

The Role of the Basement and Salt Tectonics on the Cenozoic Contractional Deformation in the Southeastern Zagros Fold Belt*

**Ralph Hinsch¹, Martin Vögele¹, Gholamreza Gharabeigli², Abbas Majidi², Davoud Morsalnezhad²,
Christopher Sellar¹, Bernhard Bretis¹, Karin Gruber¹, Tam Lovett¹,
Ali Asghar Julapour², Gabor Tari¹, and Walter Kosi¹**

Search and Discovery Article #51667 (2020)**

Posted May 25, 2020

*Adapted from oral presentation given at 2019 AAPG Middle East Region, Geosciences Technology Workshop, 2nd Edition Structural Styles of the Middle East, Muscat, Oman, December 9-11, 2019

**Datapages © 2020. Serial rights given by author. For all other rights contact author directly. DOI:10.1306/51667Hinsch2020

¹OMV Upstream, Exploration, Vienna, Austria (Ralph.Hinsch@omv.com)

²National Iranian Oil Company, Exploration Directorate, Vienna, Austria

Abstract

OMV Upstream and the NIOC conducted a joint geoscientific study in the southern Fars area from 11/2016 until 10/2018. The study area is located within the Simply Folded Belt of the Zagros, famous for its large-scale whaleback folds and salt glaciers. However, despite decades of research there are still many uncertainties regarding aspects of the structural style. How much do basement structures and Hormuz salt control deformation? The amount of shortening in published sections in and around the study area varies from 6-20%. The main differences between the sections are variations of the primary salt and non-salt stratigraphic thicknesses, presence or absence of hidden thrust faults, and contribution of basement to the shortening or not. We use outcrop and surface geology observations, well data, reflection seismic (on- and offshore), and gravity data to assess the salt tectonic and structural history in the SE Fars and constrain two balanced and many local sections. We first assess uncertainties related to the stratigraphic thickness by sensitivity analysis of seismic reflection time-to-depth conversion and gravity inversion. Results show that the stratigraphic thickness has uncertainties of up to 4km. In a second step we use an area balancing method to calculate alternative sections and the associated shortening. Shortening values of 4-25% have a large spread and show that it is impossible to determine how much the basement is involved in the deformation based on section balancing alone. Consequently, other methods must be used to constrain basement effects on deformation. The folding pattern in areas of outcropping diapirs is complex and shows usually double plunging folds with two main orientations (approx. W-E, perpendicular to shortening) and ENE-WSW. We consider that these directions constrain some basement and halokinetic control on the young shortening deformation. The ENE-WSW direction is interpreted to be inherited from the Precambrian-Cambrian rifting. We consider that primary salt thickness is higher in graben areas with the ENE-WSW orientation. Halokinetic down building since the Paleozoic increased the post-salt stratigraphic thicknesses especially in these graben areas. During N-S shortening these thicker packages are inverted and folded dominantly in a thin-skinned manner, obliquely interfering with the W-E folding direction. In addition to the thin-skinned deformation we postulate some additional thick-skinned inversion below the Hormuz salt

level. Minor inversion movements are considered to restore steps in the structured basement, thereby creating a smoother basal decollement plane. Therefore, we consider that the inversion movements partly control the propagation of the thin-skinned deformation. Furthermore, the deformation pattern and the halokinetic history of the diapirs is not uniform throughout the study area. Diapirs in the eastern part of the study area show pronounced phases of apparent higher activity. We interpret this to be caused by reactivation of basement structures due to far-field effects of tectonic movements at the plate margin (i.e. ophiolite obduction during Late Cretaceous). Even though some input parameters and section balancing have a large uncertainty range, detailed observations indicate a complex control of basement structures on the halokinetic evolution and on the young shortening deformation in the SE Fars.

The role of the basement and salt tectonics on the Cenozoic contractional deformation in the southeastern Zagros Fold Belt

Ralph Hinsch¹,
Martin Vögele¹, Gholamreza Gharabeigli², Abbas Majidi²,
Davoud Morsalnezhad², Christopher Sellar¹, Bernhard Bretis¹,
Karin Gruber¹, Tam Lovett¹, Ali Asghar Julapour², Gabor Tari¹, Walter Kosi¹
1:OMV, 2: NIOC

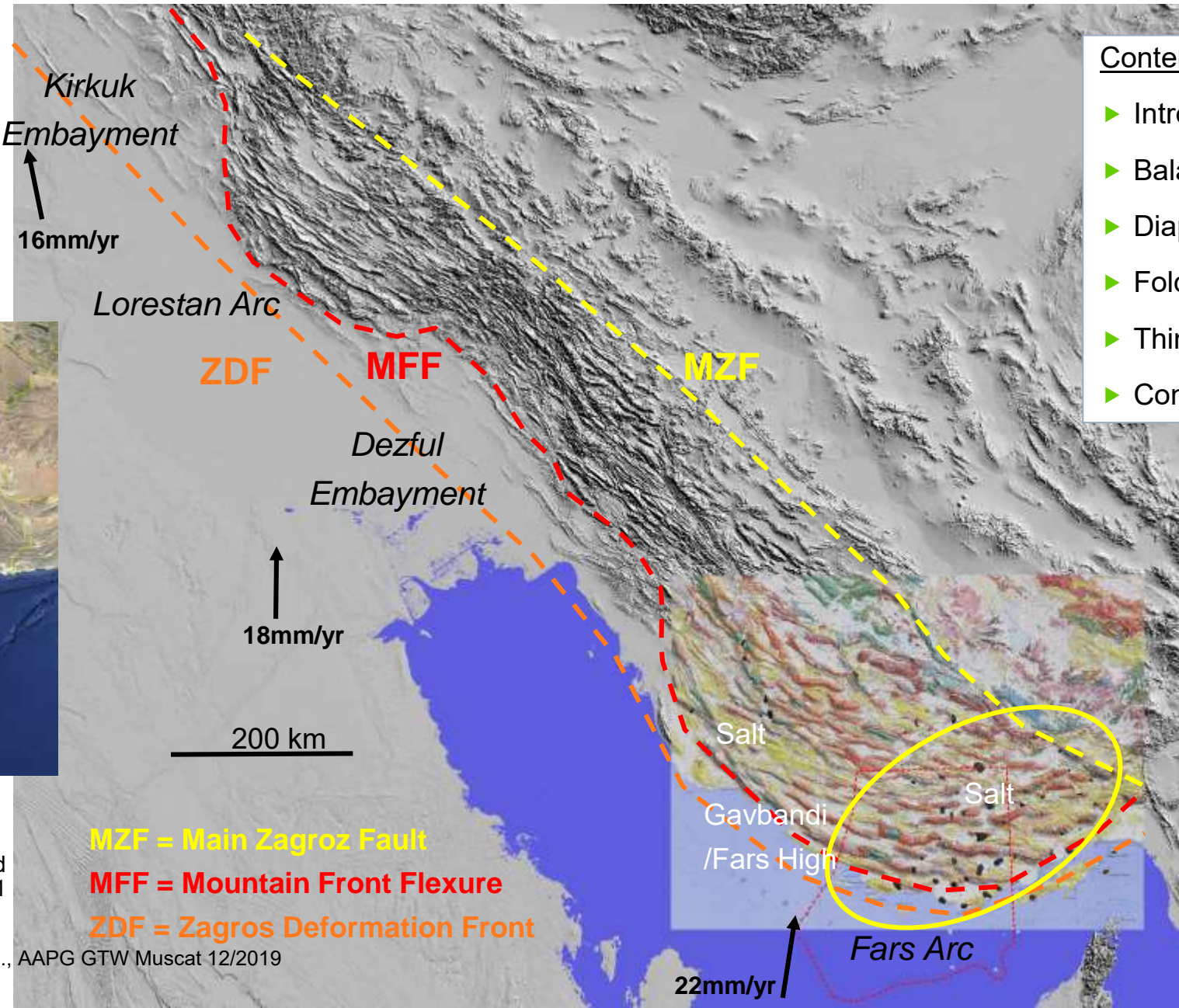
OMV Upstream



Introduction: Regional setting

Joint geoscientific study
OMV + NIOC
11/2016 until 10/2018.

Content
▶ Introduction
▶ Balancing issues
▶ Diapir development
▶ Fold pattern
▶ Thin-skinned/thick-skinned
▶ Conclusions



Area of distinct
physiognomy

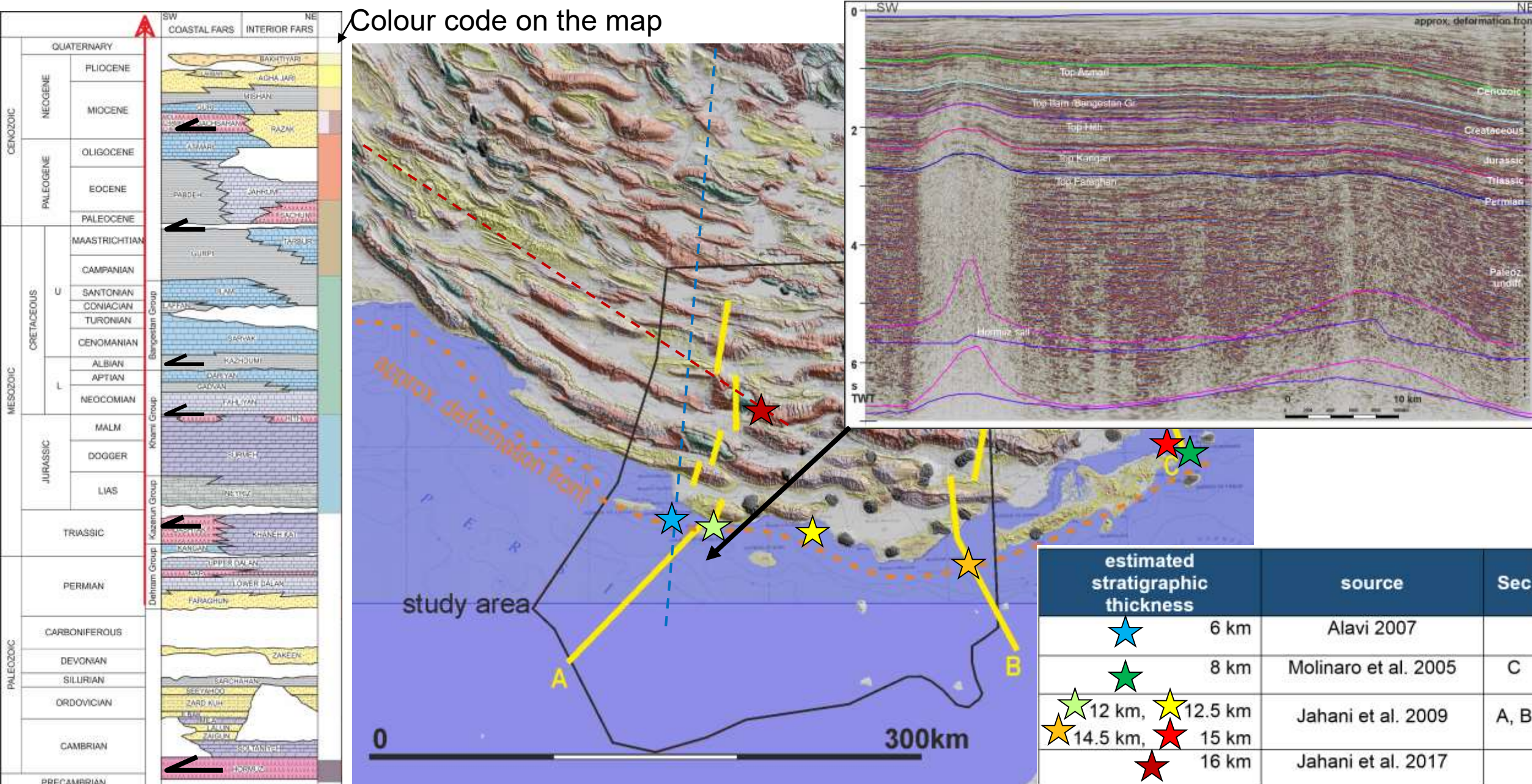
Setting elements modified
after Verges et al. 2011

MZF = Main Zagros Fault
MFF = Mountain Front Flexure
ZDF = Zagros Deformation Front

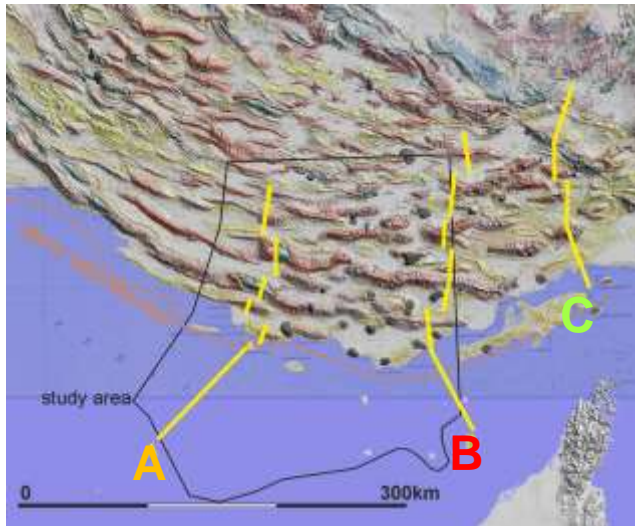
OMV Upstream, Hinsch et al., AAPG GTW Muscat 12/2019



