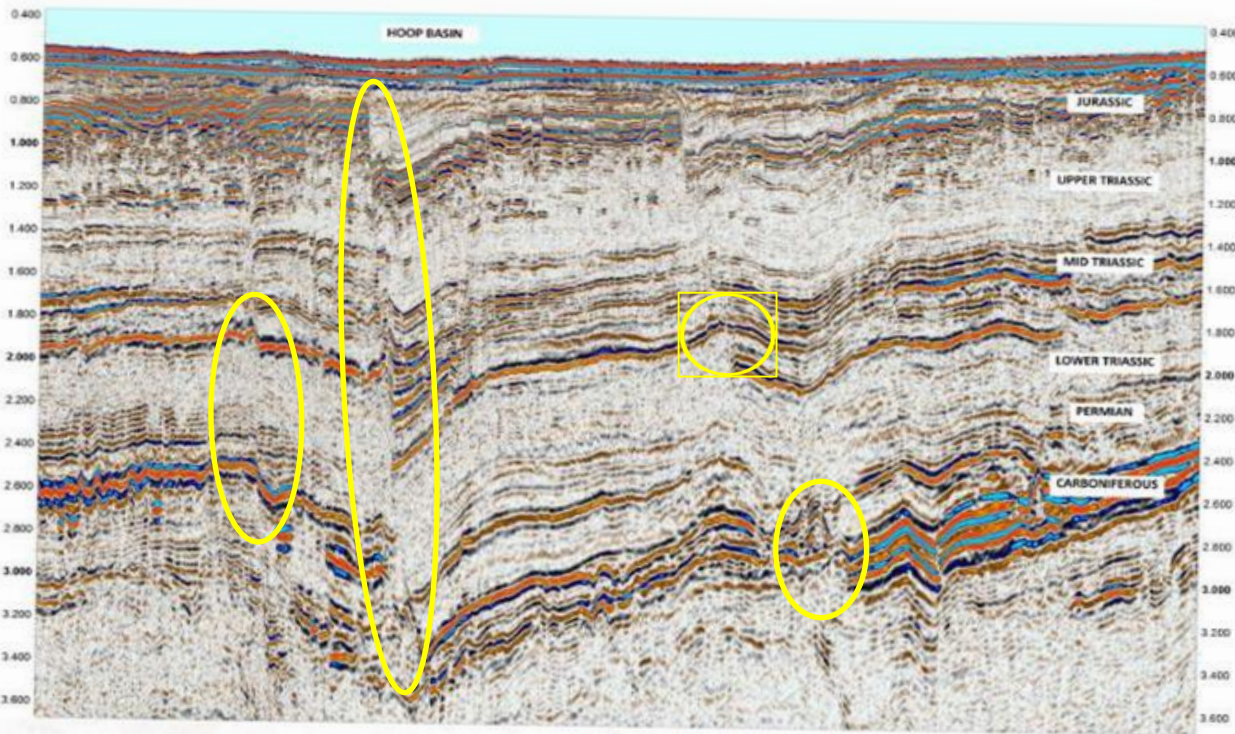
They are stratigraphic intervals deposited during the deformation.

Their age defines, therefore, the age of the deformation.

An extensional regime produces a characteristic **sedimentary wedge**: in this context, *tuning* phenomena can assume a great importance.



To the left:  
sintectonic  
sedimentary wedge  
in the west Ionian  
Sea, testifies a  
deformation with an  
extensional  
character.



Del Ben Anna - Interpretazione Sismica - Faglie

# Example of a *Growth Stratum* in the Southern Appennine

Il *growth stratum* is evidenced by the yellow (sintectonic) arrow: to the left with *pinch-out* terminations, to the right with *on-lap* terminations. The sub-horizontal overlaying sequence, with *on-lap* termination on both the sides, follows the tectonic phase.

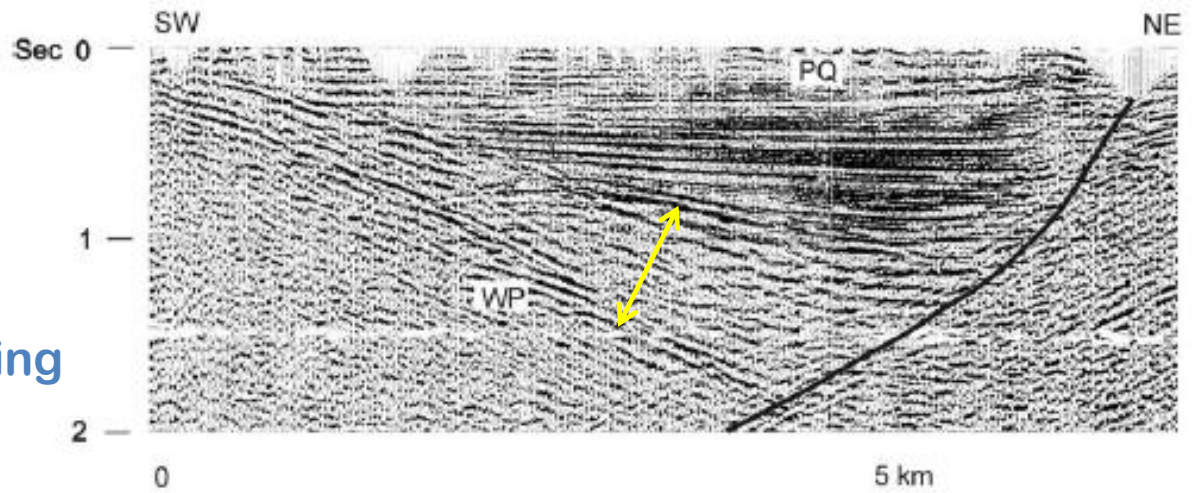
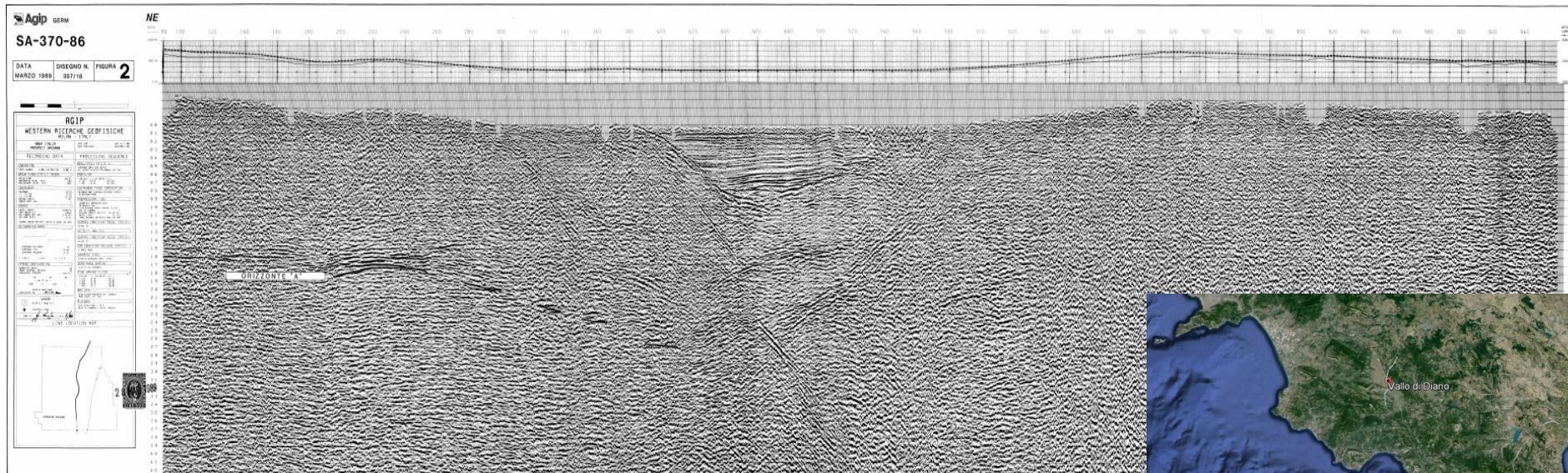


Figure 9. Seismic line over the Vallo di Diano Basin.



# GROWTH o SYNTECTONIC STRATA

In regime compressivo i *growth strata* si assottigliano verso l'alto strutturale.

La variazione laterale di spessore denota la sedimentazione sintettonica.

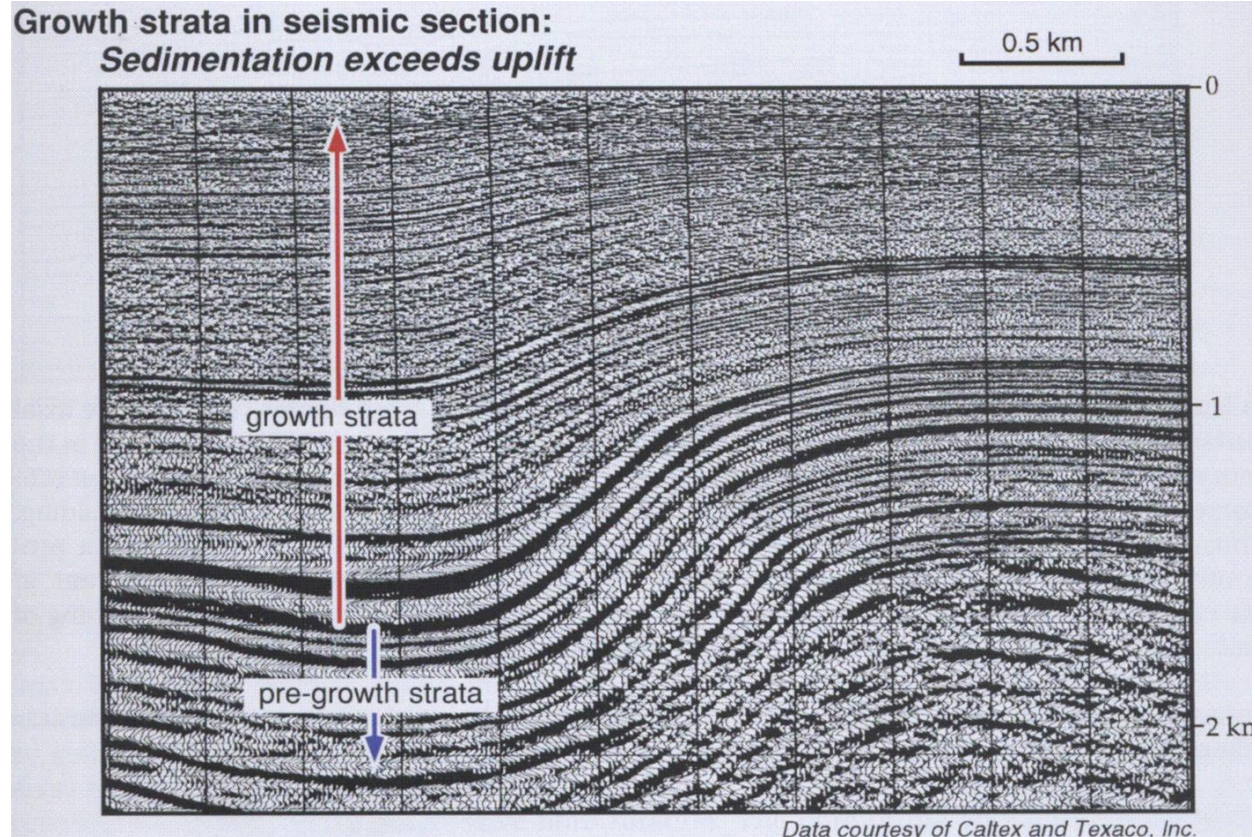
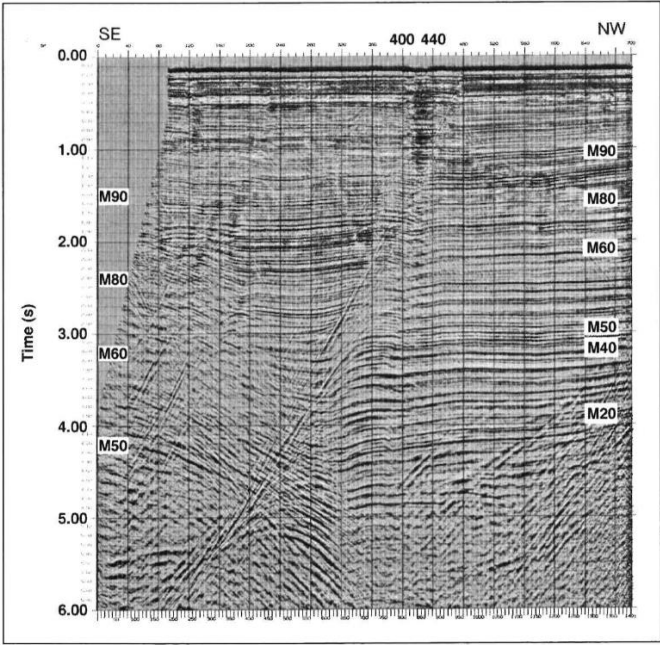


Fig. 2.

This is a full offset stack section of a proprietary data line, which is a dip line across a major fault. The stratigraphy is annotated to highlight the major growth intervals. Note the area of shallow gas and associated multiples between shotpoints 400 and 440.



# Importance of depth conversion/migration in imaging a prospect

Fig. 3.

An iso-velocity plot of the stacking velocities clearly displays the slower velocities in the hanging wall section, when compared to the equivalent times in the footwall. Also, the stacking velocities vary rapidly between shotpoints 330 and 480 because of the nonhyperbolic moveout of the ray-paths in the gathers across the fault.

