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EA Fault Pattern in the Southern Campos Basin, Brazil: 3D Seismic Insights and Implications for Albian Carbonates of the Macae Group*

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Abstract

Normal listric faults played a major role in the structural and stratigraphic framework of the post-salt reservoirs in Campos Basin, offshore Brazil, helping in the entrapment of hydrocarbons in rollover systems. Although several factors are involved, such as basement pre-existing structures, rifting, overburden thickness and overall structural style, the salt movement is the main mechanism for the overall post-salt fault pattern. This study focuses on understanding the relation between the fault pattern related to salt tectonics and the distribution of carbonates of the Albian Macae Group. The main objective was to understand the interaction between sets of faults and their influence on the Albian carbonates of the Macae Group. To do so, we used an approximate 1050 km² 3D seismic survey in the southern Campos Basin and derived discontinuity seismic attributes to characterize the fault pattern. The structural style of the study area has a relationship with the salt-related structures and the basement-inherited structures. We defined that relationship using discontinuity seismic attributes, which highlight the background structure and the strata variability pattern, such as maximum curvature, steered minimum similarity, variance, dip-steering, and ant tracking.

Interpreted time-slices, cross-sections, and horizon surfaces allowed the characterization of different sets of faults affecting the strata as well as accommodating extensional structures. The identified fault types include: (1) listric, (2) growth-fault systems, and (3) high-angle normal faults. The faults are grouped into three trends: (1) WSW-ENE (striking N70-80°E), (2) NE-SW (striking N45-50°E), and (3) NNE-SSW (striking N15-20°E). The structural and stratigraphic patterns are summarized in six tectonic-stratigraphic units (TSUs): (1) rollover and tilted block systems, (2) growth extensional wedge, (3-4) extension by a main growth-fault system, (5) normal-faulted blocks, and (6) highly-faulted and fractured graben areas. TSU1 is formed by frequent listric faults with rollover systems characterized by differential extension, recognizable in the seismic reflectors. TSU2 is characterized by an overall prograding pattern with dipping reflectors. TSU3 is composed of the main growth-

fault rooted at the top of the salt, which appears to be accommodating syn-tectonic growth strata. TSU4 is structurally constrained by the outer limit of NNE-SSW and WSW-ENE fault sets, which separates the prograding wedge from the package mostly controlled by the main growth-fault system. TSU5 is affected by the normal-faulted blocks with uniform extension, creating a stepped pattern in the sedimentary package. TSU6 is highly affected by high-angle faults and a high density of fractures, which makes interpreting and establishing a relation between fault structures and seismic units a challenge due to the noisy seismic character. To summarize, the structural style of the Albian interval has correlation with salt-related and basement-inherited structures and is characterized by a normal and listric fault pattern, dipping basinward and rotating strata landward, trending dominantly NE-SW, parallel to basement major extension axis.

Introduction

One of the most relevant discussions in salt tectonics is the relationship between the stratigraphic and the structural framework, as well as the formation timing of the halokinetic-related structures. So establishing a reliable relationship between distribution, geometry and pattern of the tectono-sedimentary framework plays a key role in the understanding of salt tectonics.

The overall structural pattern of Campos Basin was built by the interaction between the salt layers and the overlying brittle strata, defined as thin-skinned salt tectonics (Fetter, 2009). The Albian interval, comprised by the carbonate formations of the Macae Group, which the Pinda Group in Kwanza Basin is its analog (Eichenseer et al., 1999), is highly faulted and fractured. The faults are mainly due to the salt kinematics over the period, and several fractures have been developed during the subaerial exposure of the carbonate platform. The subaerial exposure was also responsible for the development of karst systems (Winter et al., 2007). The salt and raft tectonics explain the structural and stratigraphic evolution of the basin. The similarities between the structures found in the Angolan margin and in the Brazilian southeastern margin lead several authors to consider the Kwanza Basin an analog model for the Campos Basin. According to Eichenseer et al. (1999), the Albian stratigraphic record in the Angolan margin that characterizes the Pinda Group is comparable to the Macae Group present in the Campos Basin.

In this study, based on 3D seismic data from the southern Campos Basin, we studied the distribution and geometries of the salt-related faults and structures. To do so, we combined minimum similarity, dip-steering cube and maximum curvature, post-stack geometric seismic attributes, for the structural analysis. Then, we suggest a structural division in six domains, defined as Tectono-Stratigraphic units.