Introduction: surface geology and stratigraphy

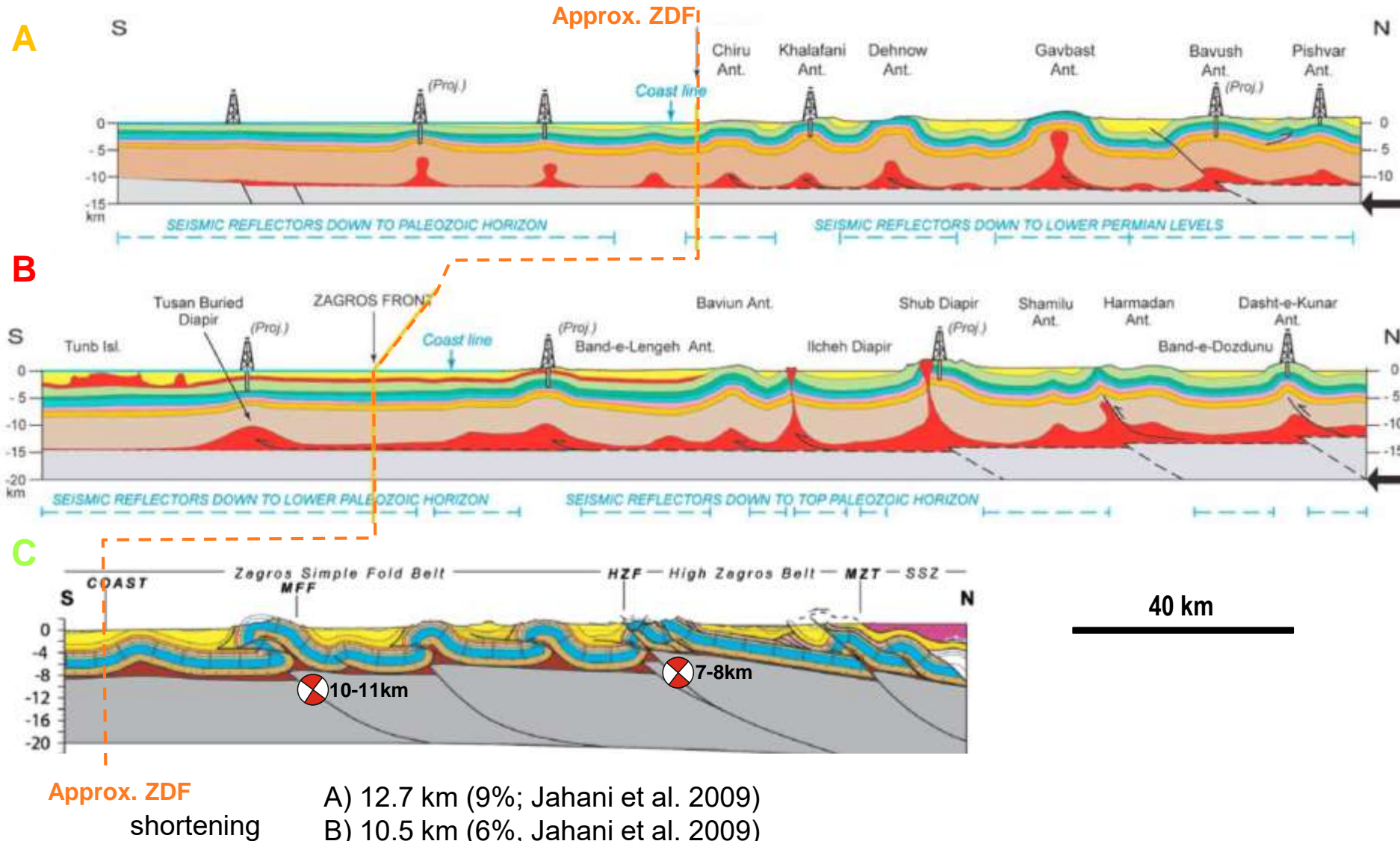


Example published structural cross sections



Some of the key questions:

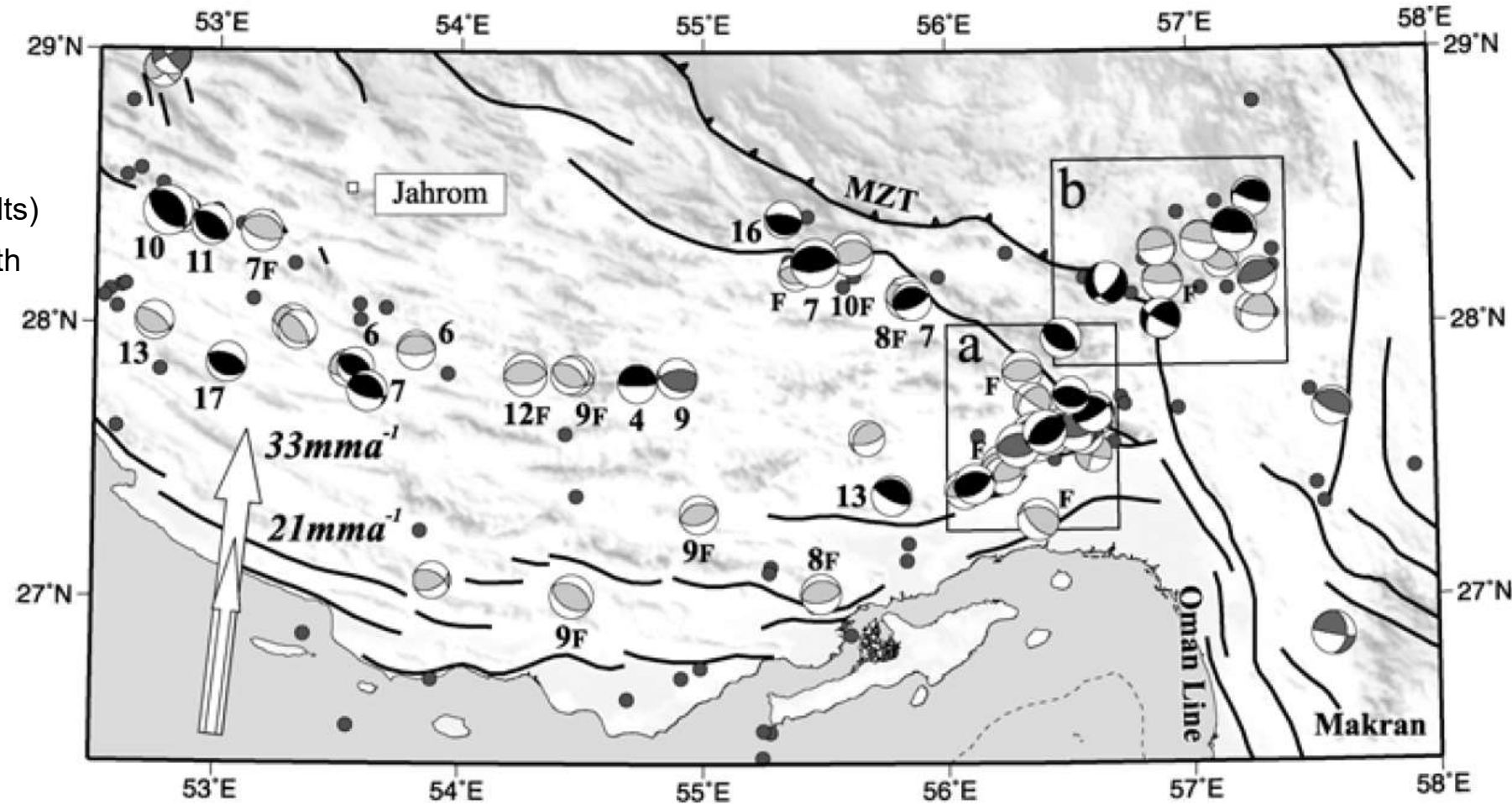
- ▶ Varying deformation style?
- ▶ Basement involvement
- ▶ Salt and stratigraphic thickness evolution



Introduction: Seismicity

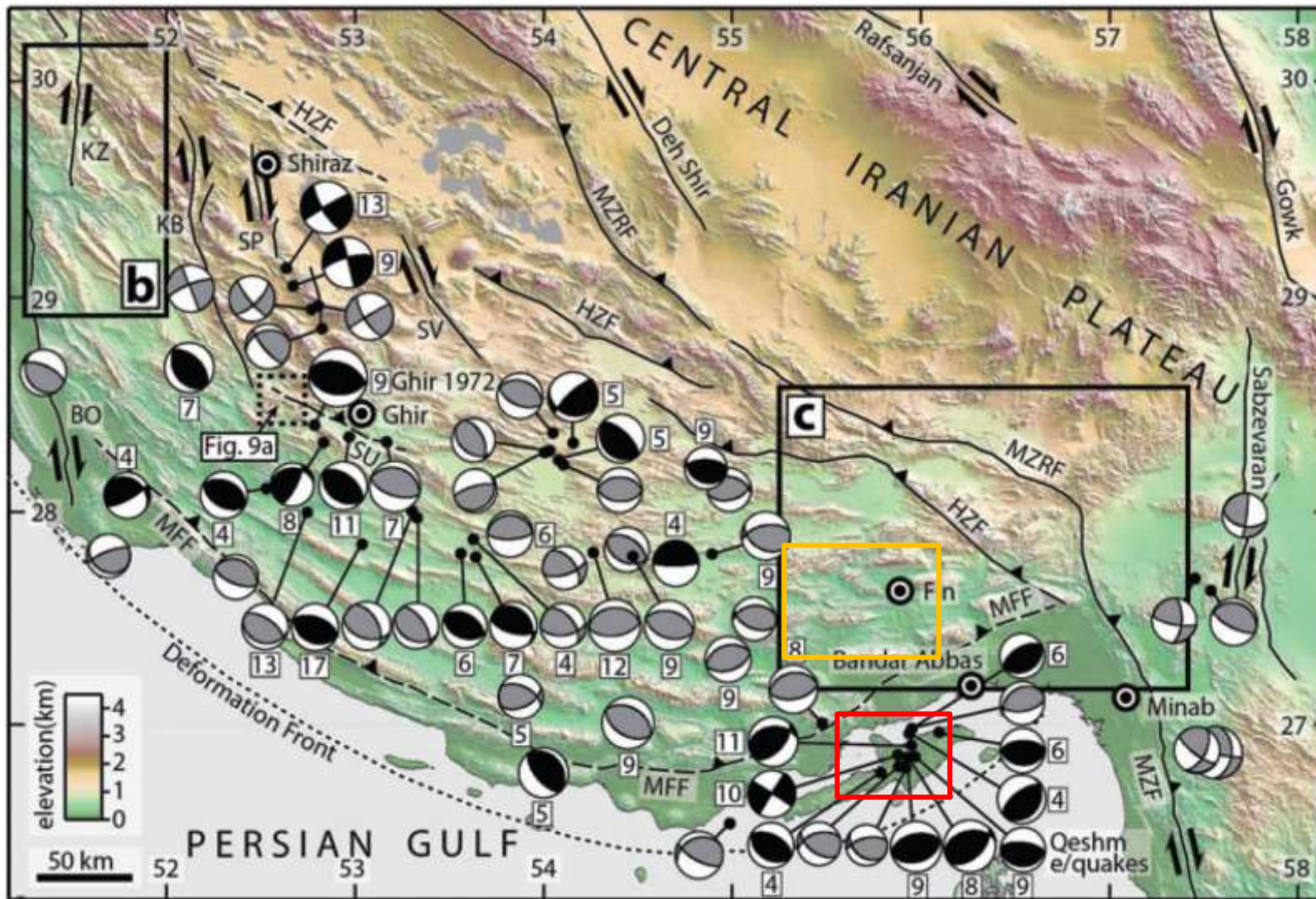
Telebian and Jackson 2004:

- ▶ Simple Folded Belt = carpet folding
- ▶ Basement fractured by large faults (High angle seismogenic reverse faults)
- ▶ ~ Top basement only at 5-10 km depth



Centroid depths in km, determined from waveform modelling, are marked alongside

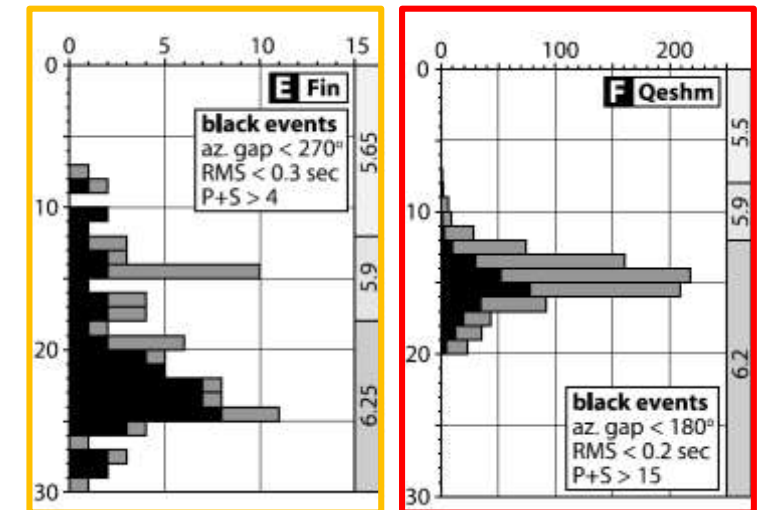
Introduction: Seismicity



Nissen et al., 2014:

- ▶ Most large earthquakes in carbonate rocks (midlower sedimentary cover)
- ▶ Crystalline basement shortens mostly aseismically.