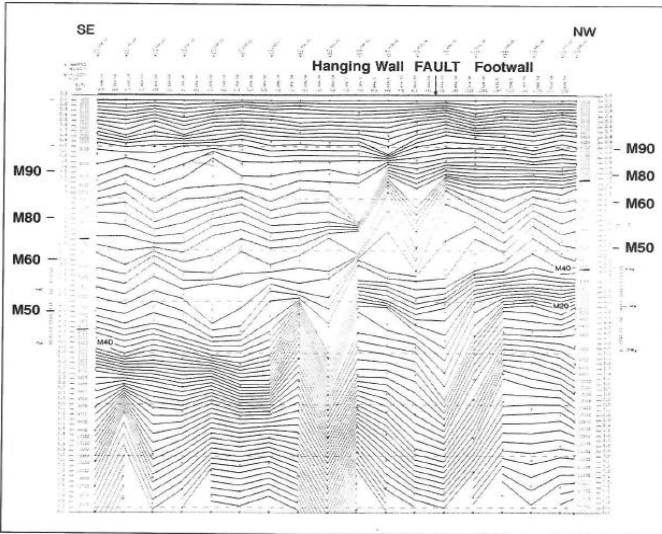
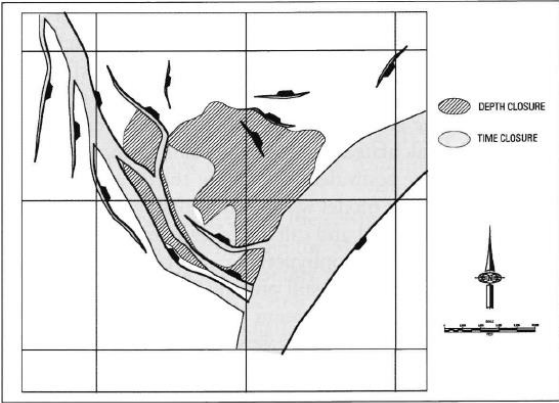
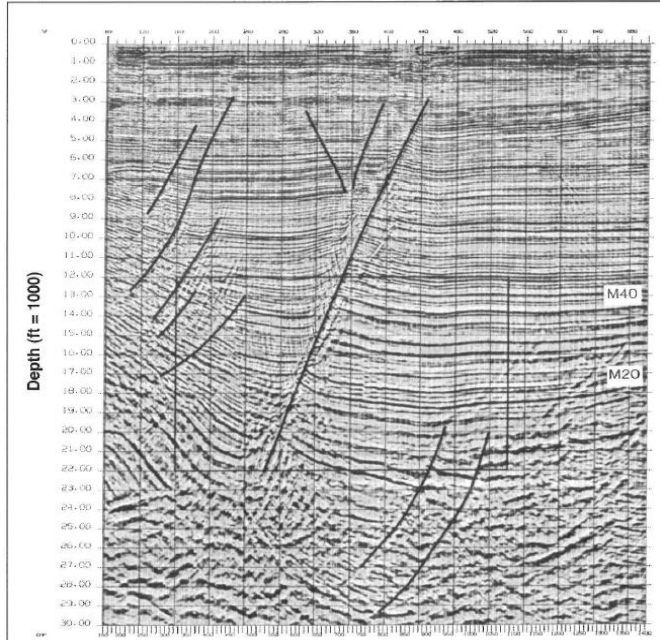


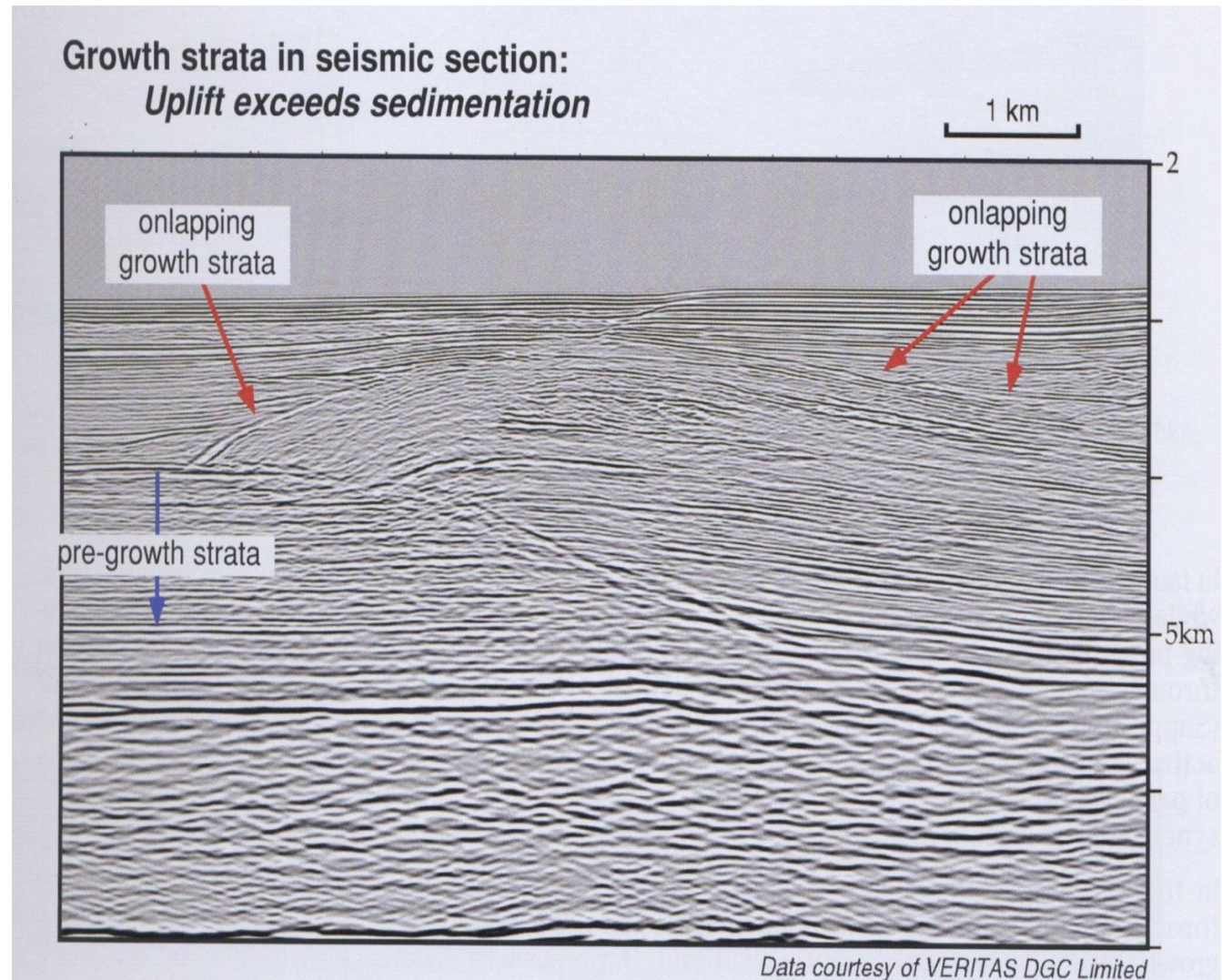
Fig. 16.

This is the poststack depth migration generated using the derived velocity model (Fig. 16). A comparison with Fig. 14 shows improved imaging of the M20 in the vicinity of the fault, and significant enhancement in imaging below M20.



# GROWTH STRATA - Example

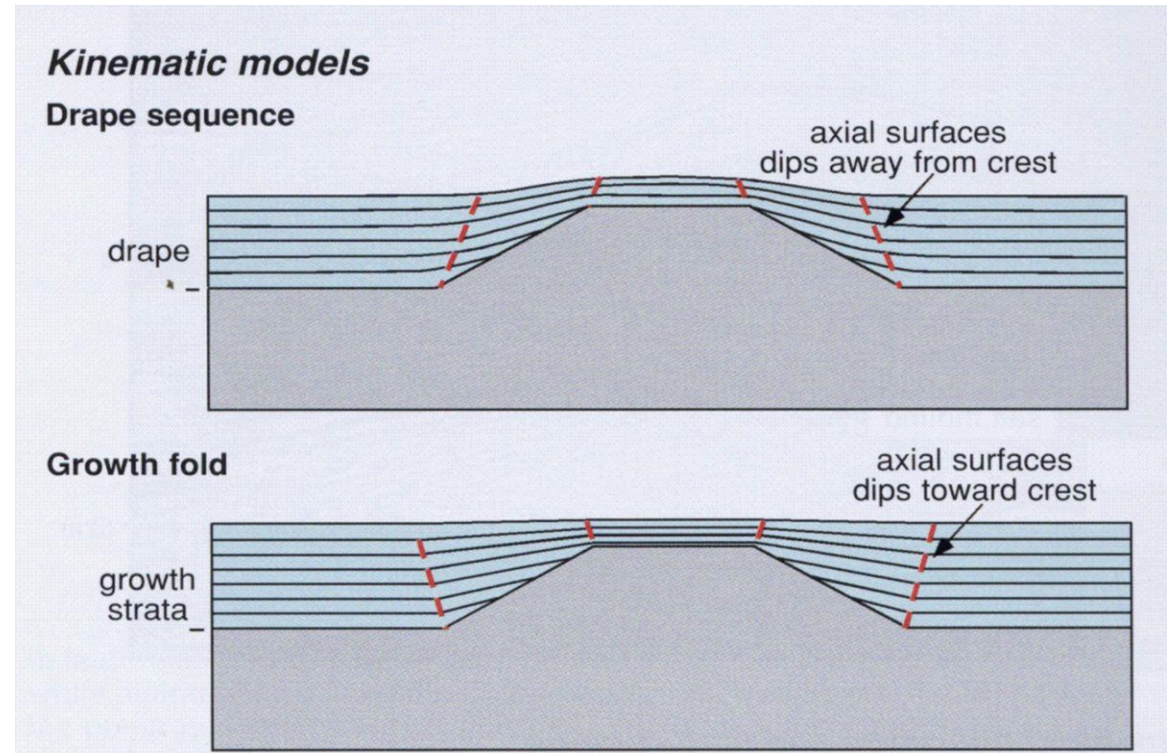
In genere i *growth-strata* non sono presenti sopra il culmine della struttura piegata, ma accompagnano spesso il piegamento ai lati della struttura stessa, terminando in *on-lap* su di essa. Sono solitamente ricoperti da sedimenti post-tettonici (paralleli e orizzontali).



# Analogia tra “*growth folding*” e “*drape folding*”

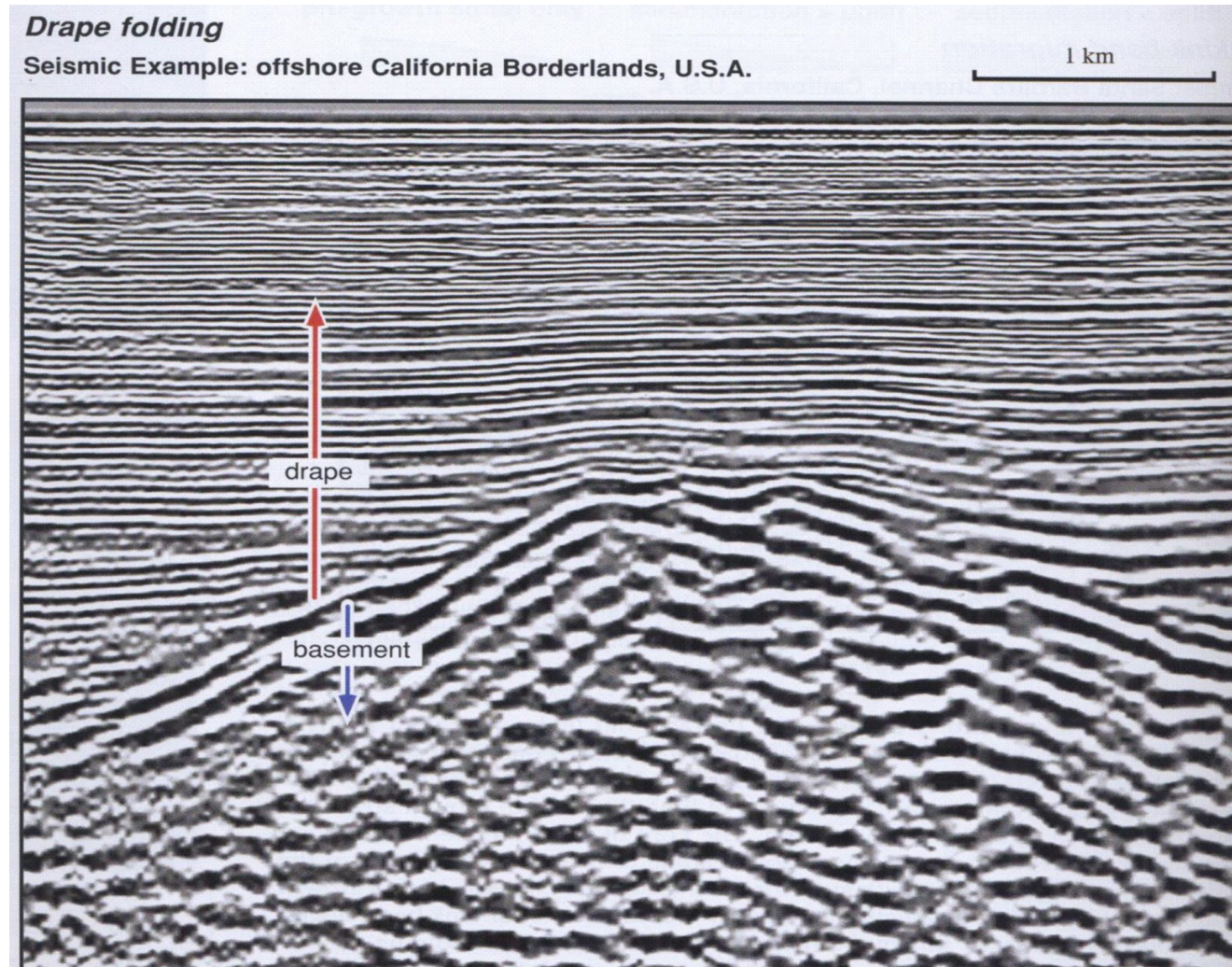
A “*sedimentary drape sequence*” is a stratigraphic interval deposited above a structure after that deformation ended. The sediments can be inclined, due to both the primary deposition and the differential compaction.

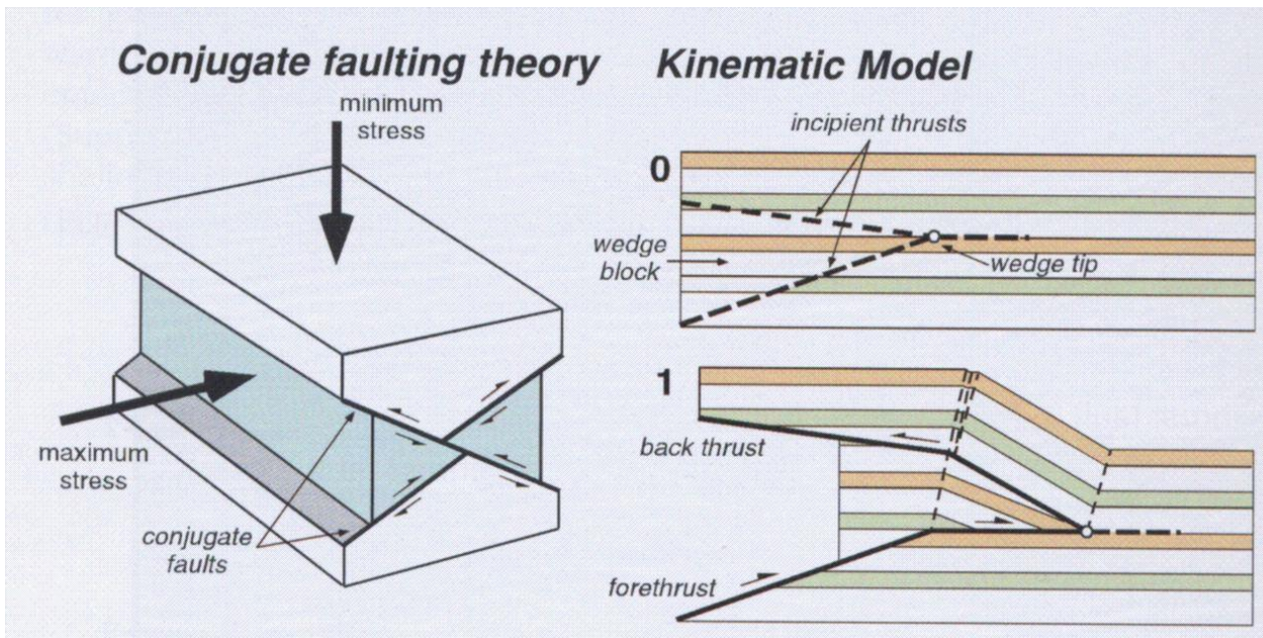
Sometimes these sequences can appear as *growth strata*, leading to a not correct evaluation of the deformation timing. Also if they are not easy to distinguish, we can recognize the different stratigraphic setting: note different vergence of the axial surfaces.





# Example of a silicoclastic *drape sequence on-lapping* a structural high composed by metamorphic rocks



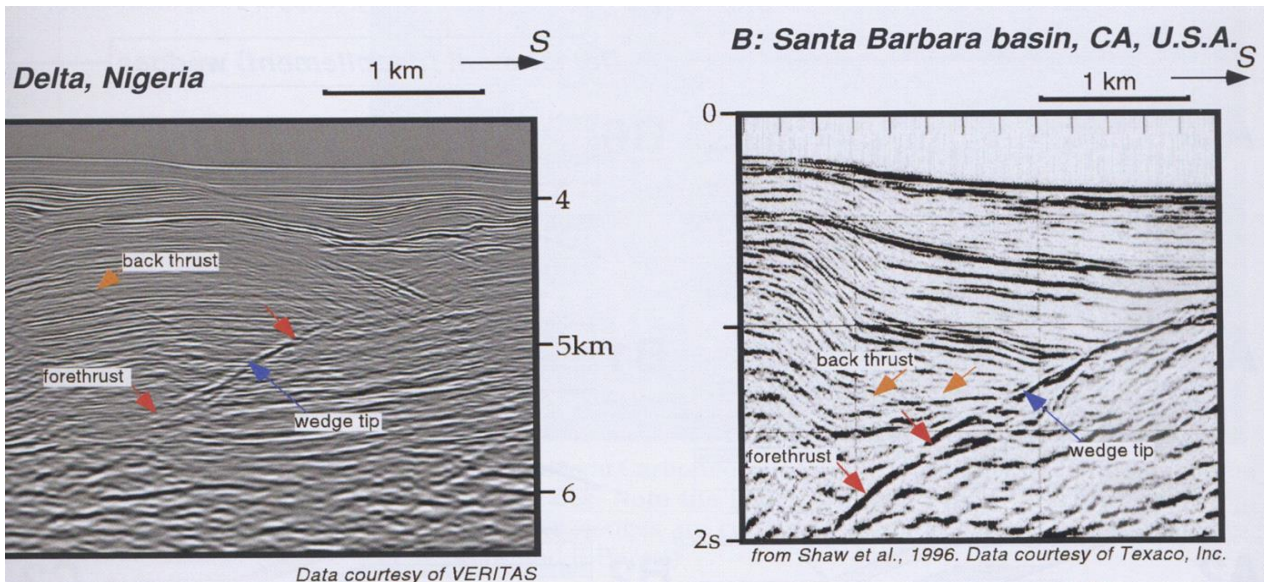
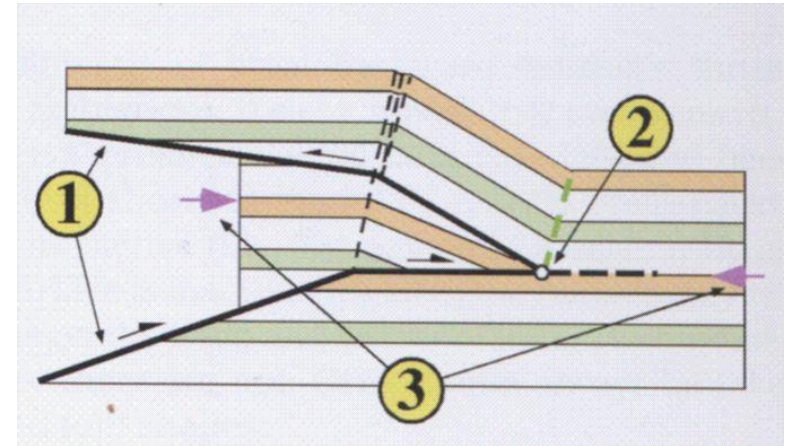


La fratturazione per compressione spesso porta allo sviluppo di due *thrust faults* coniugate con pendenze opposte. I piani di debolezza (per esempio superfici tra strati, ma anche antiche superfici di frattura), possono svilupparsi come piani di *detachment*.

I due *thrusts* coniugati limitano un *wedge-shaped block* e convergeranno nel *wedge tip*. Lo scivolamento lungo entrambe le faglie causa la propagazione del *wedge*. Il *thrust* inferiore è generalmente definito *forethrust* o *sole thrust*, quello superiore *back* o *roof thrust*.

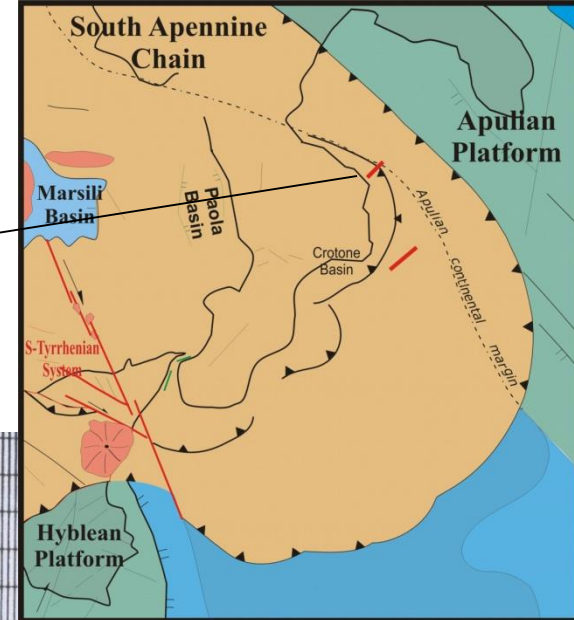
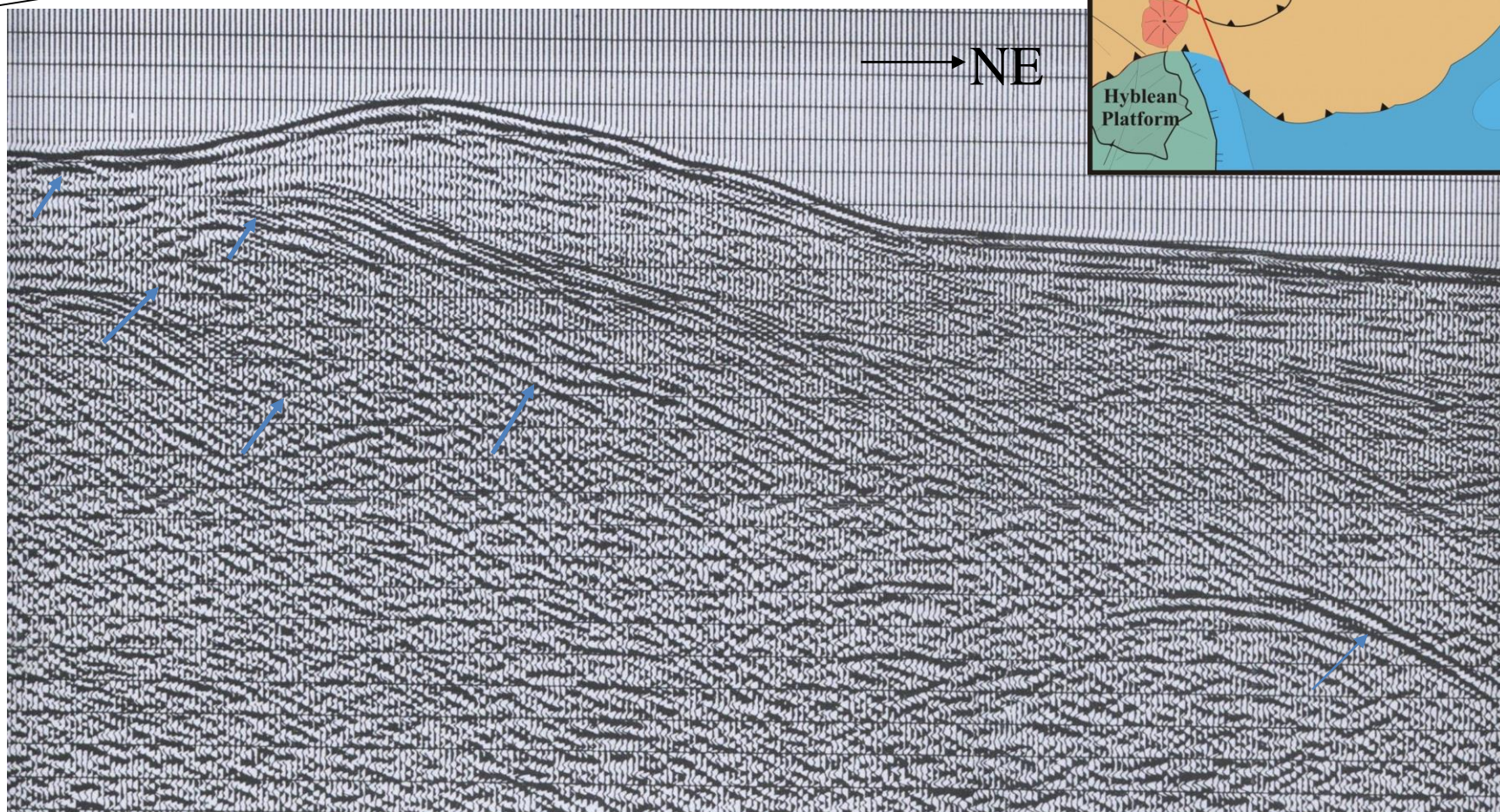
I *wedges* in regime compressivo possono assumere geometrie molto varie, comunque si possono riconoscere alcune caratteristiche comuni:

- 1 – presenza di *fore-thrust* e di *back-thrust* coevi
- 2 – piega localizzata lungo una superficie assiale attiva che parte dal *wedge tip*
- 3 – pieghe nel *footwall* del *back-thrust* che producono un rilievo.