Locally recorded microseismicity



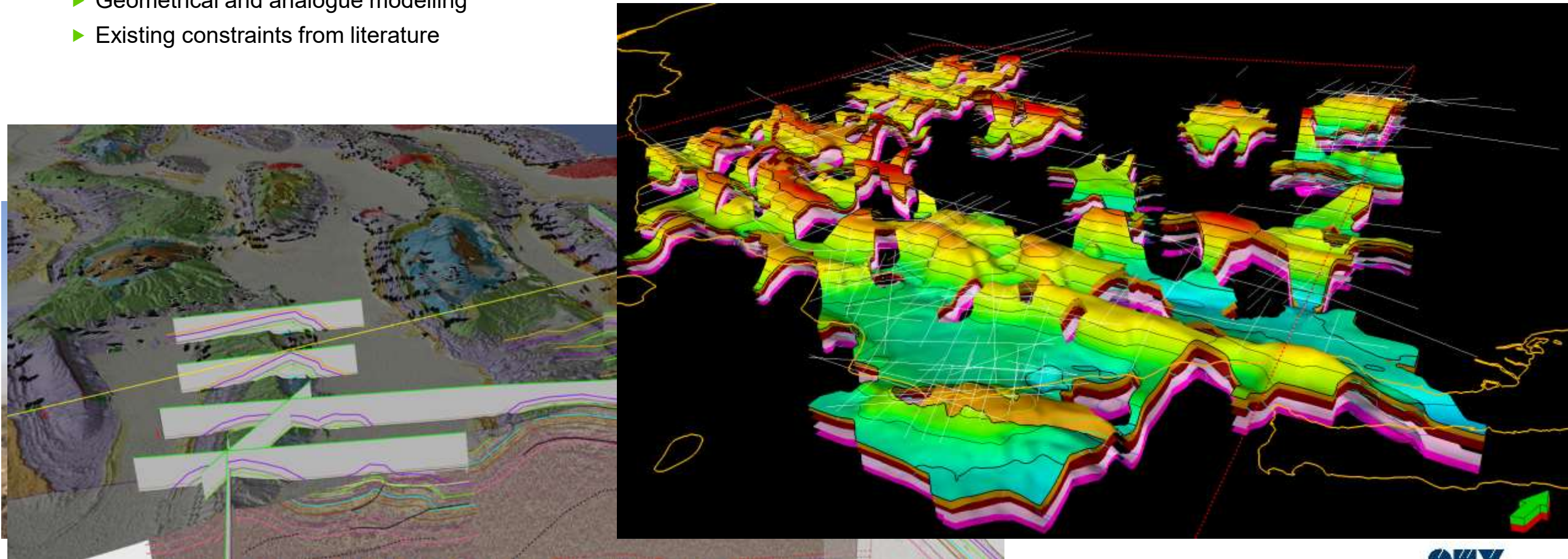
Centroid depths (in kilometre) independently constrained from P and/or S waves or InSAR (Nissen et al. 2011)

Quick overview of the study

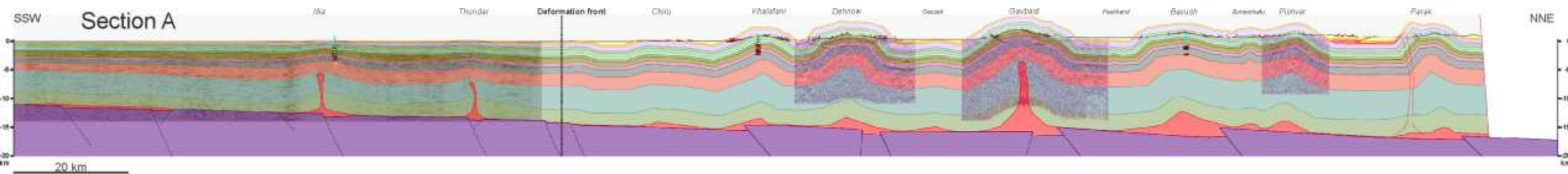
In our study (10/2016 - 10/2018) we used:

- ▶ Outcrop and surface geology observations (about 5-6 weeks of fieldwork)
- ▶ Gravity and other potential field data + modelling,
- ▶ Well data and reflection seismic (on- and offshore) + interpretation
- ▶ Geometrical and analogue modelling
- ▶ Existing constraints from literature

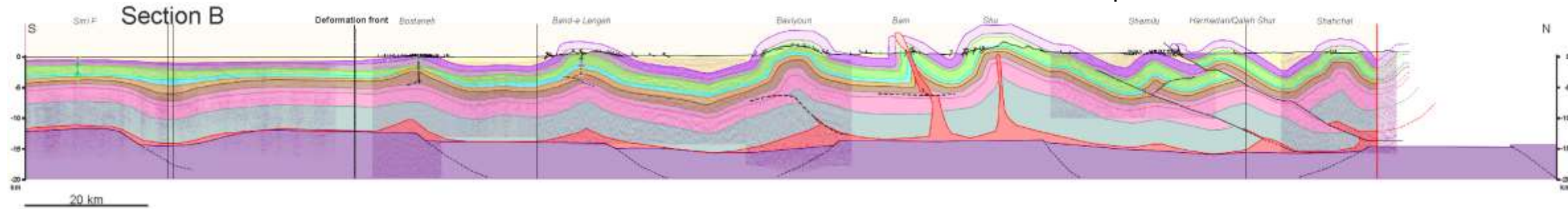
Example onshore 2D seismic structural interpretation



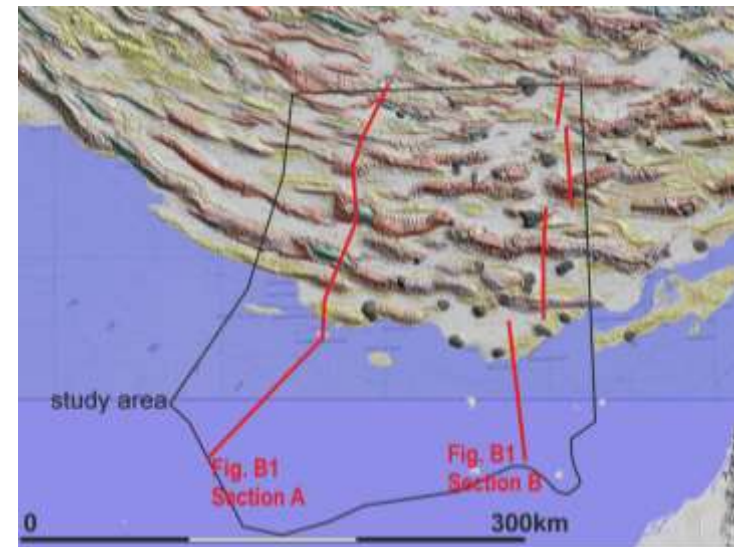
Balanced section



A simple solution in the west

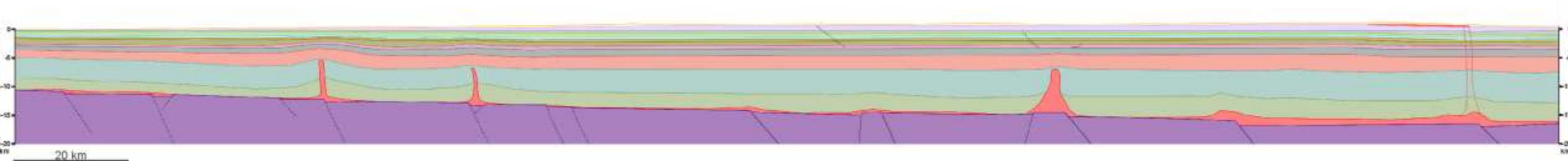


A more complicated solution in the east

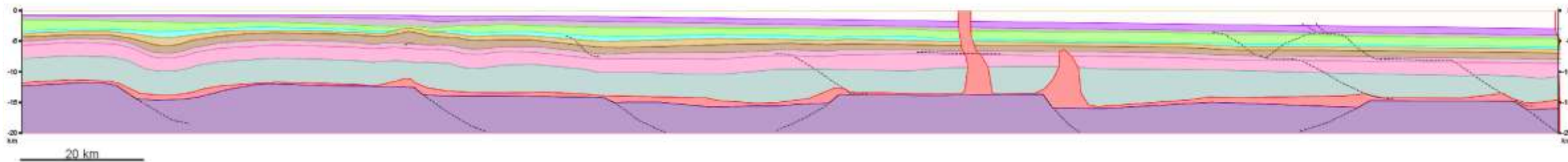


	Strat. thickness @ def. front. [m]	Shortening [m]	Shortening [%]
Section A	13873	13000	7.5
Section B	11575	34500	13.5

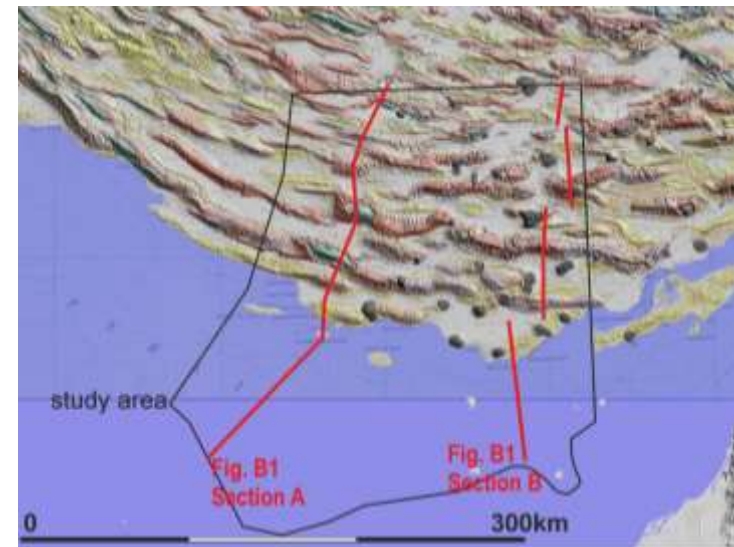
Balanced section



A simple solution in the west



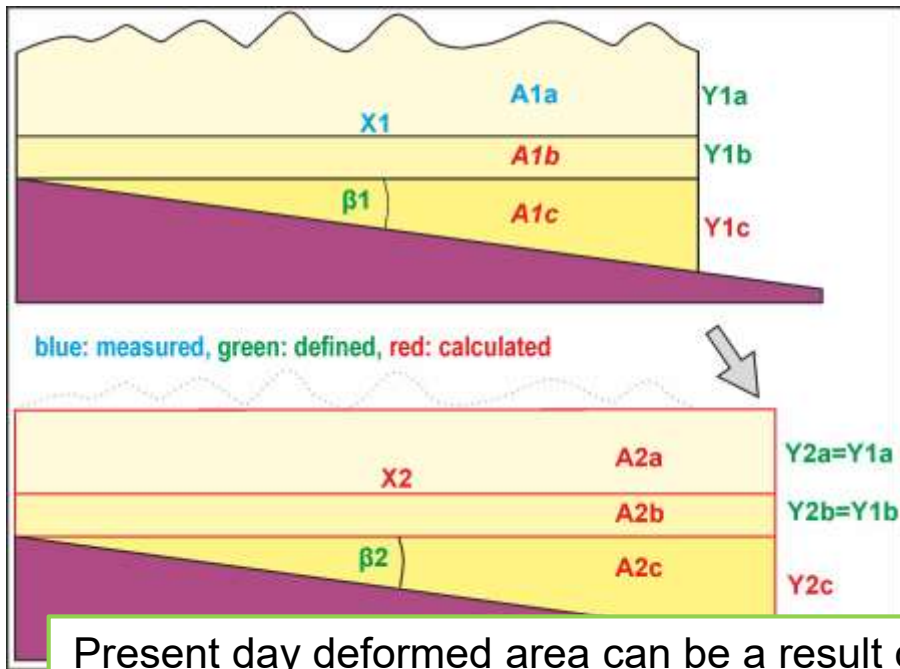
A more complicated solution in the east



	Strat. thickness @ def. front. [m]	Shortening [m]	Shortening [%]
Section A	13873	13000	7.5
Section B	11575	34500	13.5

Areal balancing

Sensitivity analysis with areal balancing



Present day deformed area can be a result of

- Different shortening values
- Combinations stratigraphic thickness + basement dip
- Unable to define basement contribution

case	Strat. Thickness [m]	Basement dip β1 [deg]	Basement dip β2 [deg]	Shortening [m]	Shortening [%]
Section A simplified	13873	1	1.11	13000	7.5
constant low β	7000	0.50	0.50	21977	12.1
	9000	0.50	0.50	17817	10.0
	11000	0.50	0.50	14974	8.6
	13000	0.50	0.50	12911	7.5
	15000	0.50	0.50	11345	6.6
constant β	7000	1.00	1.00	17063	9.7
	9000	1.00	1.00	15648	8.9
	11000	1.00	1.00	13419	7.8
	13000	1.00	1.00	11742	6.9
	15000	1.00	1.00	10436	6.1
Increasing β 0.25	7000	1.00	1.25	11292	6.6
	9000	1.00	1.25	10403	6.1
	11000	1.00	1.25	8987	5.3
	13000	1.00	1.25	7908	4.7
	15000	1.00	1.25	7060	4.2
Increasing β 0.5	7000	1.00	1.50	6158	3.7
decreasing β 0.5	7000	1.00	0.50	31233	16.4
	9000	1.00	0.50	28298	15.1
	11000	1.00	0.50	23813	13.0
	13000	1.00	0.50	20547	11.4
	15000	1.00	0.50	18066	10.2
β 0.75	7000	1.00	0.25	40200	20.1
	9000	1.00	0.25	36120	18.5
	11000	1.00	0.25	30019	15.8
	13000	1.00	0.25	25674	13.9
	15000	1.00	0.25	22424	12.3



See poster!

Fay forward

So, what can we do?

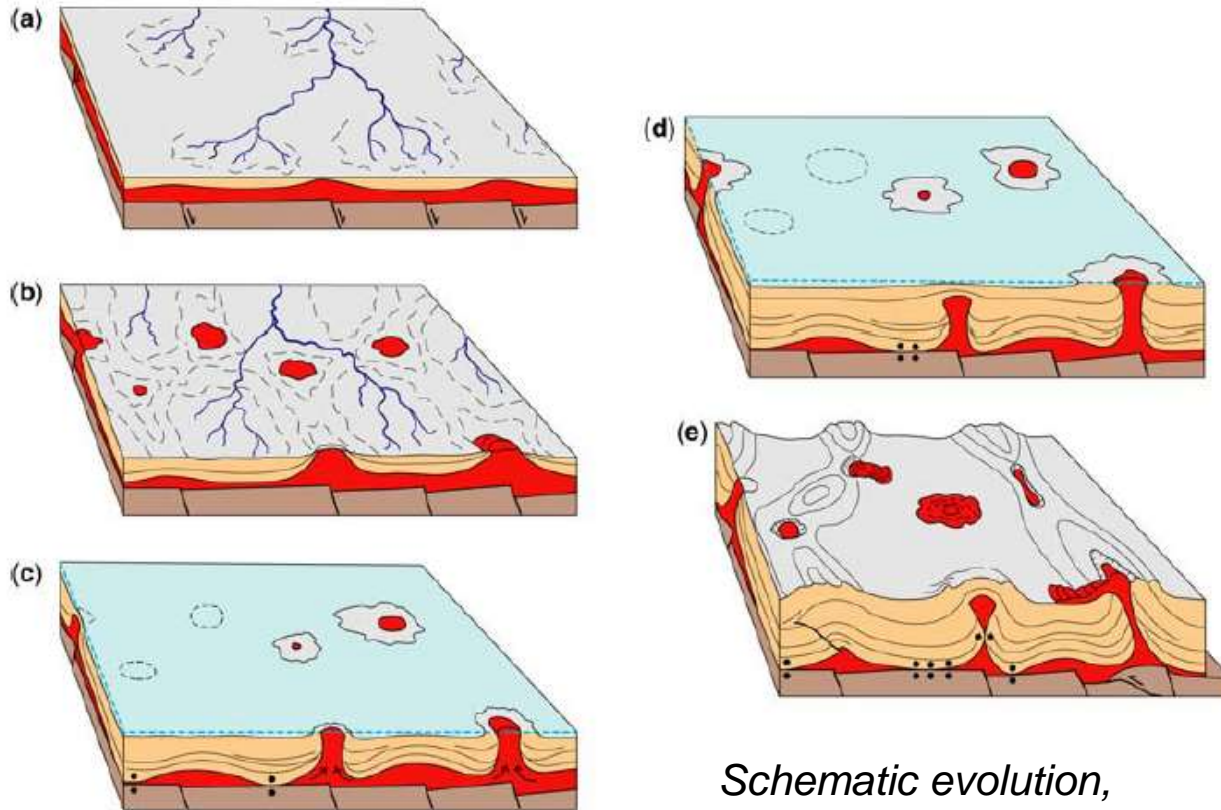
- ▶ Trying to understand processes to answer following questions:
 - ▶ What can explain the complex folding pattern?
 - ▶ What explains the distribution and the shape of diapirs?
 - ▶ Why is the deformation front located where its is?
 - ▶ Why is the deformation apparently slowly propagating to the foreland