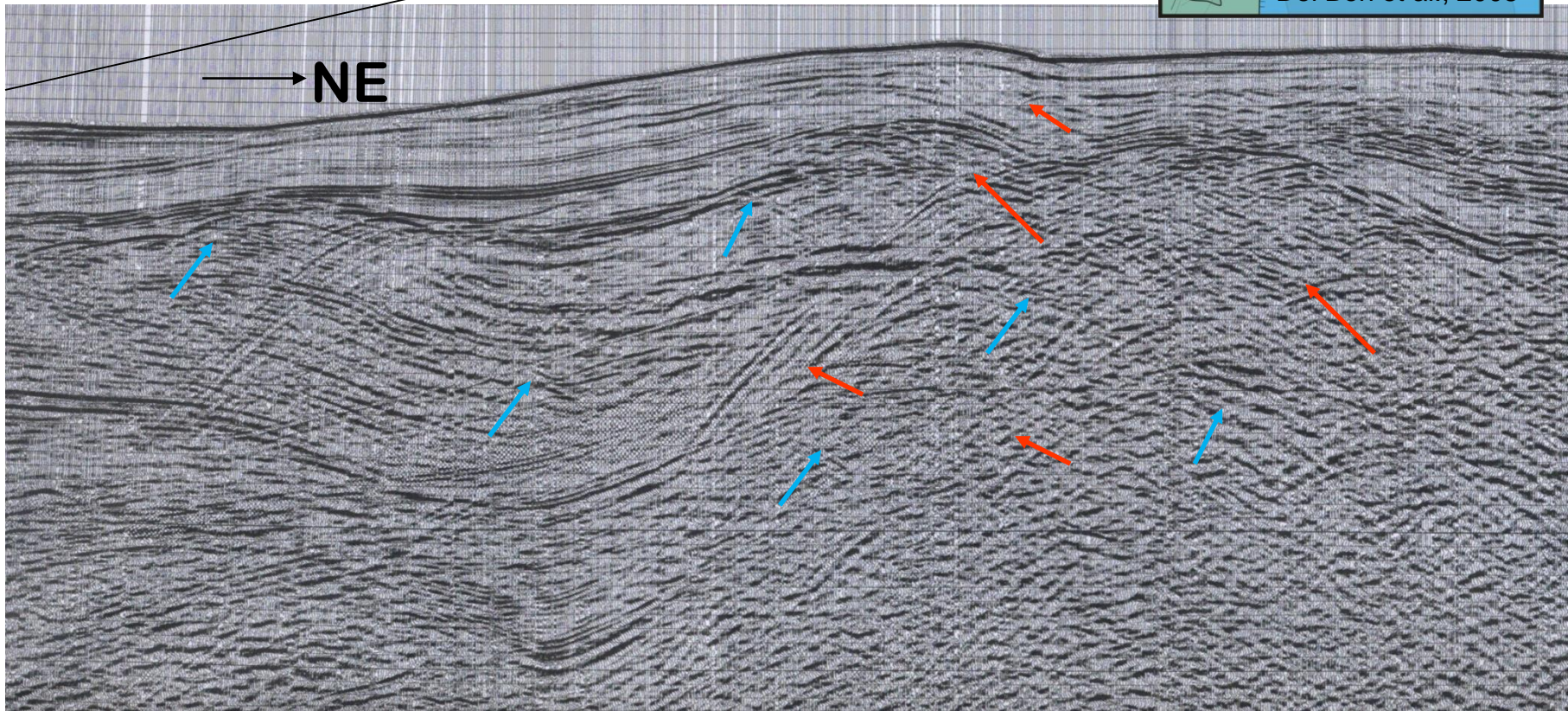
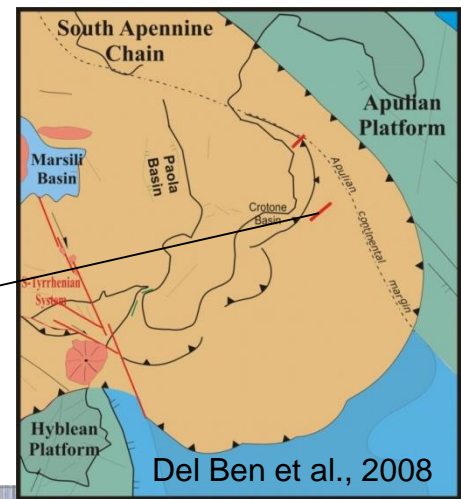


*Fault-bend folds e back-thrust: esempi*

# *Back-thrust nell'offshore Calabro*

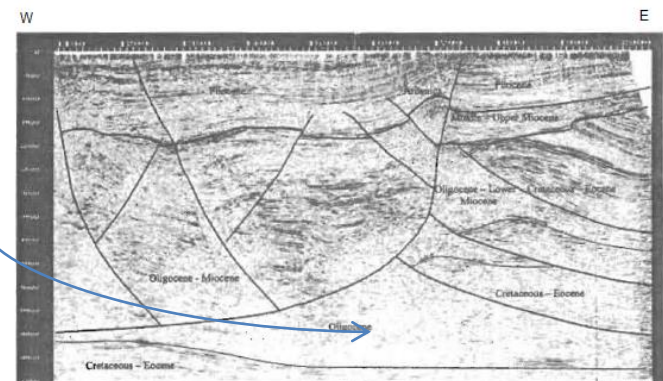
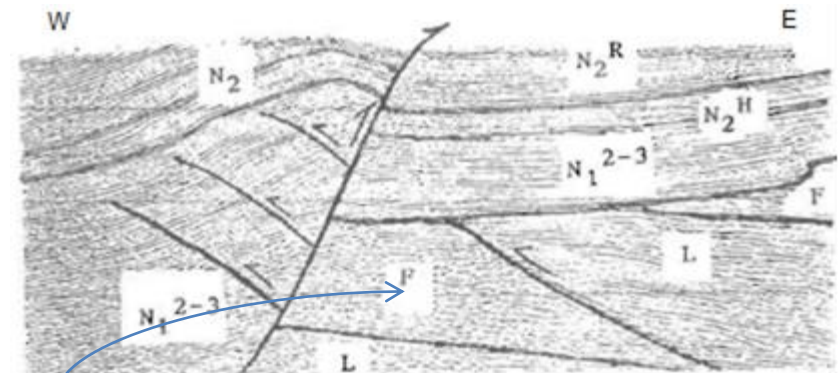
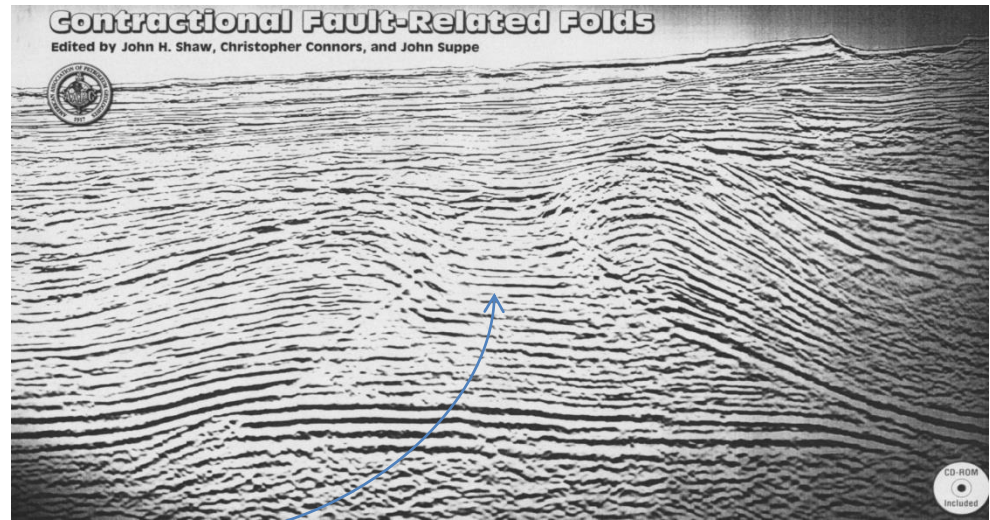


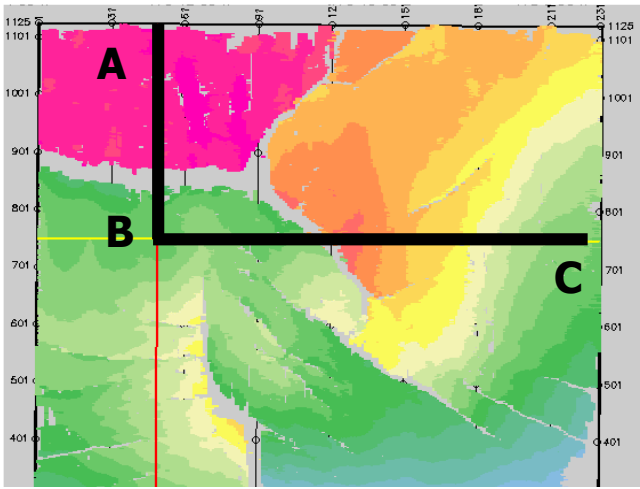
*Thrust* \ e *Back-thrust* /  
nell'offshore Calabro



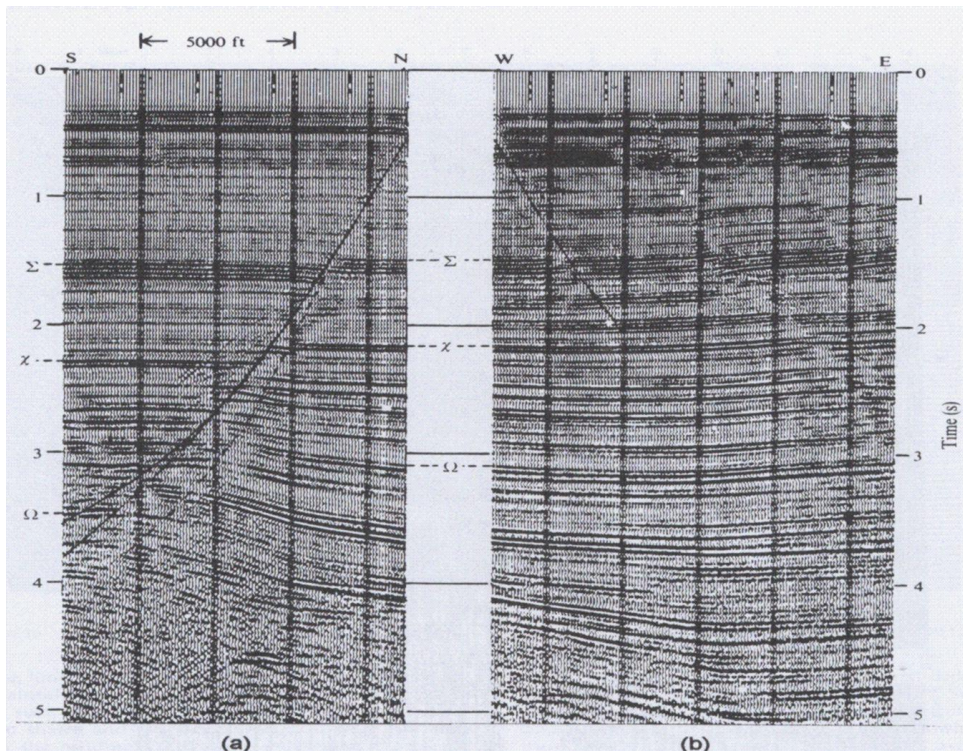
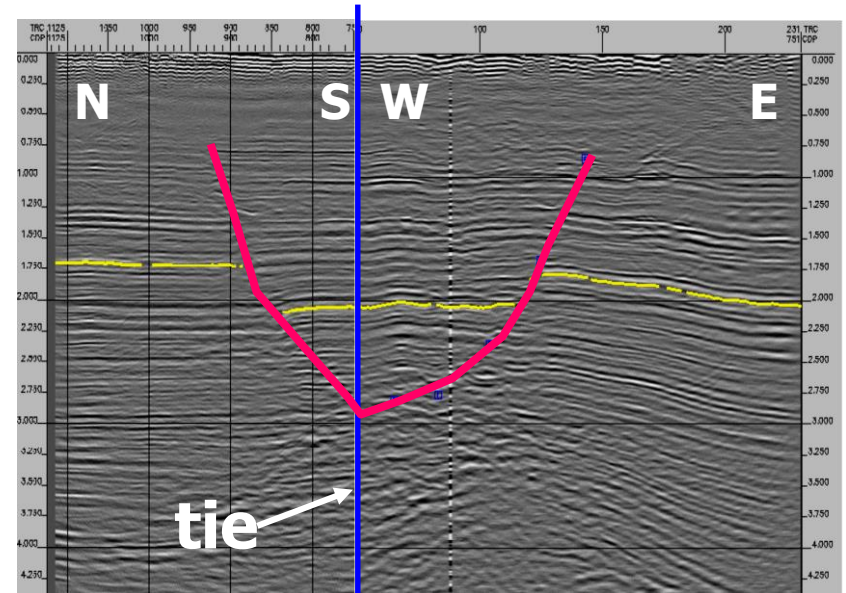
## Triangle Zone

Una combinazione data da *thrust* e *back-thrust* associati allo stesso piano di scollamento, può definire una zona a forma triangolare interposta tra tali faglie, dando luogo a tipiche strutture definite come “*triangle zones*”





Faults must tie on intersecting lines, or the interpretation is not internally **consistent**



If a fault cuts a seismic profile, the fault plane should be recognized by cutoffs, king-bands and (eventually) reflection from the plane.

A crossing profile has to see the same fault at the same depth...

...you have to consider if you are interpreting stack or migrated profiles!!

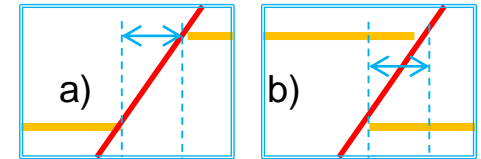
# Mapping a fault

Faults are generally represented by an inclined plane.

First of all we have to distinguish between different types of faults:

- **Extensional faults** are characterized by “not-existent” reflector along a strip corresponding to the horizontal throw of the fault for that reflector;
- **Compressive faults** are characterized by overthrusting, therefore by strip where the reflector is repeated at different depths;
- **Strike-slip faults** are related to vertical surface with horizontal throws along the fault plane → condition of “not-existent” or double reflector can eventually be related to secondary components, that are transtension or traspression.

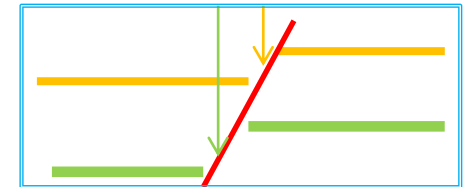
faglia normale faglia compressiva



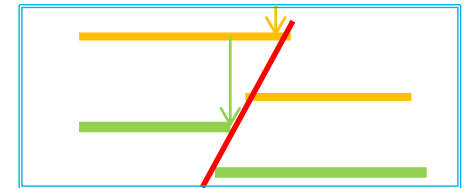
Fault position in the map

→ How and where we have to indicate faults in the map?

The fault should be indicated as a line (planare or listric, but we have always to consider deformation due to twt!). Its position will be in the *cutoff* of the mapped horizon; different position for different horizons.