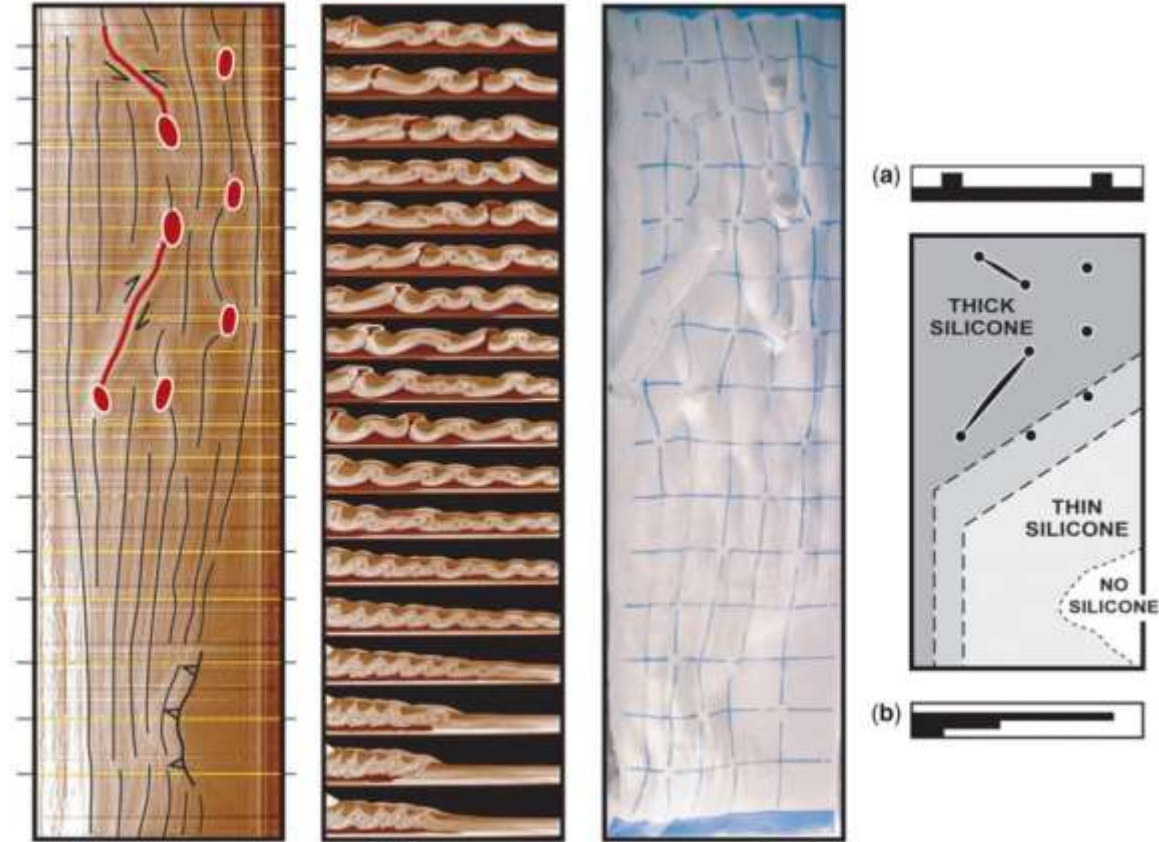
Recent insights...

- ▶ Diapirism and downbuilding active since the early Paleozoic
- ▶ Draping above some buried diapirs
- ▶ Partly localizing and interference with folds and faults

Jahani et al., 2009, Callot et al., 2007, Callot et al., 2012, Jahani et al. 2017

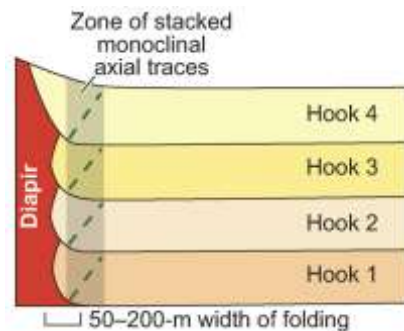
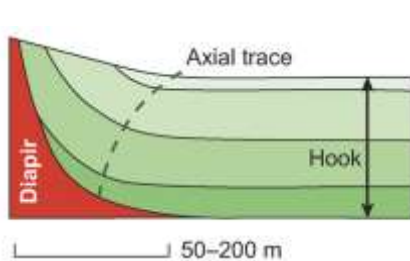
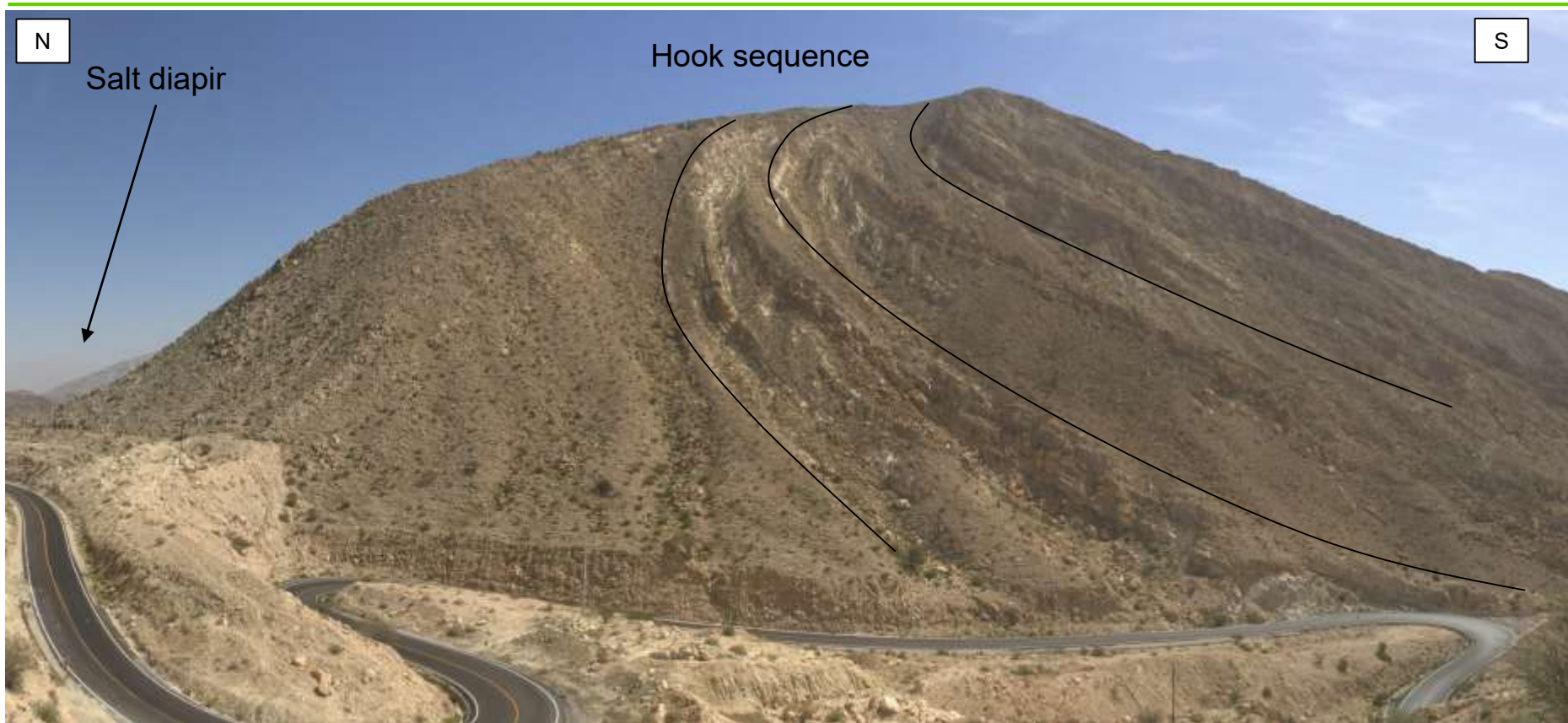


*Schematic evolution,
Callot et al., 2012*



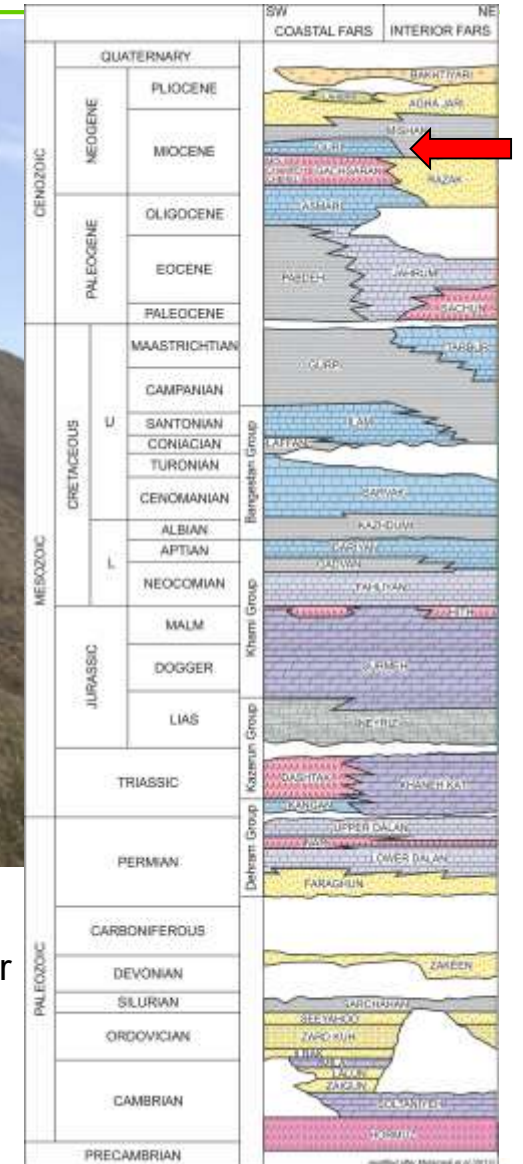
*Orientation of fold axes and faults influenced by
pre-existing diapirs and salt walls, Callot et al., 2012*

Stratigraphic evolution close to diapirs

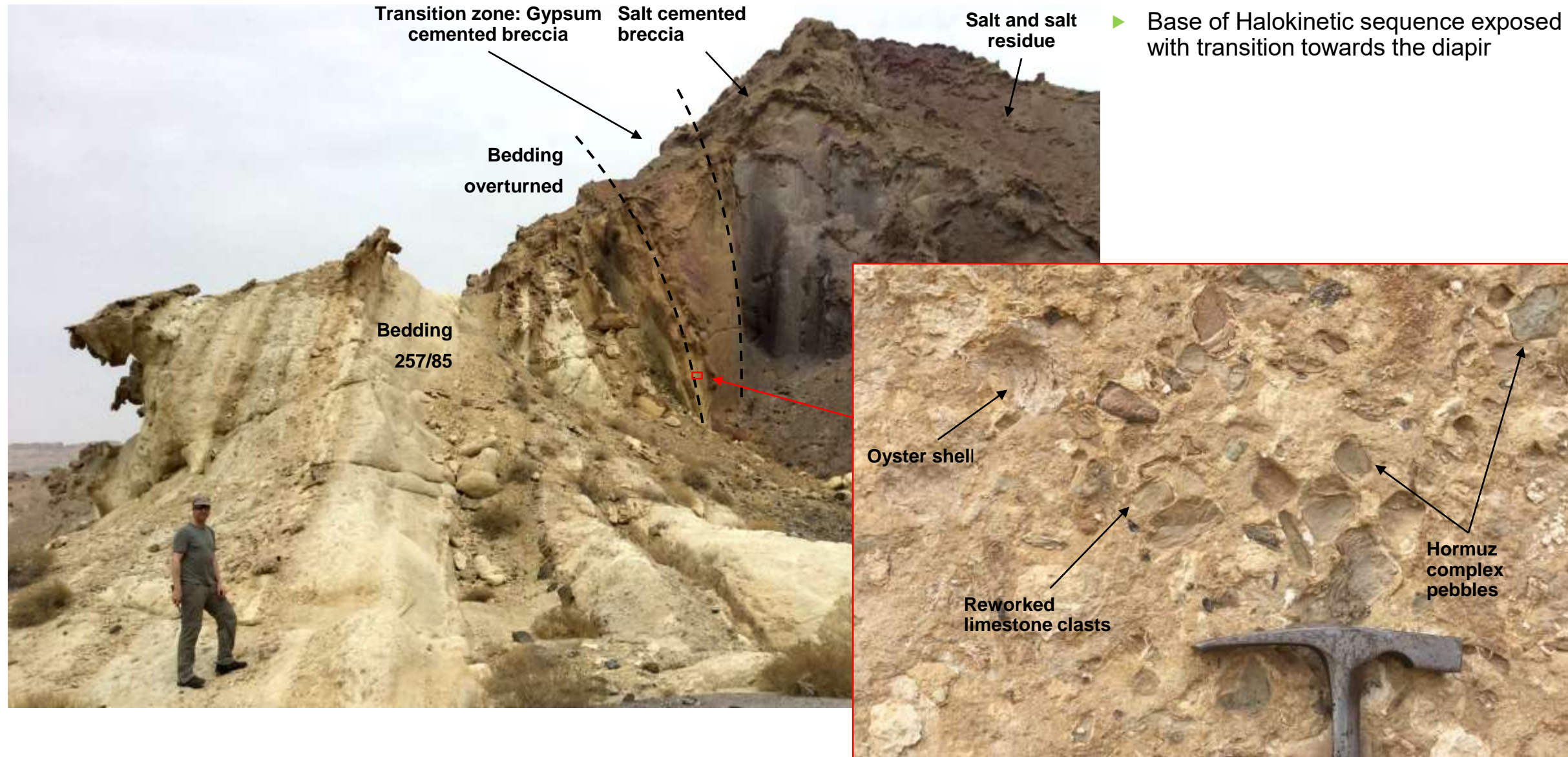


- ▶ Passive growth diapirism
- ▶ Halokinetic hook sequence in Miocene Guri Member on southern fringe of Chahar Berkeh (Herang)
- ▶ Influence radius of diapir usually < 1km

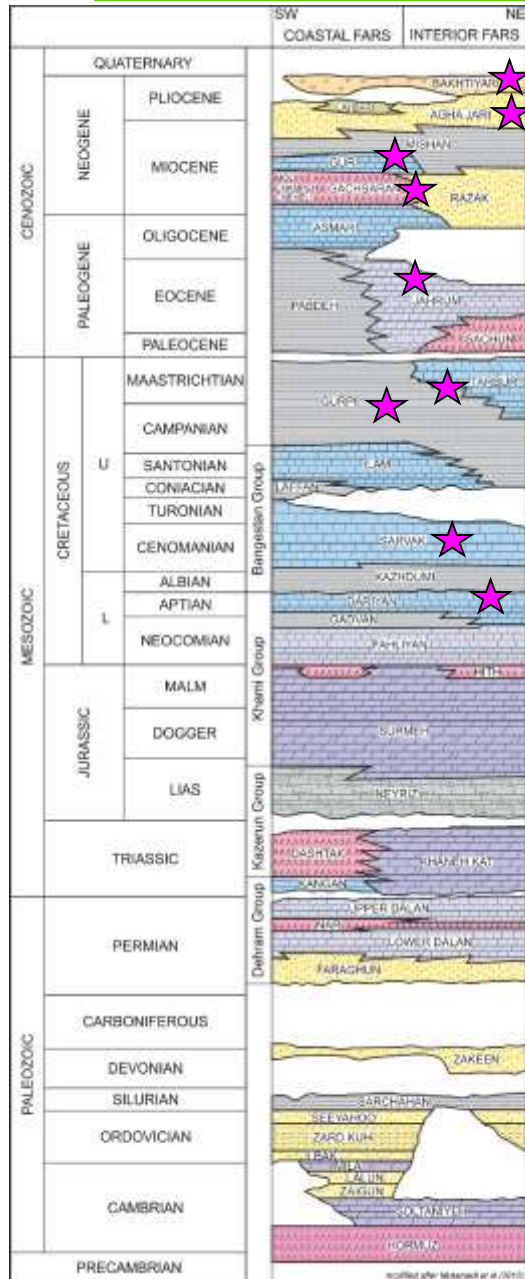
Hooks and stacked hooks
(Jackson and Hudec, 2017)



Stratigraphic evolution close to diapirs



Indication on strong salt movements



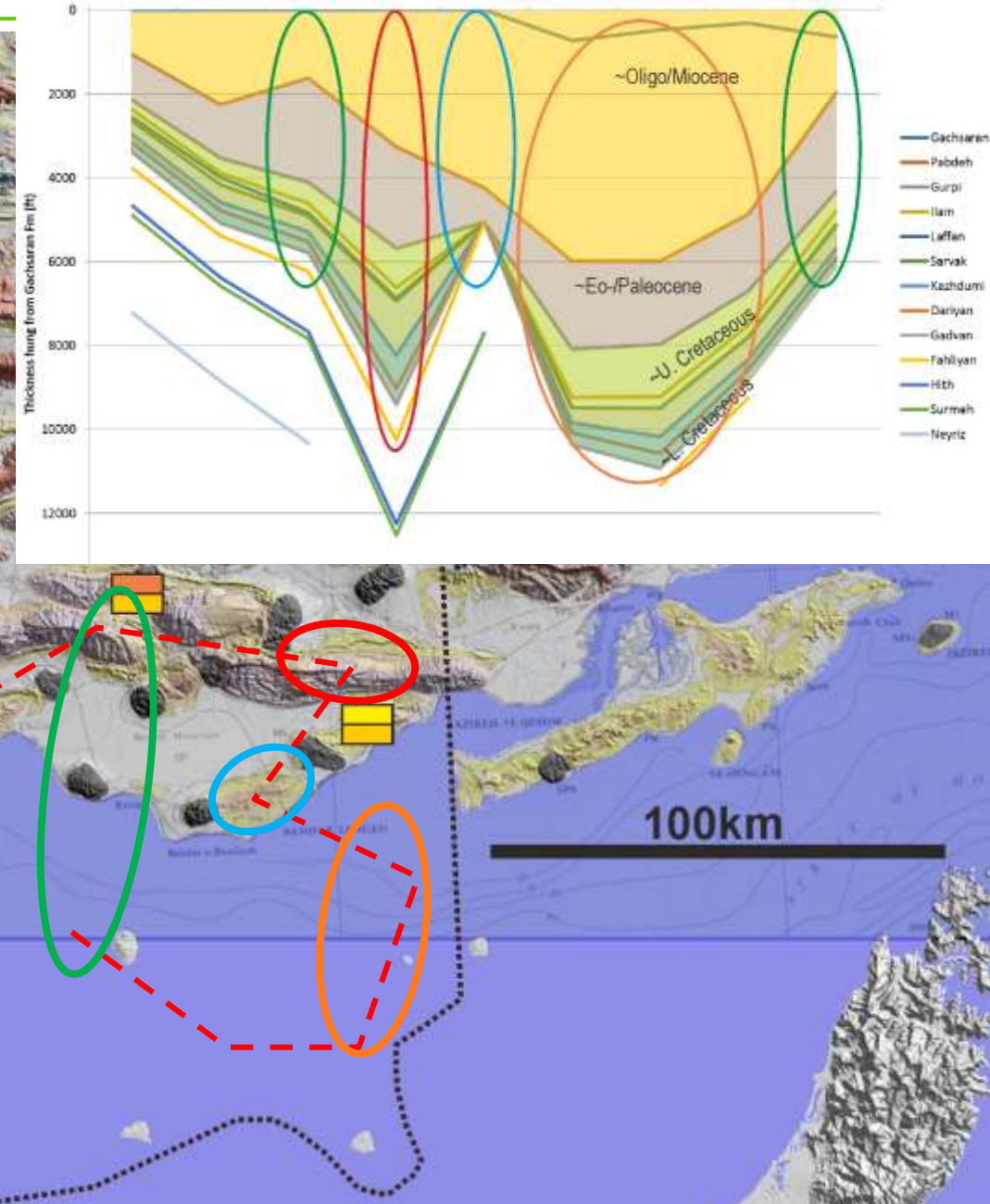
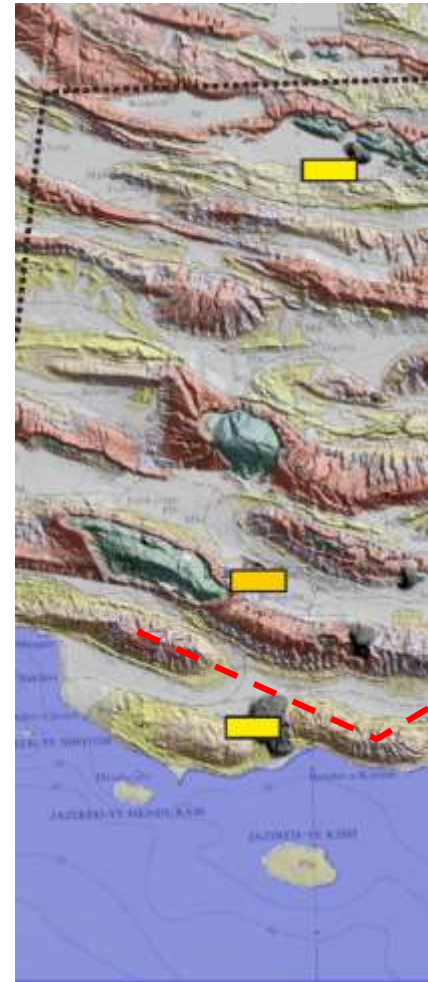
Youngest/oldest strata with Hormuz Gp./ strong indications of salt movement



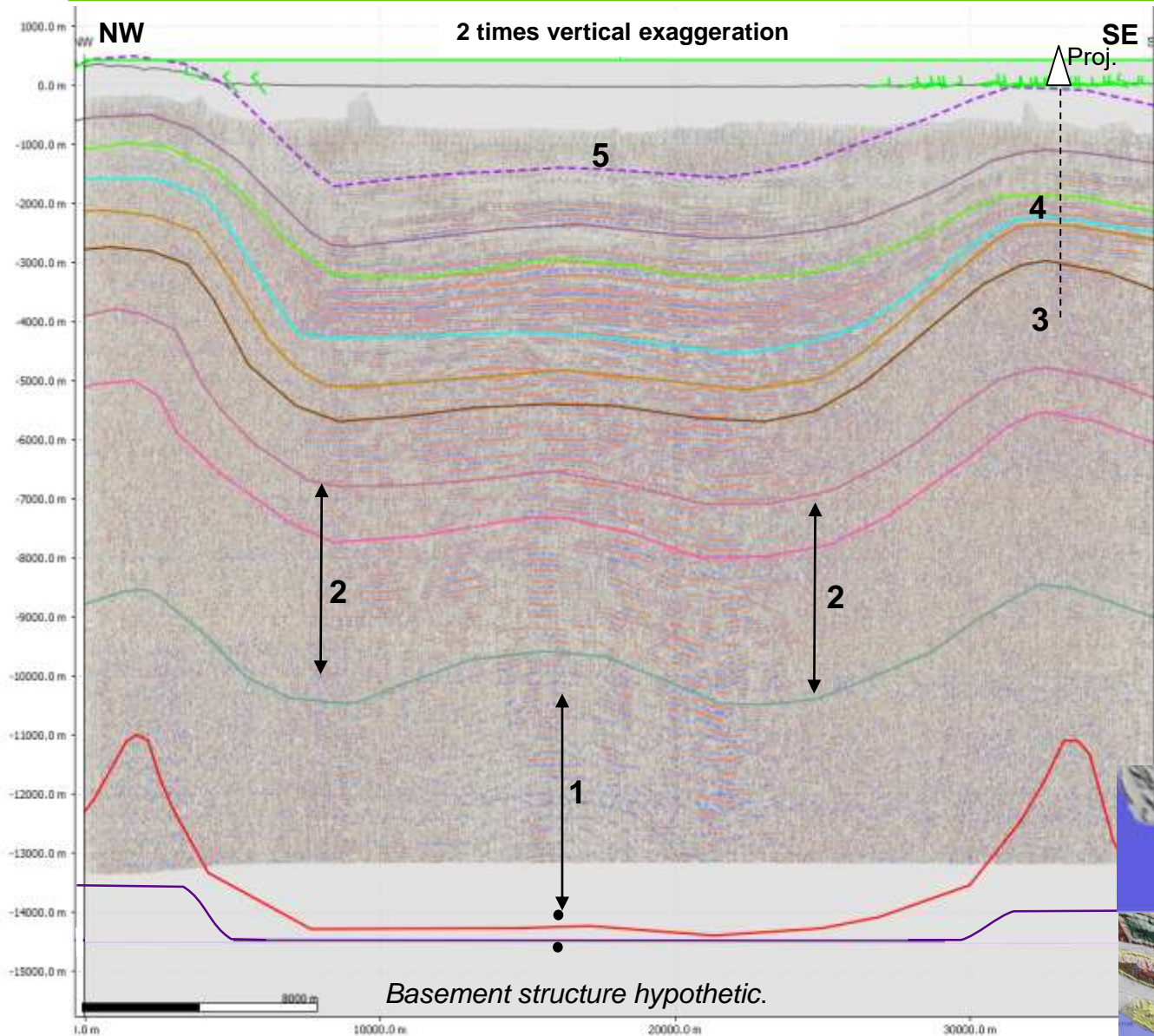
Field evidence for Hormuz Gp. material in stratigraphy

Thickness variations in Cretaceous+Post-Cretaceous

- high increase of thickness
- slight increase of thickness
- erosion of most of Cretaceous



Seismic example: Deformation history onshore



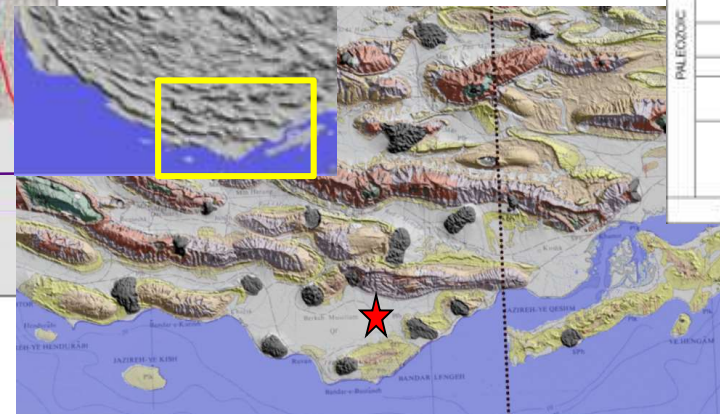
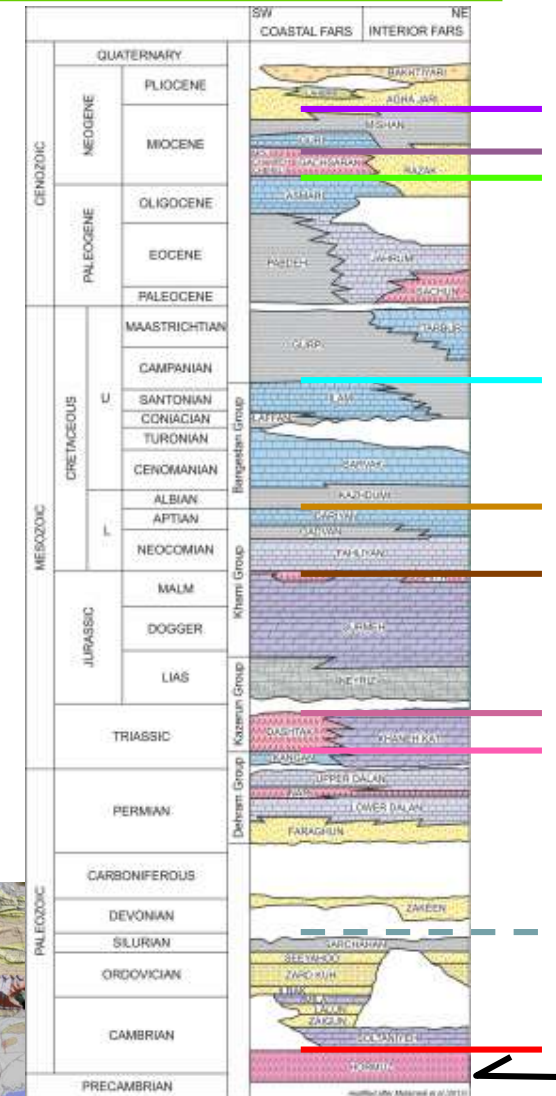
5) Post Miocene shortening