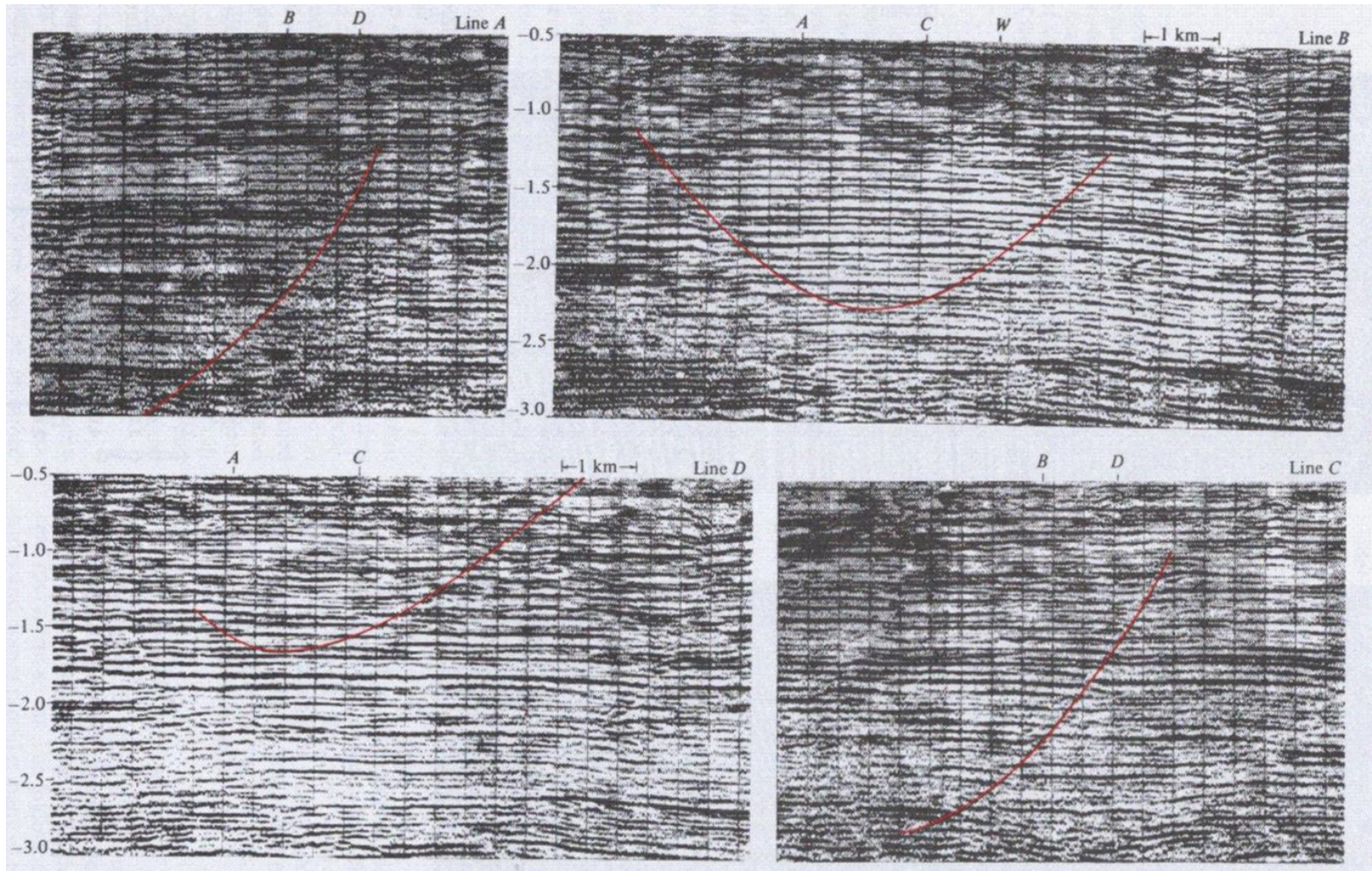
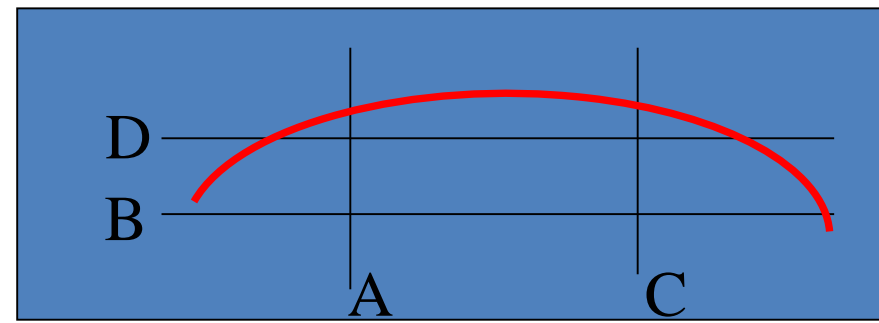


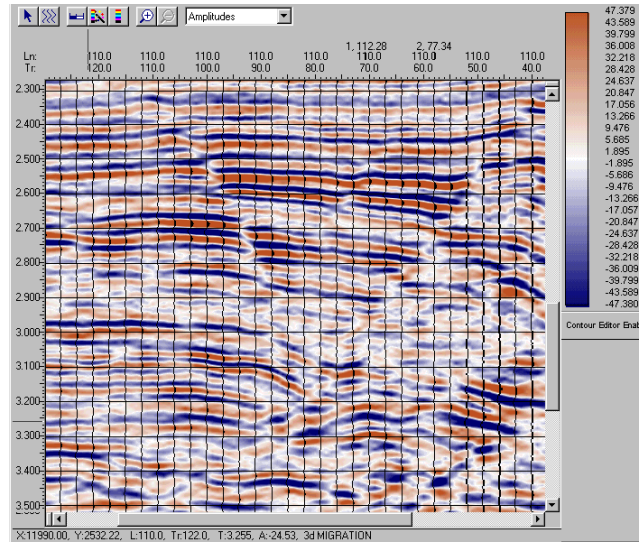
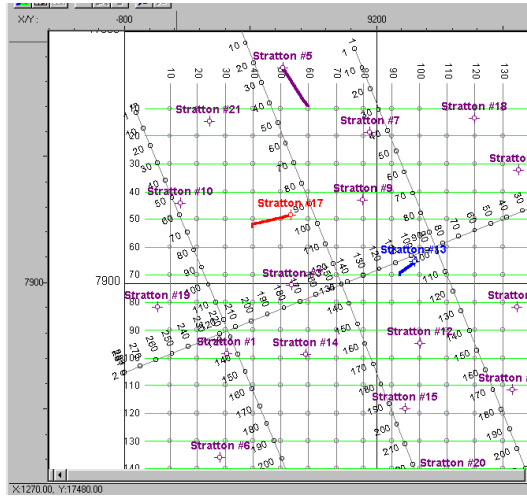
For the compressive faults we generally consider the *cutoff* of the *hanging wall*.



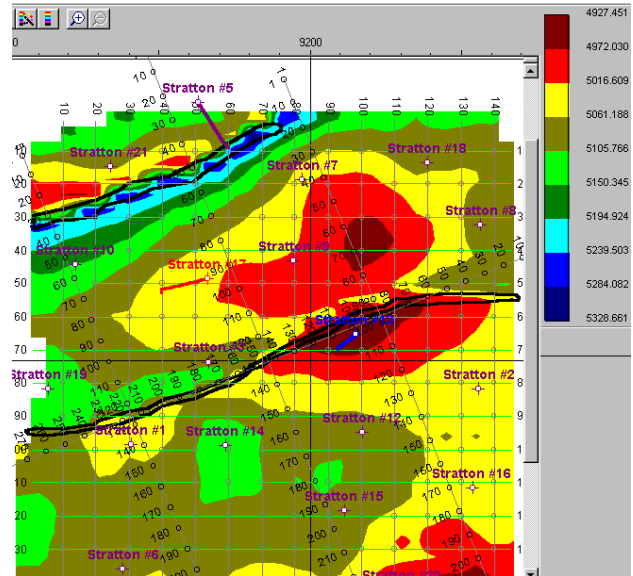
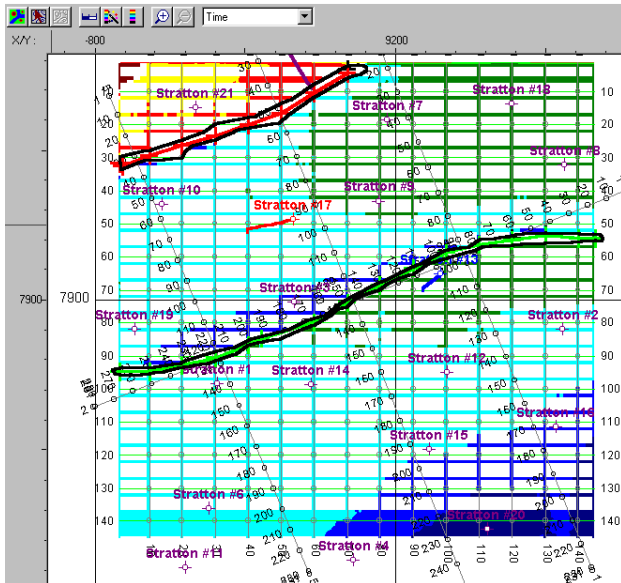


# Evidenze di faglia distensiva su più profili

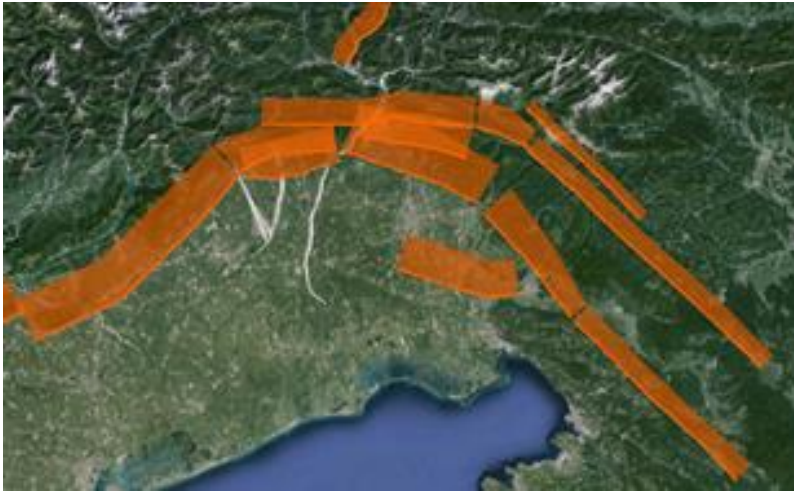




Una faglia distensiva potrà eventualmente diventare una fascia più o meno larga.  
 La larghezza in mappa rappresenta il rigetto orizzontale dell'orizzonte mappato.



# Faults position on maps: DISS



DISS: Database of Individual Seismogenic Sources (DISS), Version 3.2.0:

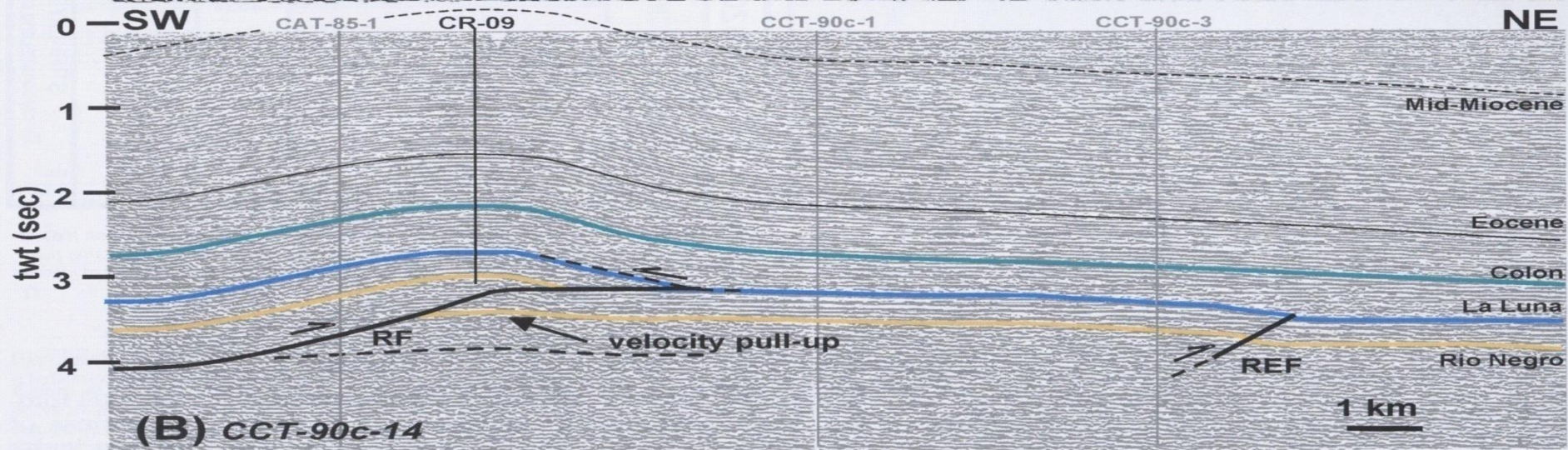
A compilation of potential sources for earthquakes larger than M 5.5 in Italy and surrounding areas.

<http://diss.rm.ingv.it/diss/>, © INGV 2015 - Istituto Nazionale di Geofisica e Vulcanologia

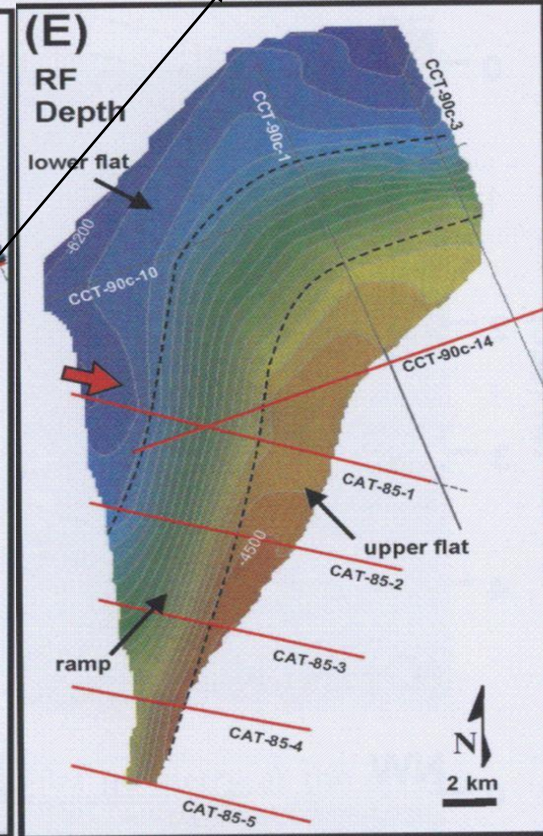
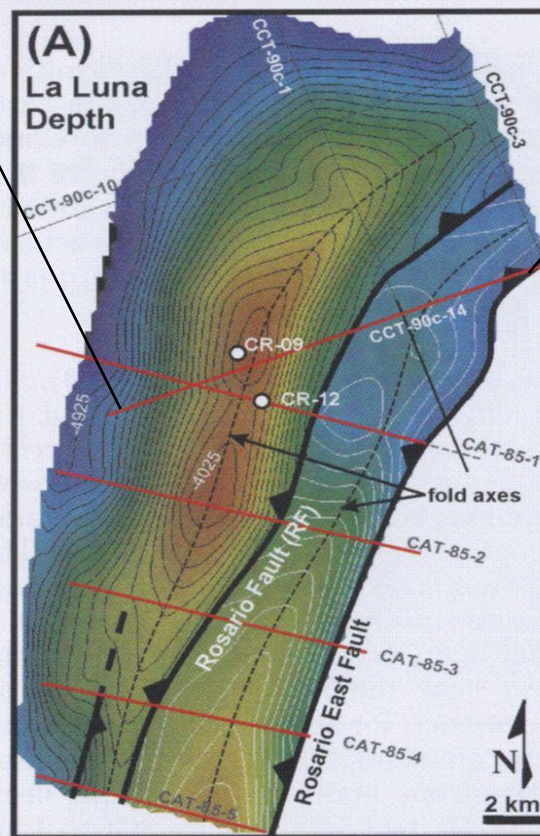
Il DISS ha lo scopo di definire i piani di faglia lungo cui potrebbero generare importanti terremoti: per questo motivo, oltre all'emersione superficiale delle faglie (linea arancione) vengono rappresentate anche le loro superfici in profondità.



Le faglie compressive avranno una maggiore larghezza (maggiore pendenza) rispetto alle faglie distensive; le faglie trascorrenti, essendo dei piani di faglia sub-verticali, saranno generalmente molto più ristrette arealmente (teoricamente delle linee)



Example of  
 “flat & ramp” geometry in the  
 Rosario  
 Field of Maracaibo Basin  
 in Venezuela.  
 The Rosario Fault,  
 has been mapped in (E)  
 as a lithological  
 discontinuity:  
 in this way the  
 “flat” (distant contour lines)  
 and “ramp” (closer lines) sectors  
 have been evidenced.



# Effetto di una faglia inversa in un profilo sismico a riflessione. Esempio con graduale aumento di velocità intervallare

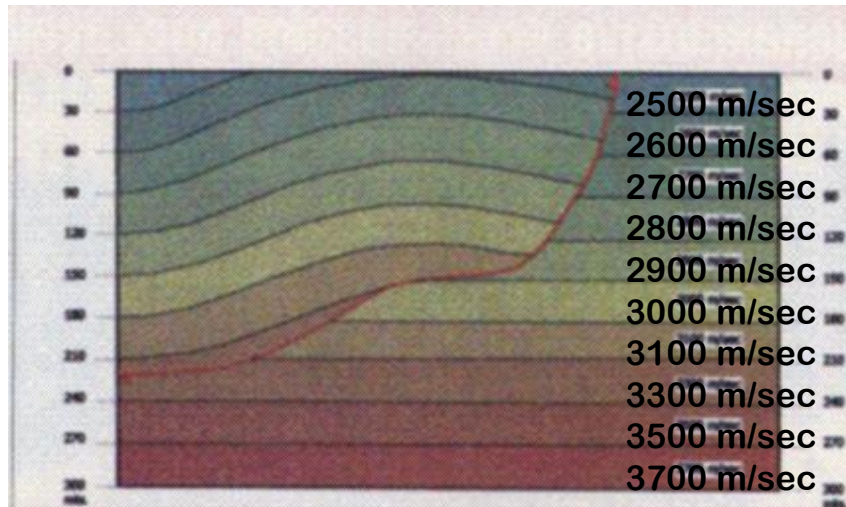


Figure 9. Geologic model (reverse fault) (depth).

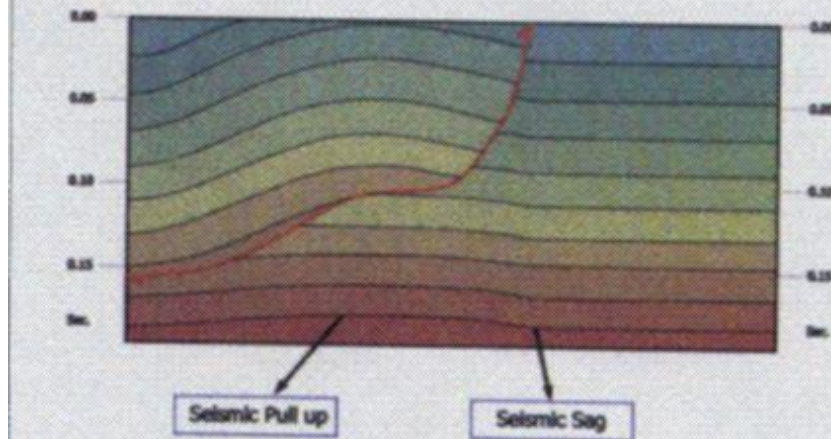


Figure 10. Geologic model (reverse fault) (time).

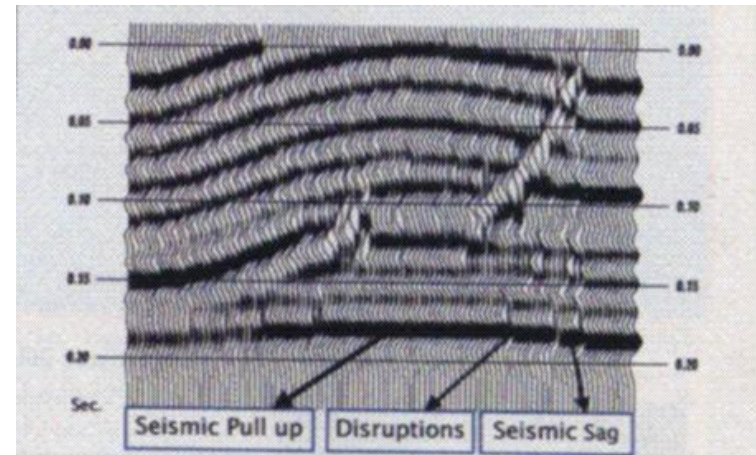


Figure 11. Normal incidence fault propagation fold model (reverse fault) (wiggle trace).

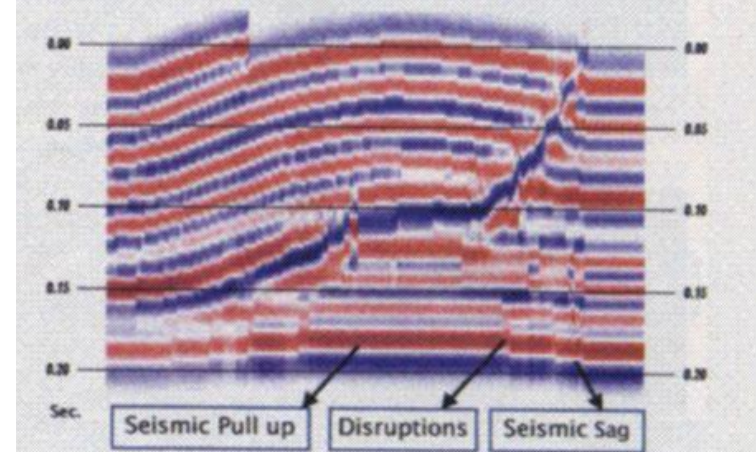


Figure 12. Normal incidence fault propagation fold model (reverse fault) (variable density).

Una faglia compressiva genera solitamente un *pull-up velocity*; localmente si possono avere avvallamenti (*sag*) con generale deterioramento del segnale

# Effetto di una faglia normale in un profilo sismico a riflessione. Esempio con strato ad alta velocità intervallare

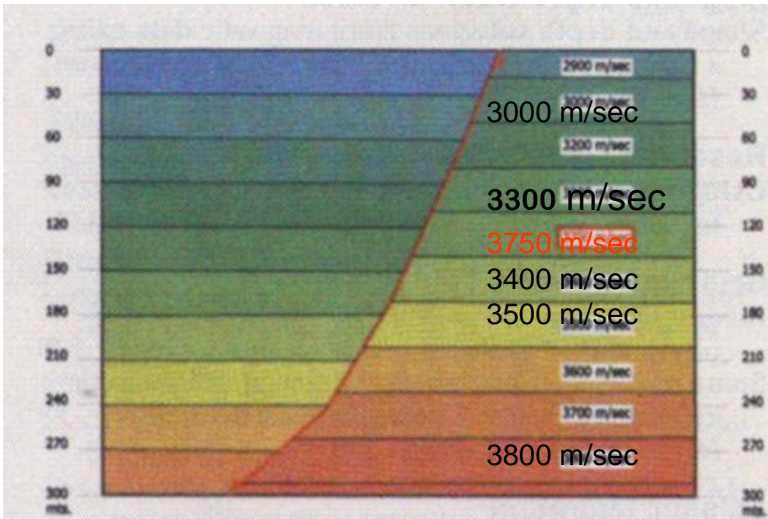


Figure 1. Geologic model (normal fault) (depth).

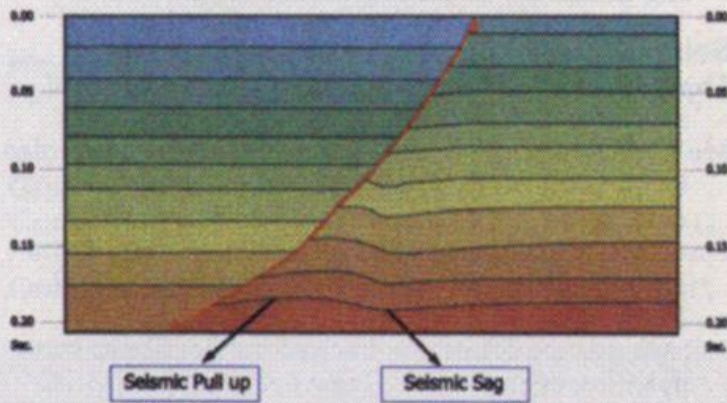


Figure 2. Geologic model (normal fault) (time).

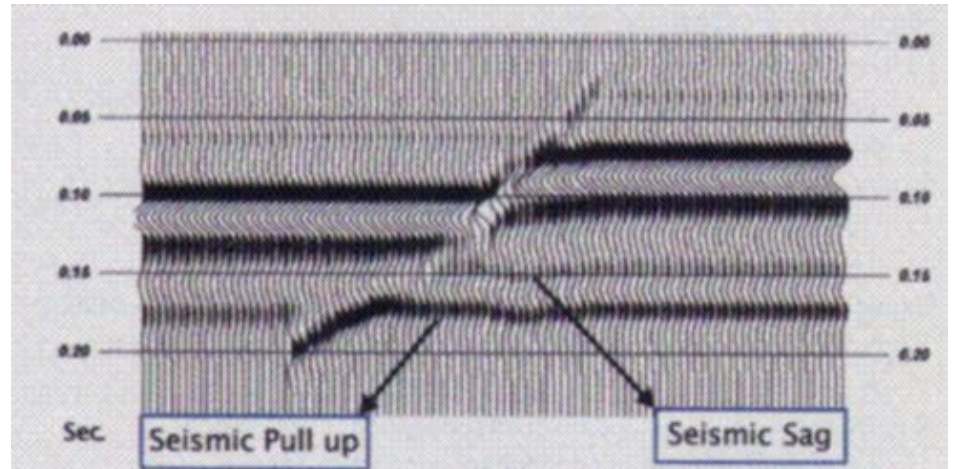


Figure 3. Normal incidence wiggle-trace model.

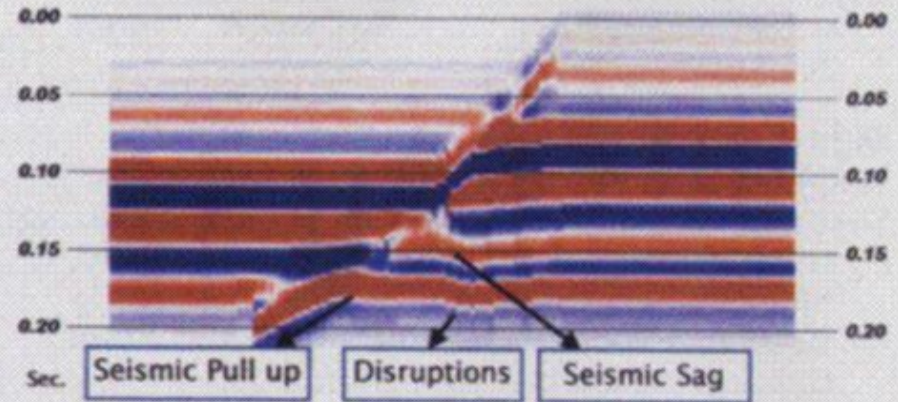


Figure 4. Normal incidence variable density model.