4) Thinning and erosion in Cretaceous and Post-Cretaceous

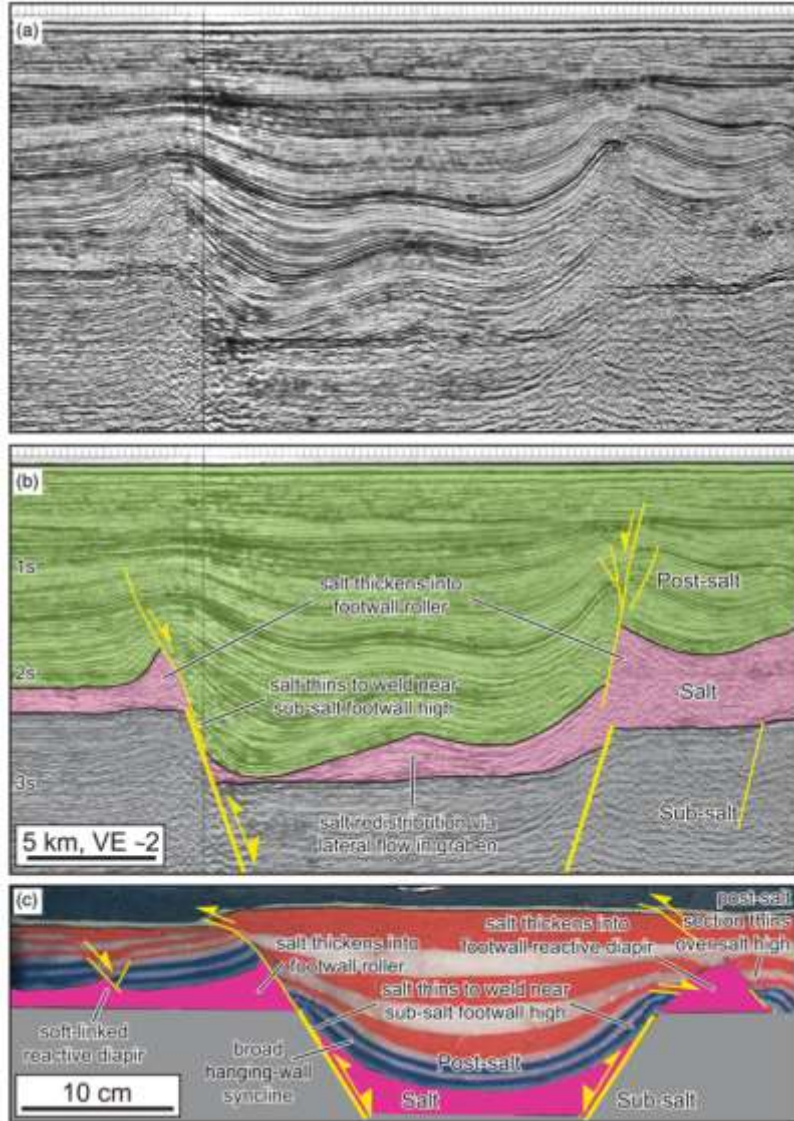
3) Thickening in Jurassic

2) Shifting depocenters in Permian/Triassic

1) Initial depocenter Lower Paleozoic

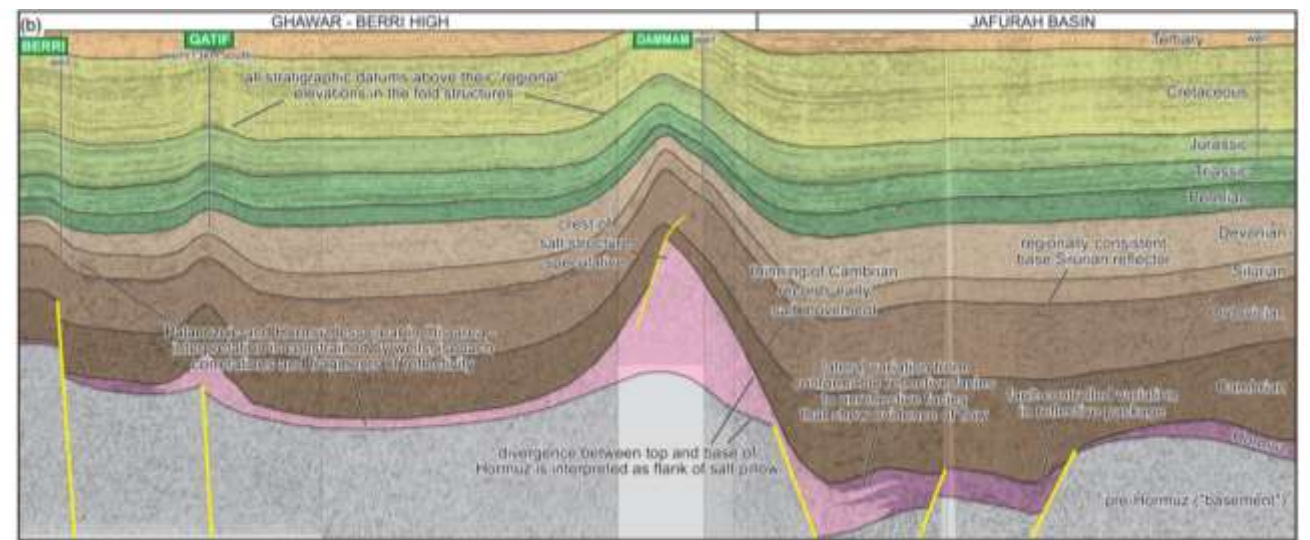


Comparing...



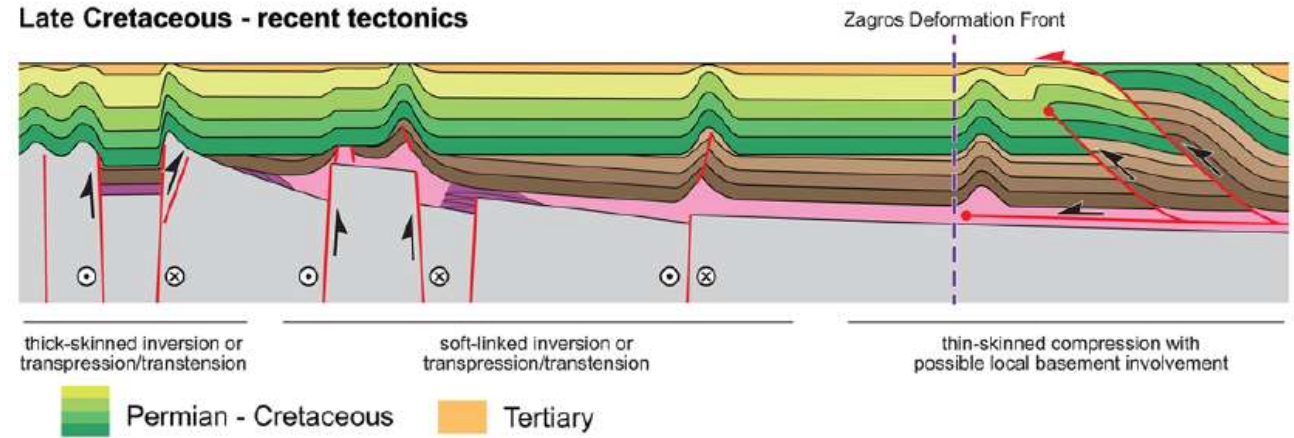
North Sea and analogue modelling example (TGS and Dooley et al. 2005), from Stewart, 2017

OMV Upstream, Hinsch et al., AAPG GTW Muscat 12/2019



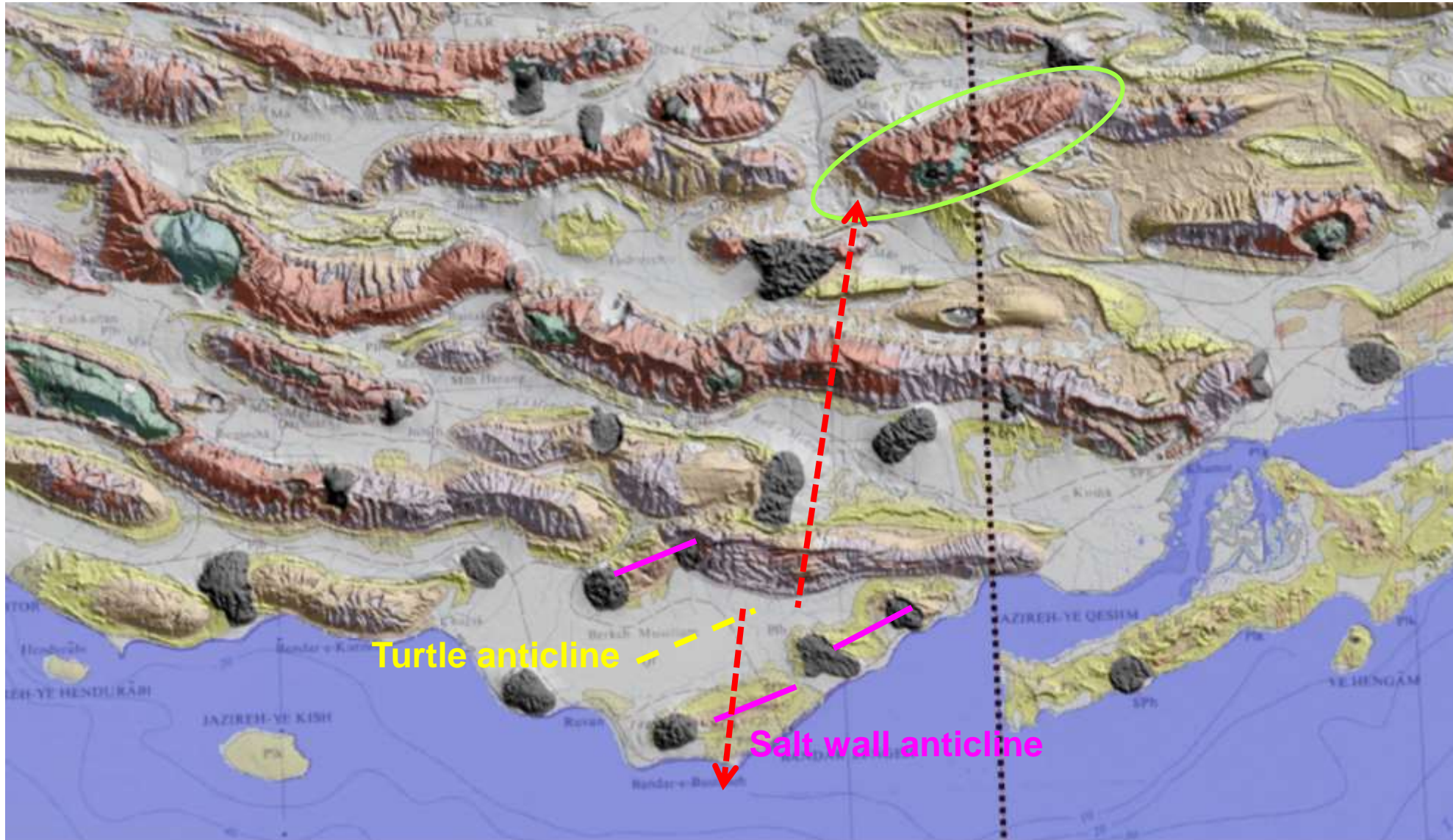
Saudia Arabia Seismic interpretation from Stewart, 2017

Late Cretaceous - recent tectonics



Structural sketch section from the Arabian Shield to the Zagros, from Stewart, 2017

Interference of inherited direction and shortening



large scale
anticline(s) ?

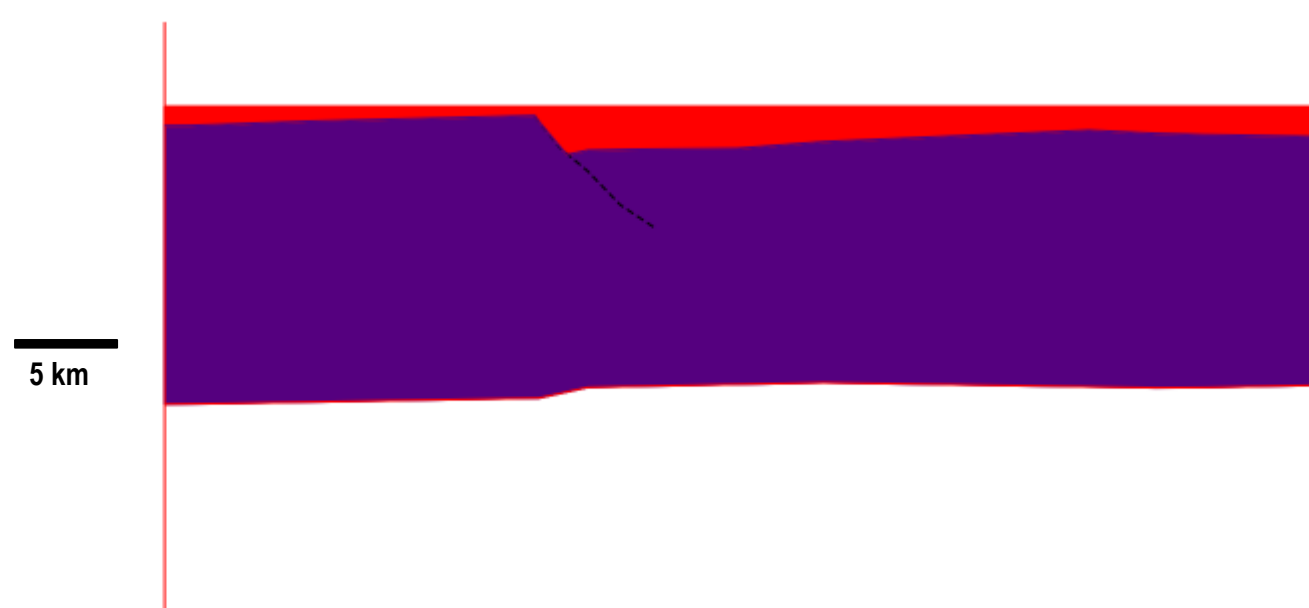
← - - -
Line length
shortening:
~ 10-11 km