# Effetto di una faglia normale in un profilo sismico. Esempio con strato a bassa velocità intervallare

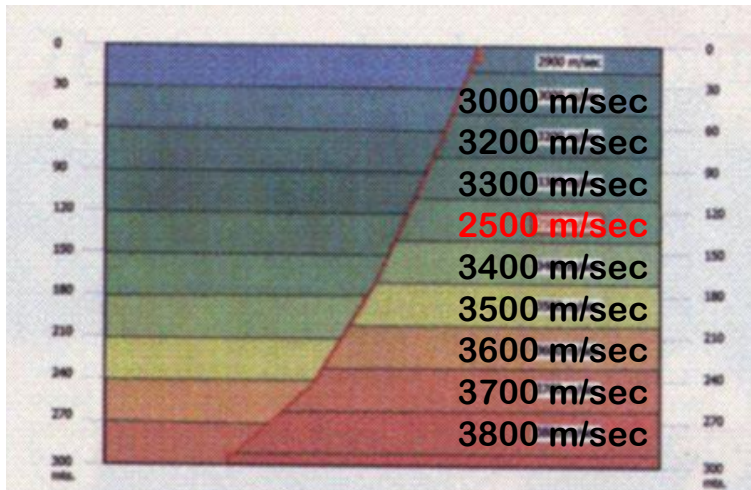


Figure 5. Geologic model 2 (normal fault) (depth).

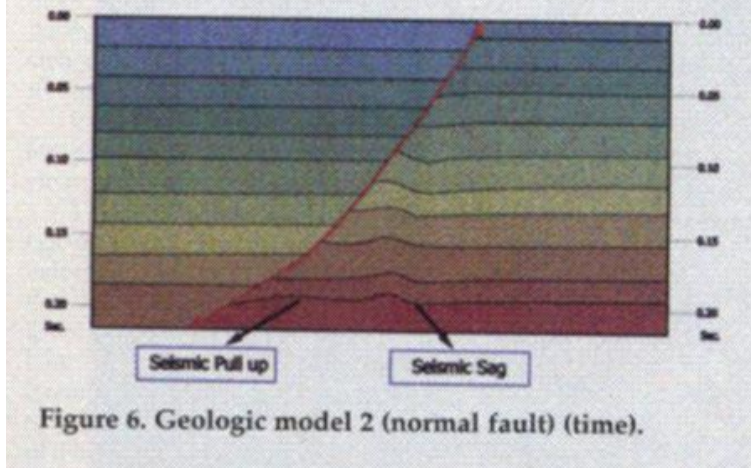


Figure 6. Geologic model 2 (normal fault) (time).

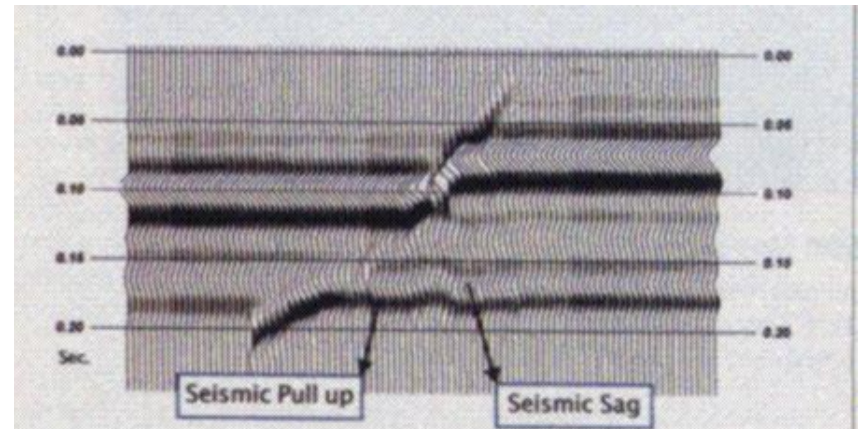


Figure 7. Normal incidence seismic model 2 (normal fault) (wiggle trace).

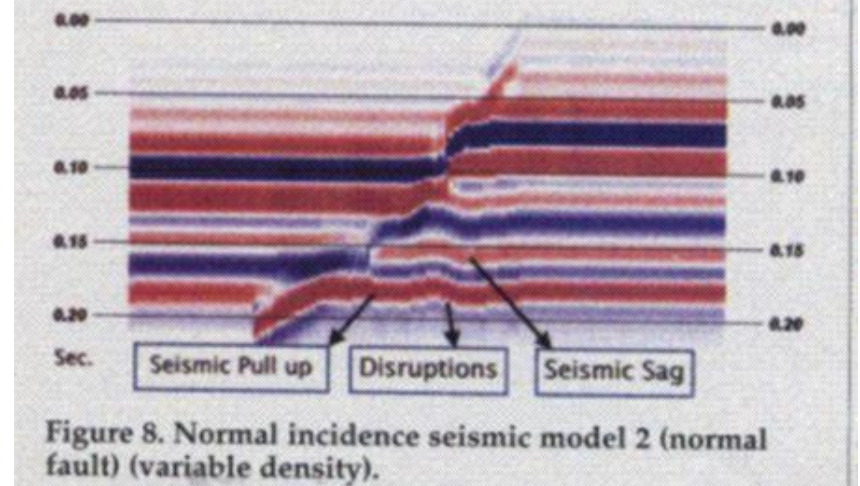
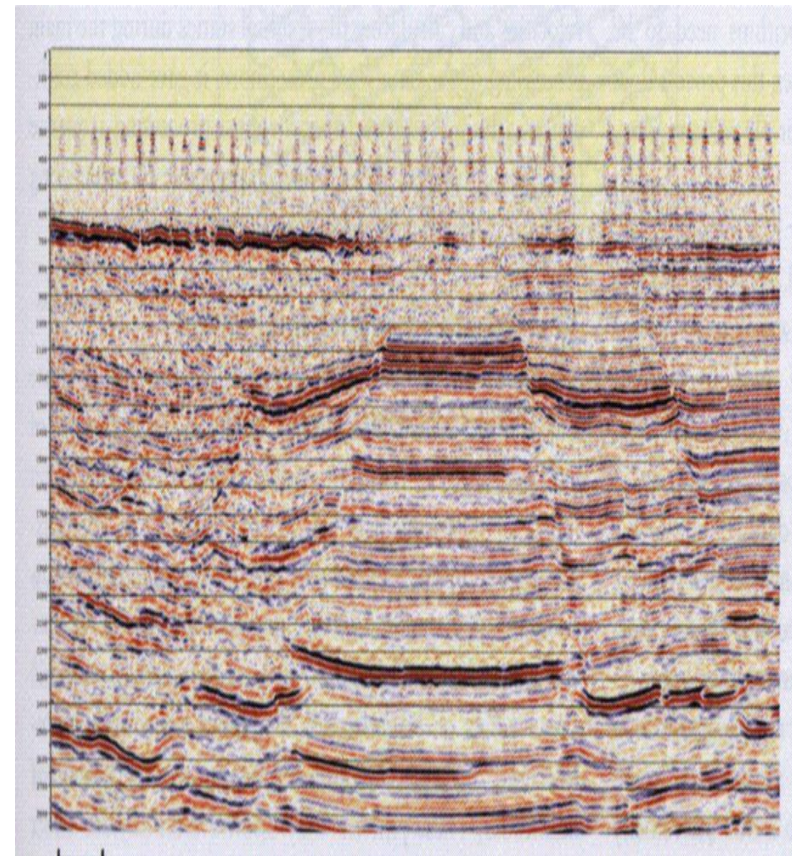
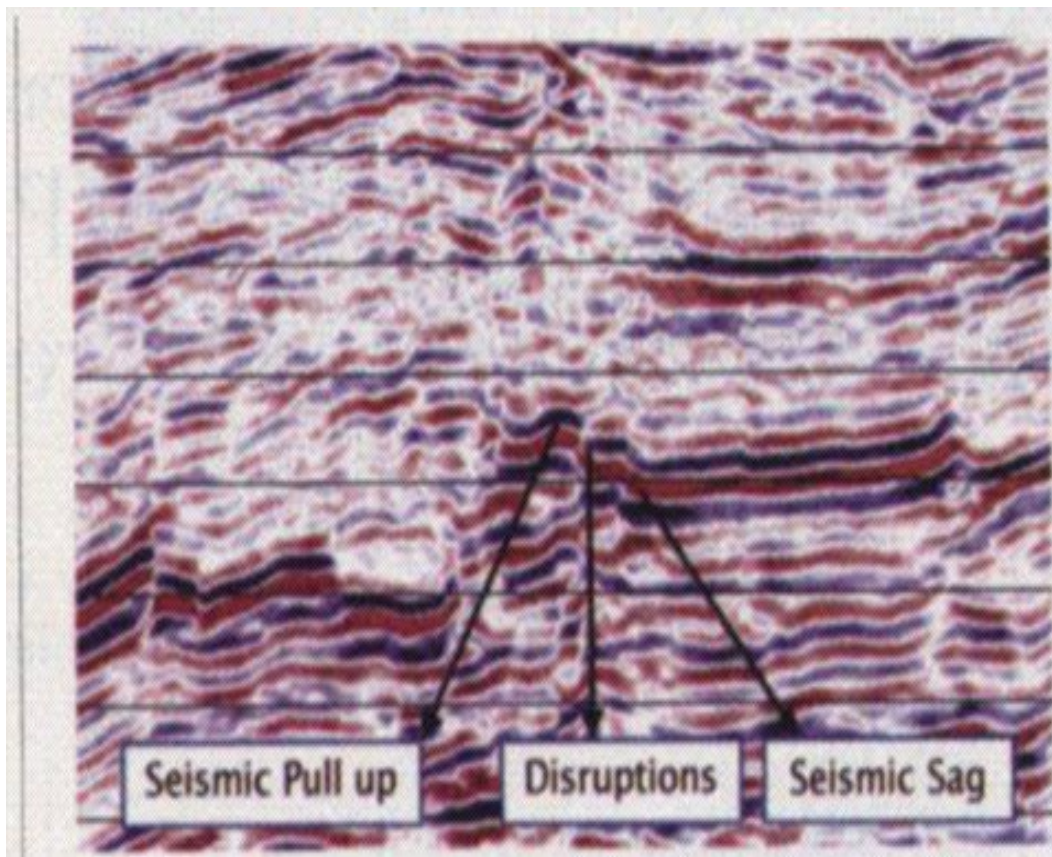


Figure 8. Normal incidence seismic model 2 (normal fault) (variable density).



Talvolta il piano di faglia può originare un riflettore continuo, ma in genere è troppo verticale per dare riflessioni utili: la sua ubicazione sarà data dall'allineamento dei *cut-off* dei riflettori

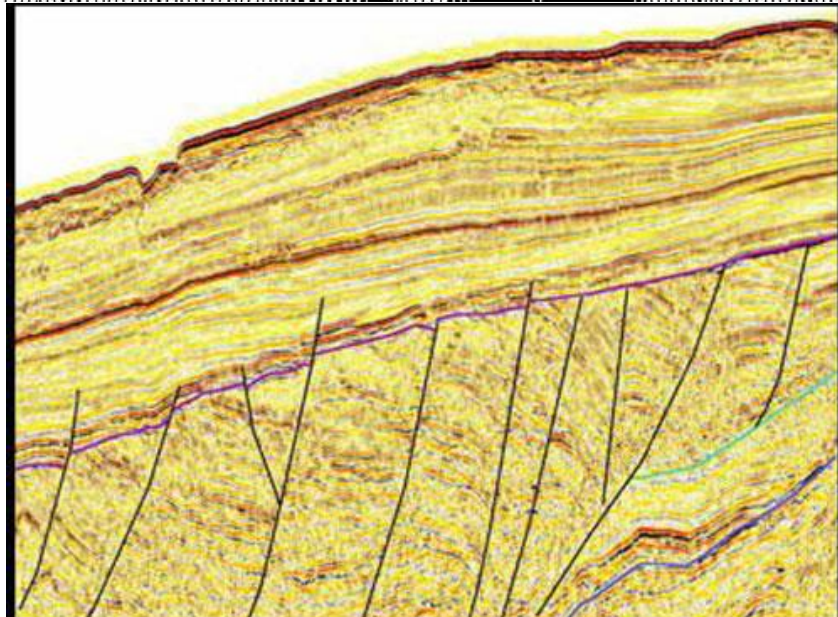
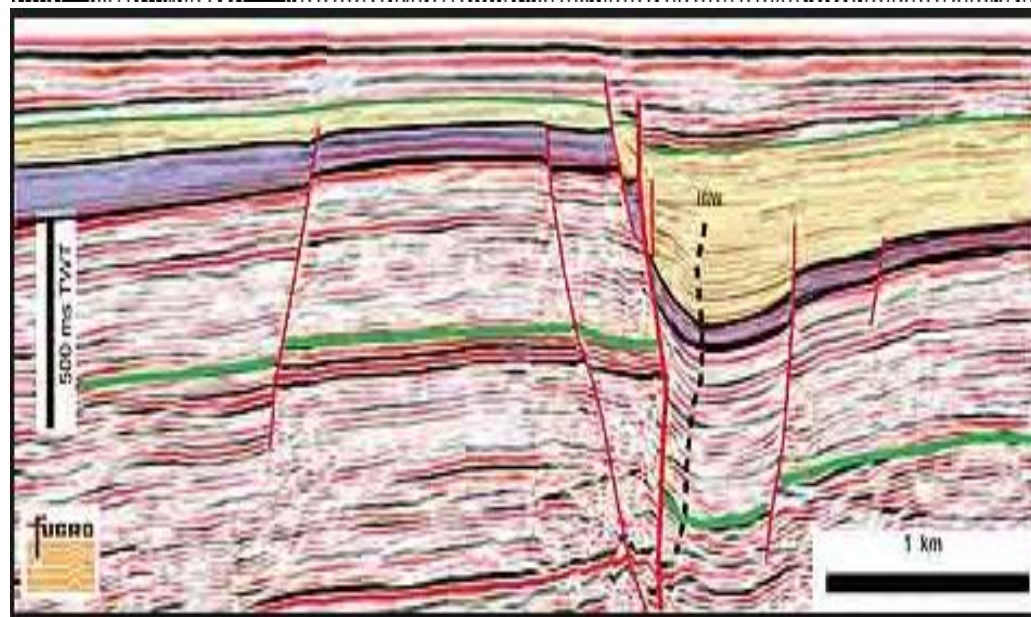
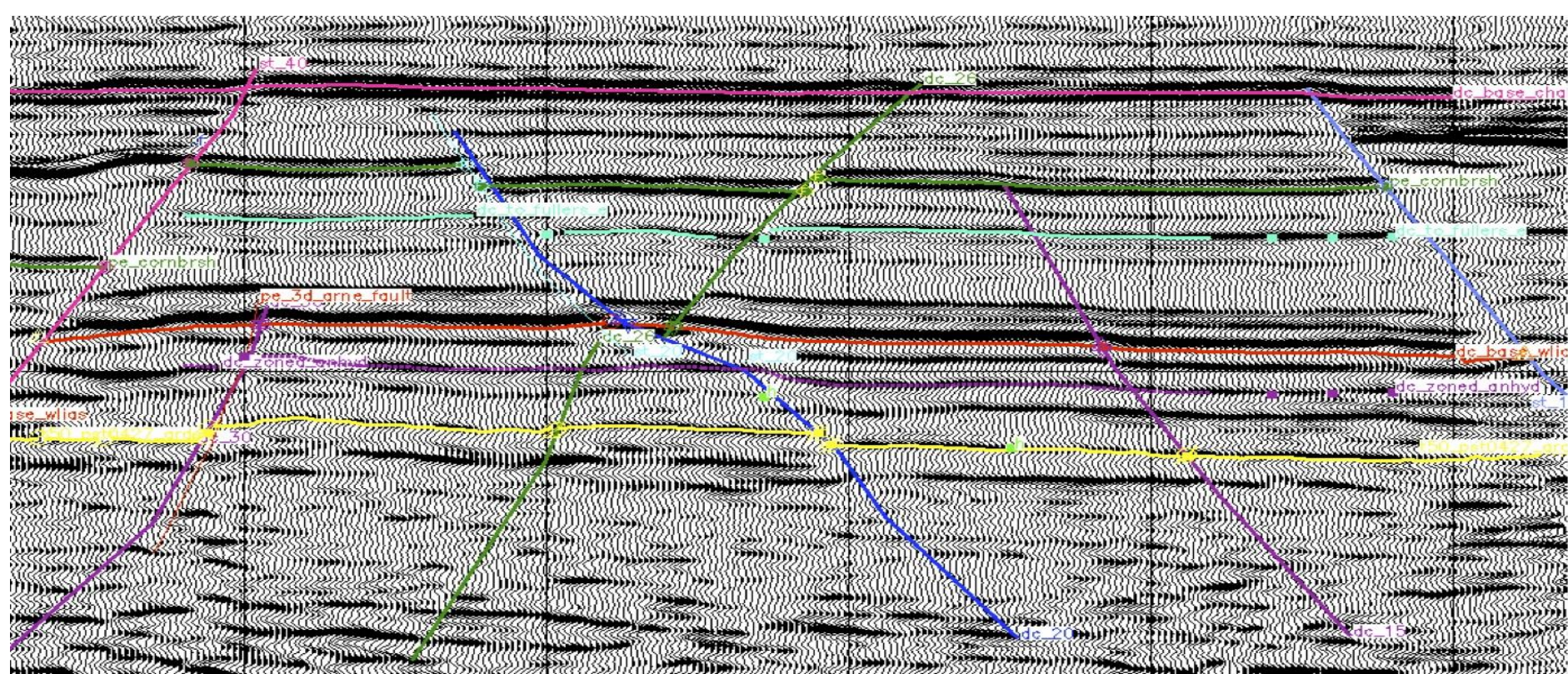
**Fault Shadow** : i contrasti di velocità lungo il piano variano notevolmente: ciò genera distorsioni tali da determinare spesso una zona d'ombra, di difficile interpretazione, sotto la faglia stessa.