Two possibilities for basement influence

Let's consider a simplistic model:

- ▶ Thicker Hz salt is deposited in extensional related accommodation space

Note: geometric algorithm artefacts not realistic

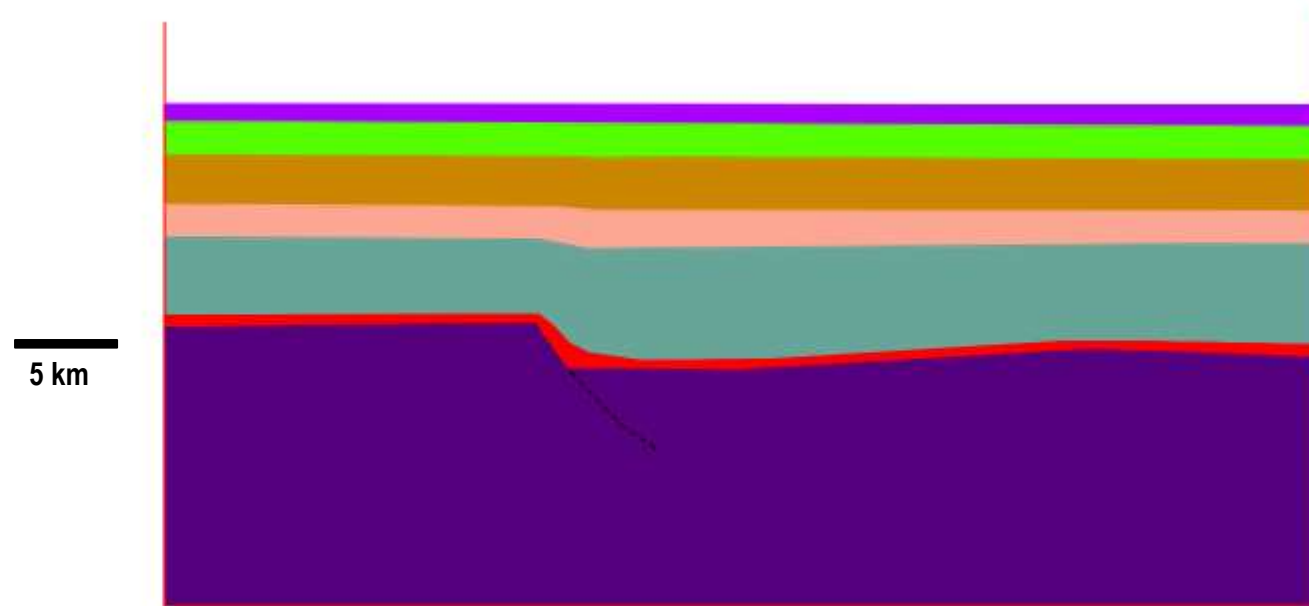


Two possibilities for basement influence

Let's consider a simplistic model:

- ▶ Thicker Hz salt is deposited in extensional related accommodation space
- ▶ Post-salt sequence thickening into salt evacuation basin – salt moves to diapir out of section.

Note: geometric algorithm artefacts not realistic

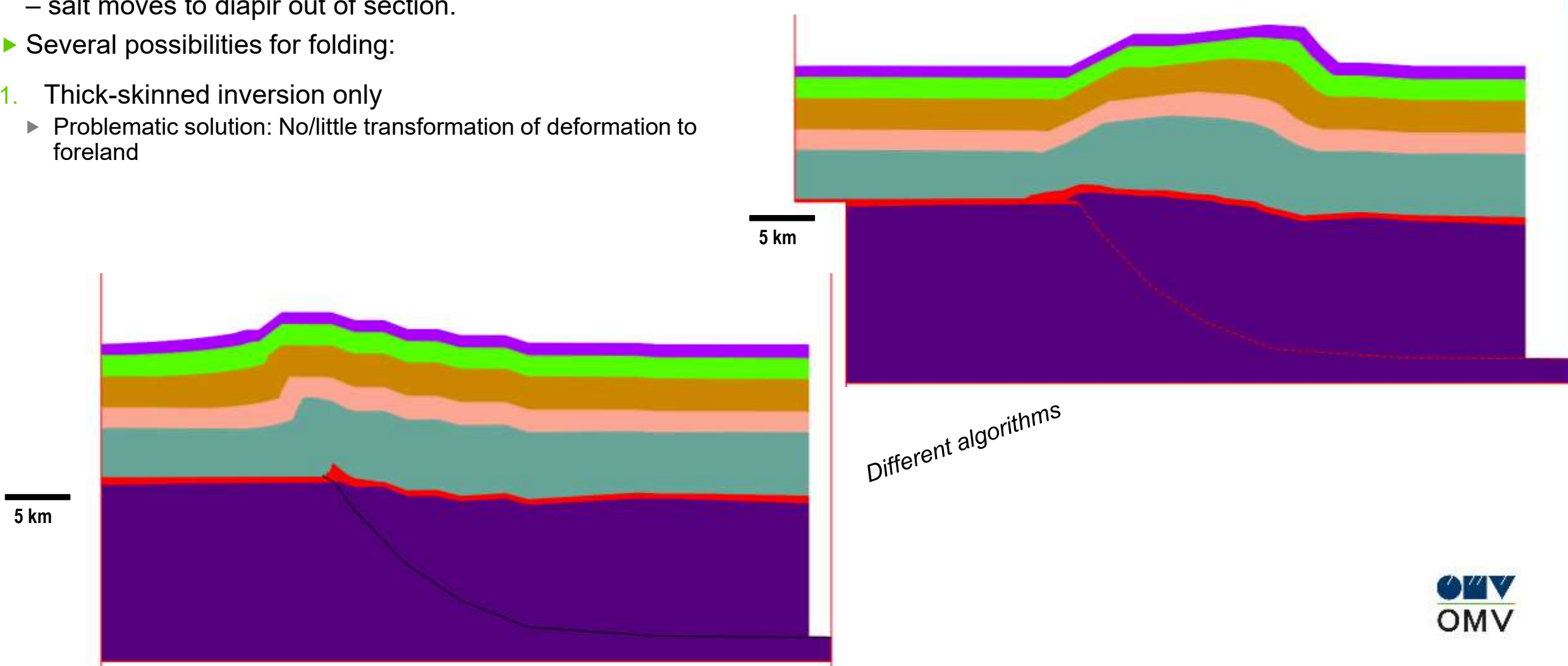


Two possibilities for basement influence

Let's consider a simplistic model:

- ▶ Thicker Hz salt is deposited in extensional related accommodation space
- ▶ Post-salt sequence thickening into salt evacuation basin – salt moves to diapir out of section.
- ▶ Several possibilities for folding:
 1. Thick-skinned inversion only
 - ▶ Problematic solution: No/little transformation of deformation to foreland

Note: geometric algorithm artefacts not realistic

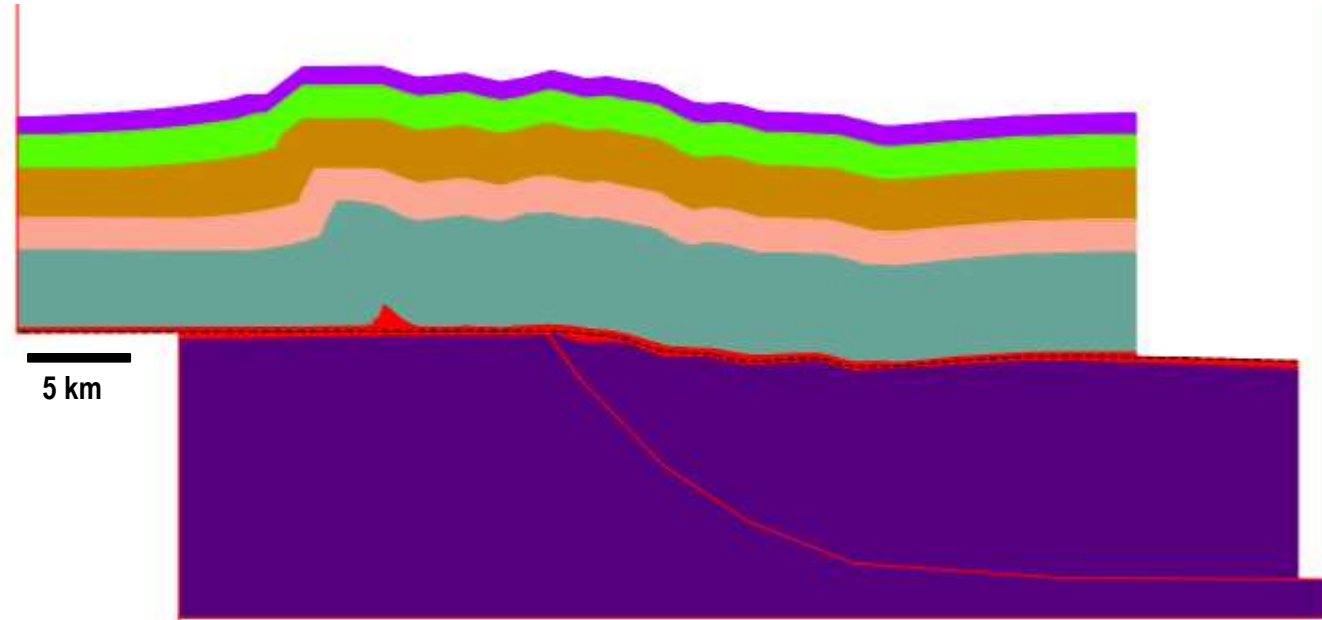


Two possibilities for basement influence

Let's consider a simplistic model:

- ▶ Thicker Hz salt is deposited in extensional related accommodation space
- ▶ Post-salt sequence thickening into salt evacuation basin – salt moves to diapir out of section.
- ▶ Several possibilities for folding:
 1. Thick-skinned inversion only
 - ▶ Problematic solution: No/little transformation of deformation to foreland
 2. Partly thick-skinned inversion + thin-skinned translation
 - ▶ Possible solution: generating an inversion anticline with long backlimb

Note: geometric algorithm artefacts not realistic

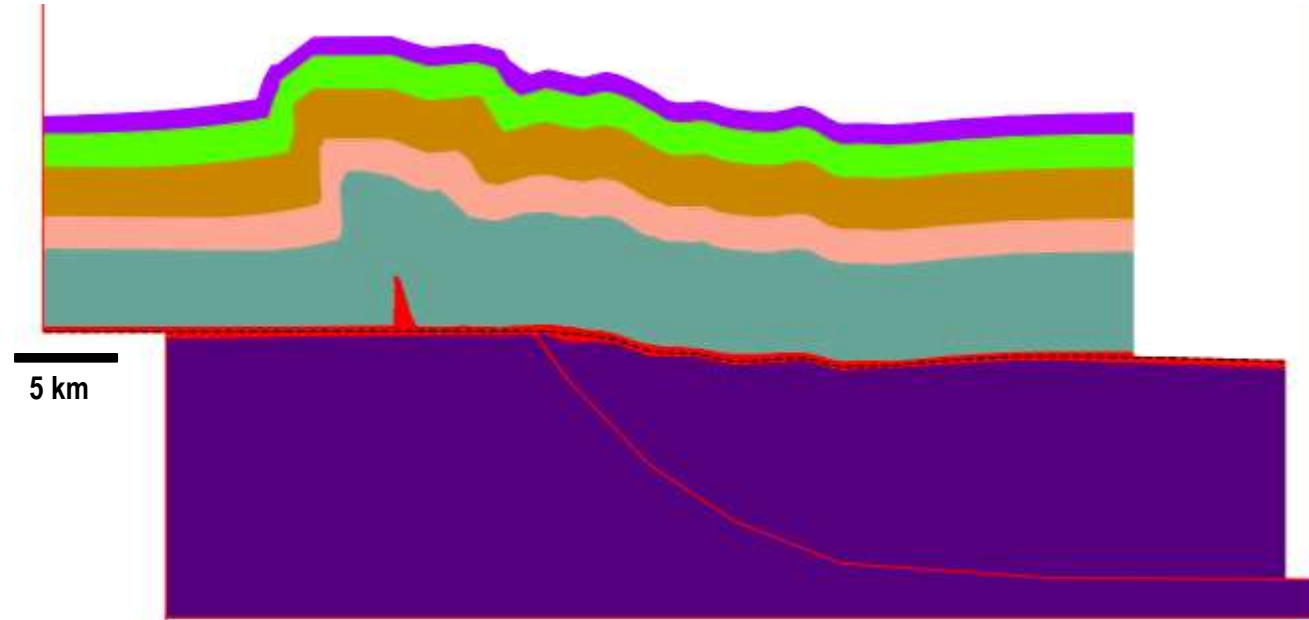


Two possibilities for basement influence

Let's consider a simplistic model:

- ▶ Thicker Hz salt is deposited in extensional related accommodation space
- ▶ Post-salt sequence thickening into salt evacuation basin – salt moves to diapir out of section.
- ▶ Several possibilities for folding:
 1. Thick-skinned inversion only
 - ▶ Problematic solution: No/little transformation of deformation to foreland
 2. Partly thick-skinned inversion + thin-skinned translation
 - ▶ Possible solution: generating an inversion anticline with long backlimb
 3. Partly thick-skinned inversion + thin-skinned folding + translation
 - ▶ Possible solution: kink-band of folding should be in thin forelimb