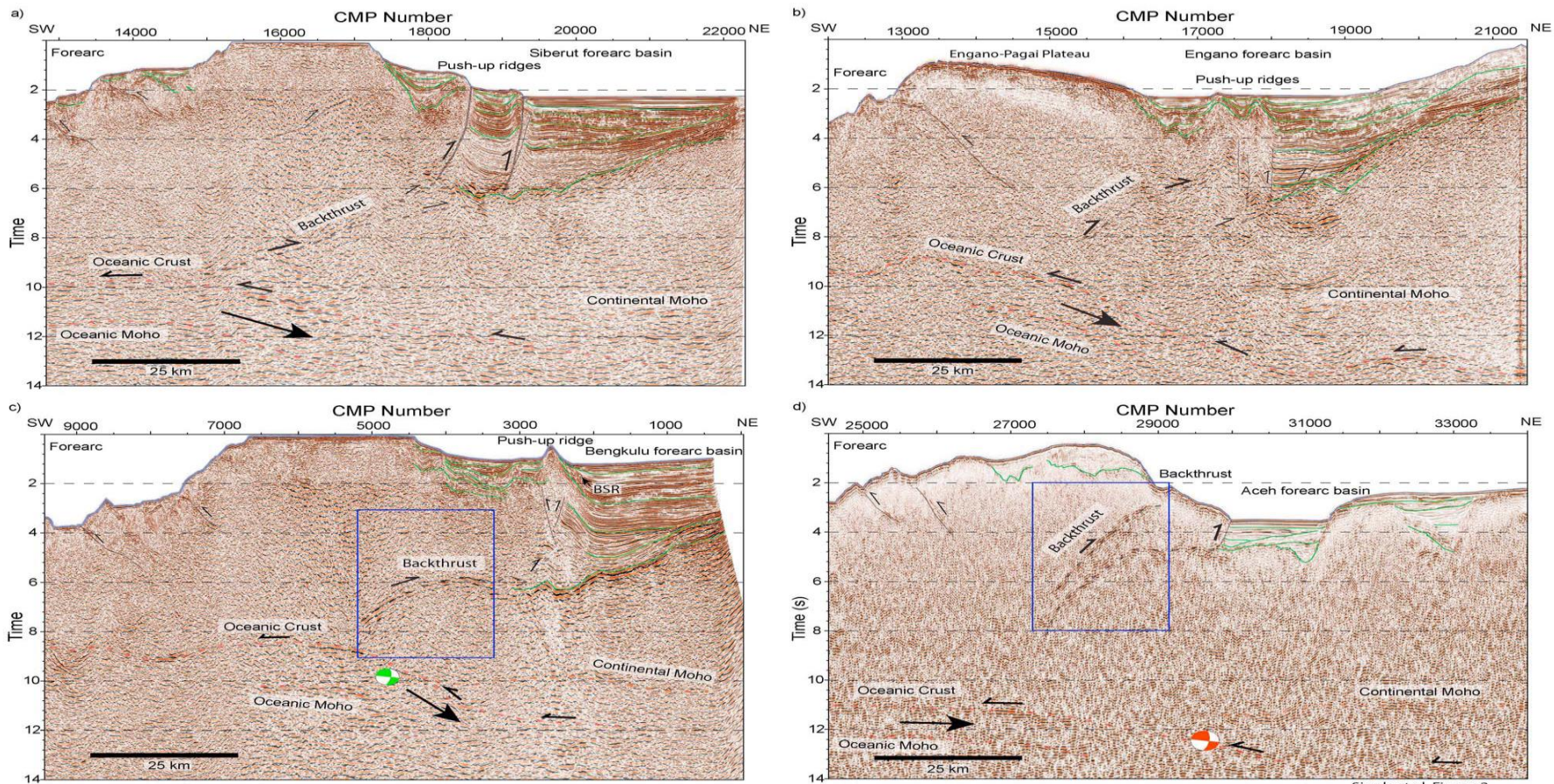


**Sistema di fratture diffuse nel volume di sedimenti.**

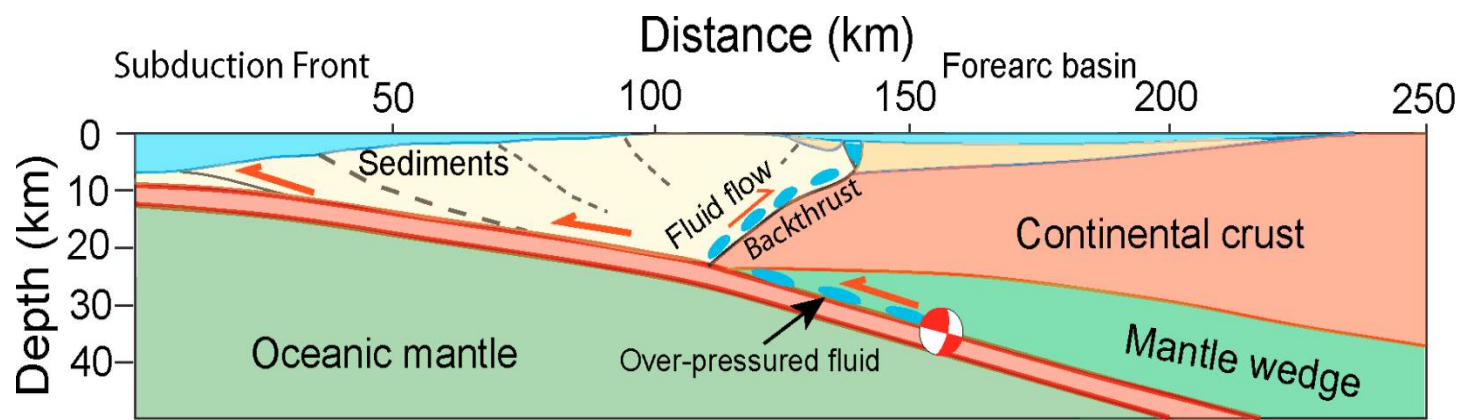
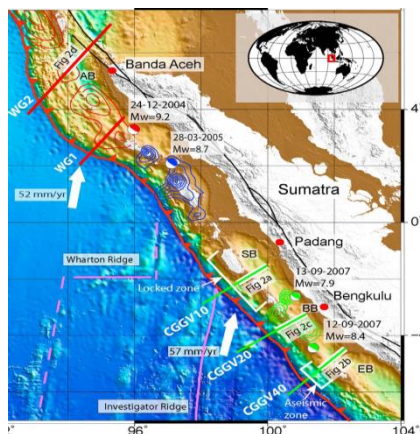
**L'interpretazione del sistema di faglie deve partire dalle fratture principali, gli obiettivi specifici determinano il dettaglio dell'interpretazione.**







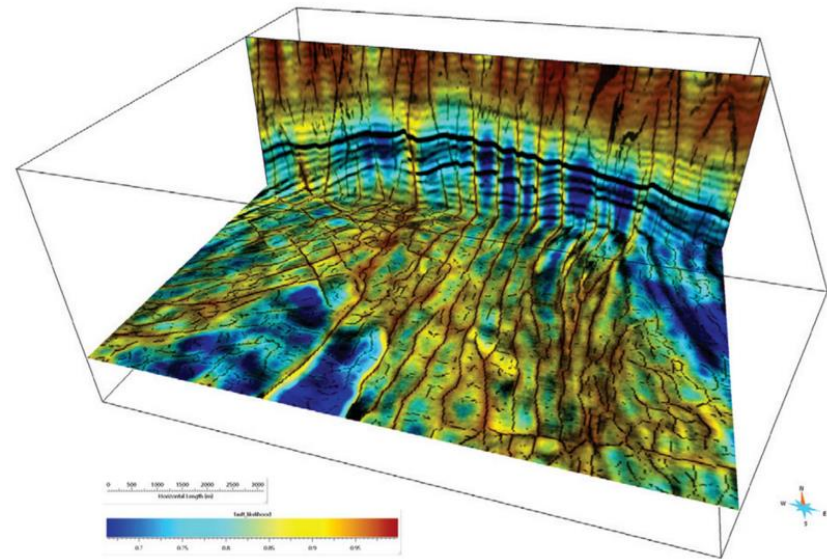
Singh et al. Figure 2



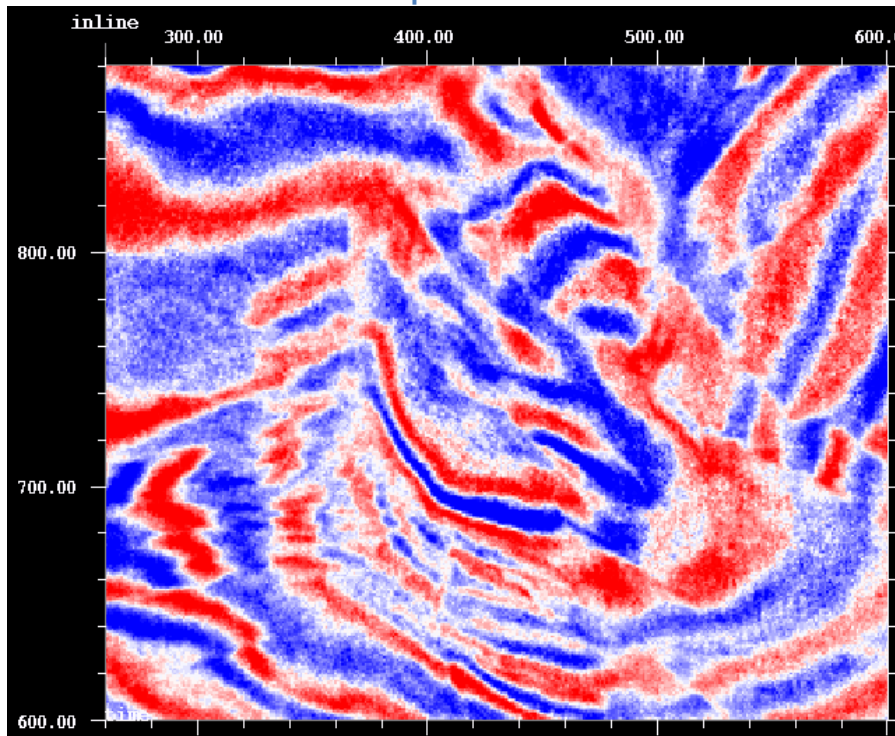
# CRUSTAL SEISMIC INTERPRETATION

ATTRIBUTI SISMICI per interpretare le faglie  
*3D volume interpretation of faults by seismic  
attribute Coherency, also known as  
Discontinuity or Variance, is a derivative data  
volume based on trace-to-trace correlation.*

*Data range from 0 to 1,  
(1 = neighboring traces are identical*



Amplitude Data



Coherency Data