Note: geometric algorithm artefacts not realistic

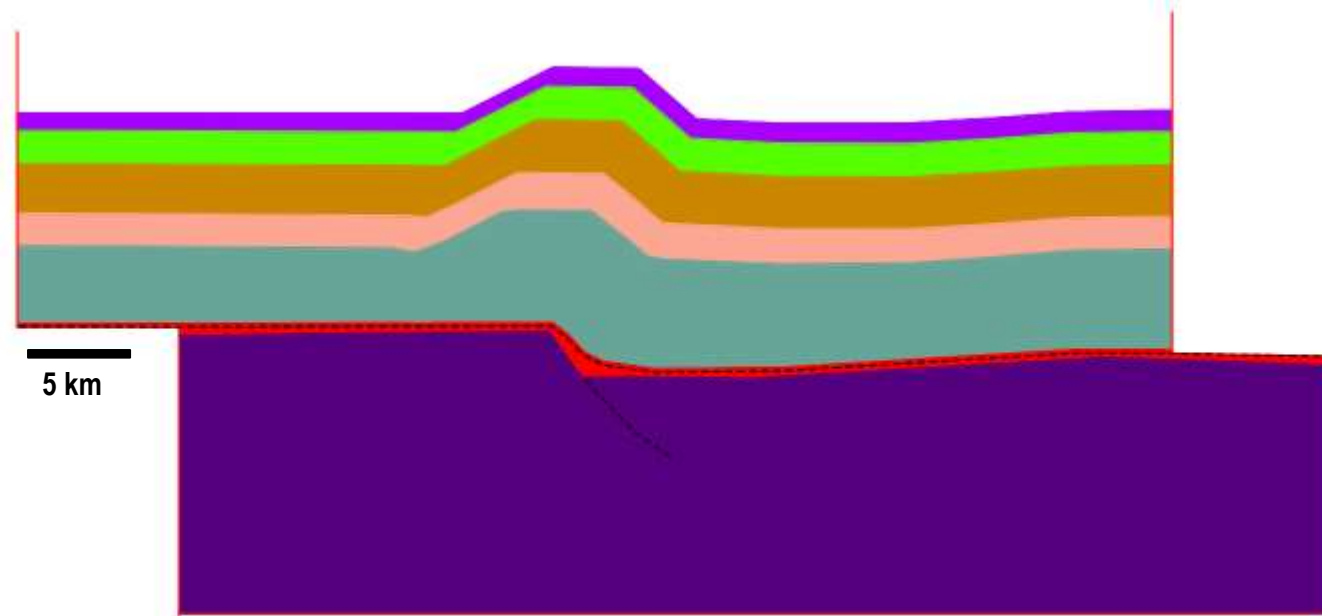


Two possibilities for basement influence

Let's consider a simplistic model:

- ▶ Thicker Hz salt is deposited in extensional related accommodation space
- ▶ Post-salt sequence thickening into salt evacuation basin – salt moves to diapir out of section.
- ▶ Several possibilities for folding:
 1. Thick-skinned inversion only
 - ▶ Problematic solution: No/little transformation of deformation to foreland
 2. Partly thick-skinned inversion + thin-skinned translation
 - ▶ Possible solution: generating an inversion anticline with long backlimb
 3. Partly thick-skinned inversion + thin-skinned folding + translation
 - ▶ Possible solution: kink-band of folding should be in thin forelimb
 4. Thin-skinned translation only
 - ▶ Possible solution: Inverting half-graben fill

Note: geometric algorithm artefacts not realistic

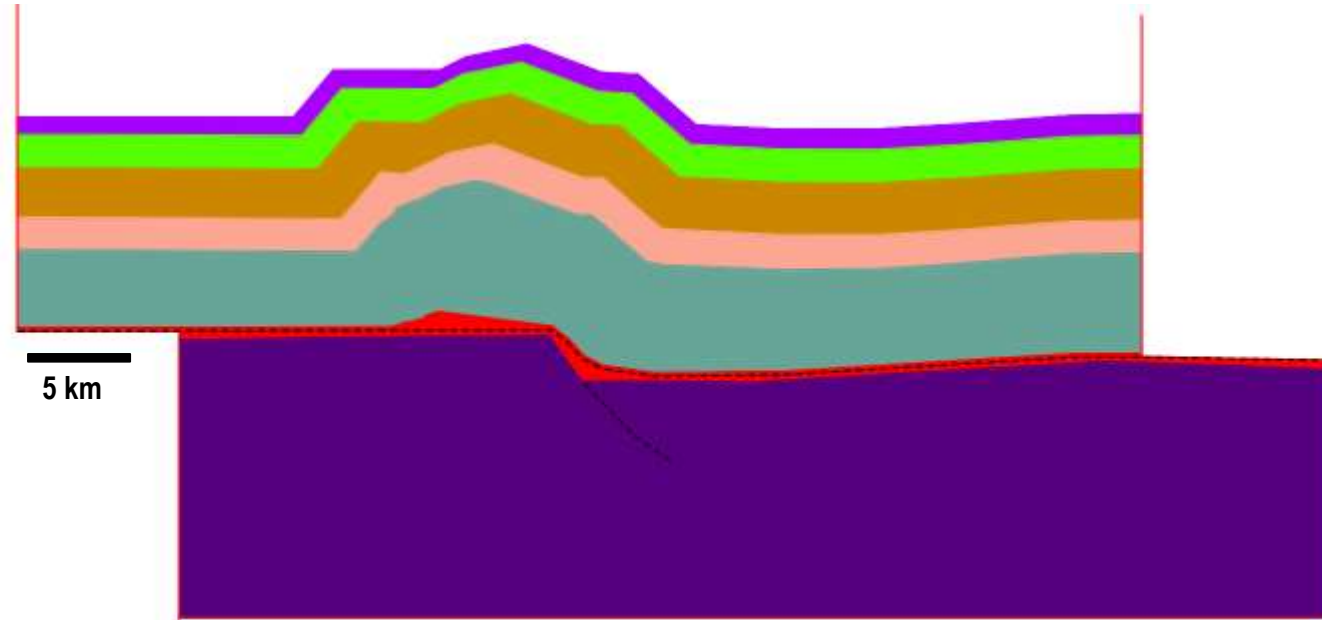


Two possibilities for basement influence

Let's consider a simplistic model:

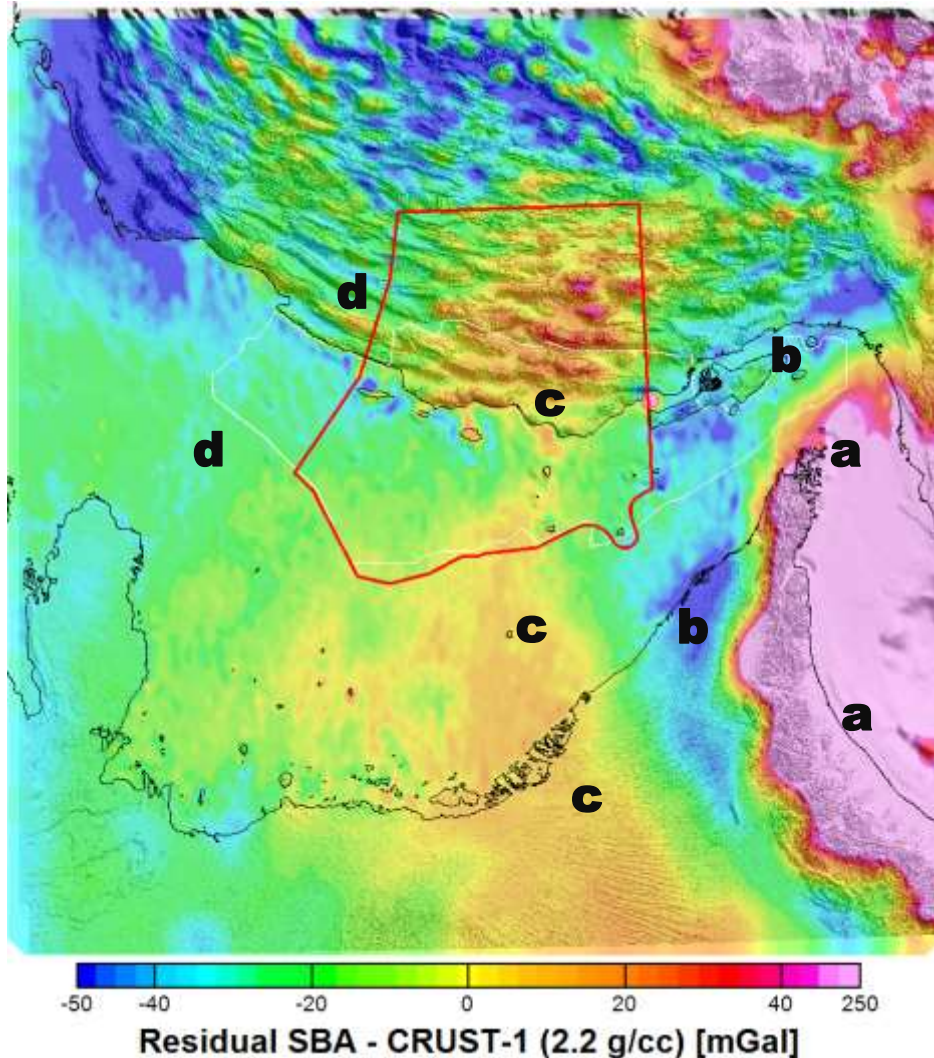
- ▶ Thicker Hz salt is deposited in extensional related accommodation space
- ▶ Post-salt sequence thickening into salt evacuation basin – salt moves to diapir out of section.
- ▶ Several possibilities for folding:
 1. Thick-skinned inversion only
 - ▶ Problematic solution: No/little transformation of deformation to foreland
 2. Partly thick-skinned inversion + thin-skinned translation
 - ▶ Possible solution: generating an inversion anticline with long backlimb
 3. Partly thick-skinned inversion + thin-skinned folding + translation
 - ▶ Possible solution: kink-band of folding should be in thin forelimb
 4. Thin-skinned translation only
 - ▶ Possible solution: Inverting half-graben fill
 5. Thin-skinned translation + some folding
 - ▶ Possible solution: Inverting half-graben fill + additional shortening

Note: geometric algorithm artefacts not realistic



→ “active” and “passive” influence from the basement on deformation

A quick gravity interpretation

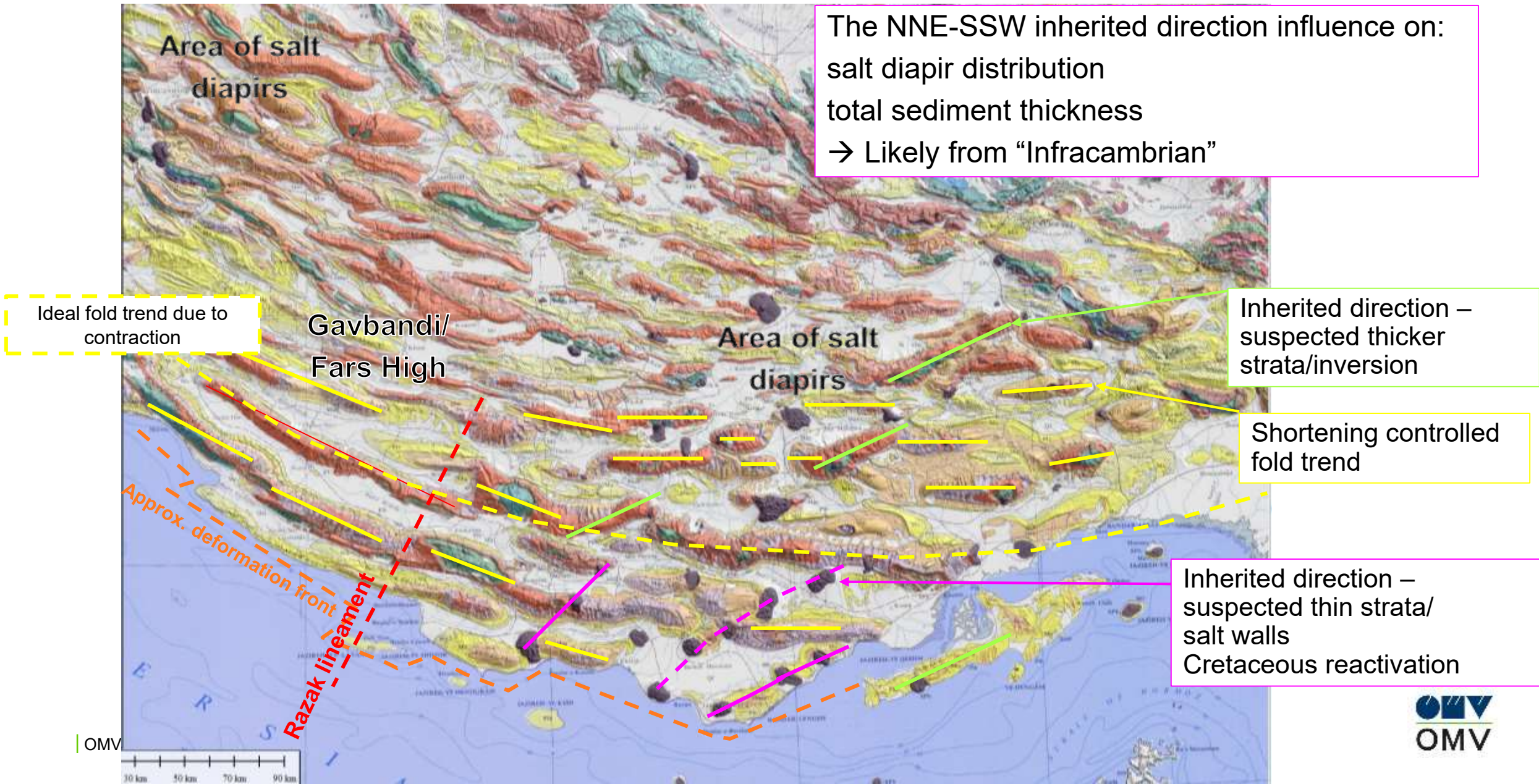


Residual map of Simple Bouguer Anomaly (SBA; @ 2.2g/cm³) of regional gravity dataset (Sandwell) reduced by *CRUST-1* gravity model

- a) orogenic wedge/ophiolite belt = gravity high
- b) flexural foreland basin = gravity low
- c) parallel relative gravity high
- d) Gavbandi high/ Fars Arch – not specific signature

- Orogen – foredeep – forebulge ?
- Cretaceous and post-Cretaceous halokinetic movements on top and east of the interpreted forebulge.

Interference of inherited direction and shortening



Summary and conclusion

- ▶ high uncertainty/problematic deep structures and basement contribution (active/passive)
- ▶ +/- W-E striking structure trend from Cenozoic shortening interfering with a ENE-WSW inherited trend
- ▶ Inherited trend possibly from Infracambrian rifting.
- ▶ Far-field effects of ophiolite collision reactivate structures at/inside forebulge.
- ▶ Stratigraphic thickness variations: Basement structuration, salt distribution and halokinetic evolution.
- ▶ Deformation front: likely the result of discontinuous basal salt layer.
- ▶ Propagation of inversion restoring basal detachment, enabling thin-skinned fold propagation



**The energy
for a better life.**