Geological Setting

Campos Basin was developed on the Precambrian basement, with a mean strike direction NE-SW similar to the major extension axis of the basin. The lateral movement associated with the NW-SE transfer faults is extremely relevant to the development of the initial structures ([Figure 1](#)). These were inherited-basement structures reactivated as horsts and grabens during the Mesozoic (Chang et al., 1992).

Two main structures are present in the basin: (1) faulted blocks associated with the rift phase, characterized by horsts, grabens, and half-grabens limited by high-angle normal faults, which comprise the basement and the pre-salt sediments; and (2) halokinetic-related structures, mainly listric faults, controlling the post-salt sequence (Guardado et al., 1989).

One of the first signatures of halokinetic activity in the basin corresponds to the period of tectonic quiescence during the transitional phase. The progressive tilting of the basin towards the east is associated with the differential compaction of the deposited sediments over the evaporitic layers. This tilting induced an intense diastrophic deformation and the salt movement during the Albian (Demercian et al., 1993).

During the Neo-Albian, syn-kinematic listric faults were generated with the continuous development of the salt structures and tilted blocks. This process was responsible for the growth-fault systems. This faulting type is associated with the development of rollover structures (Guardado et al., 1989).

The majority of the synthetic faults dipping basinward are associated with raft tectonics. These faults generated raft structures in the Albian, with increased magnitude and movement towards offshore (Guardado et al., 1989).

Dataset and Method

The main faults and related-structures were interpreted based on their geometries, orientations, and the overall patterns. We used a 1052-km² 3-D seismic survey from which were computed structurally-oriented filters and post-stack geometric seismic attributes to better highlight the structures. These attributes include ([Figure 2](#)):

- (1) Maximum curvature, that provides the inflection point of a concave structure that may be associated with a hypothetical fault lineament (Roberts, 2001).
- (2) Steered minimum similarity, which highlights similar and dissimilar reflectors, directly associated with reflection continuity, and also used as a horizon interpretation constraint (Jibrin et al., 2013), since the area has many dipping reflectors.
- (3) Background dip-steering, that provided the true geological dip of the bedding and dipping reflectors (Höcker and Fehmers, 2002).

Using the background dip-steering cube as an attribute for fault mapping, or more simply for discontinuity detection, we could see that the dipping area of each color - blue basinward, and green landward - is in accordance with the proposed models for the structural framework of the basin. The dip of the beds basinward is towards the upslope direction (NW to N), and the dip of the beds landward is towards the downslope direction (SE to S).

Structural Analysis

The WSW-ENE fault set ([Figure 3](#)) is in the easternmost sector, characterized by strongly curved fault segments, which we favor to be part of the pre-existing lineaments of the NE-SW set. These two sets appear to be separated by the NNE-SSW fault set in the East sector. Some of the NNE-SSW faults set occur both in the central and southern sector, and it seems to be overprinted by the NE-SW set. The major faults set strike mainly N45-50°E as we see in the length-weighted rose diagram. Their strike is mostly parallel to the basement major extension axis of NE-

SW. It occurs with distinct geometries, both curved and linear. The major faults were interpreted to be dipping downslope, as a continuing growth set along the main strike of NE-SW. Furthermore, we have interpreted in some locations hard-linked segments. It is important to notice that the difference between the hard-linked segments and the continued growth coalesced fault lineaments are too subtle for a reliable distinction ([Figure 4](#)).

The structural style of the Albian interval has an overall normal dip-slip and listric curvature pattern, due to the dominant NE-SW faults controlling the structural development of the Albian interval. This fault strike direction (NE-SW) is related to the basement inherited structures (Fetter, 2009), so we believe they are conditioning the Albian interval structures development ([Figure 4](#) and [Figure 5](#)). In addition, this relationship might have a strong influence on the strata development during this period.

Tectono-Stratigraphic Units

In this work, six Tectono-Stratigraphic Units (1, 2, 3, 4, 5, and 6) are proposed for the study area. The limits are defined by the fault's density, strike direction and extension of the main structures. It is possible to make a distinction of the tectono-sedimentary package at the West and East of the greater fault density of the NNE-SSW set. The Top Macae horizon surface illustrates that difference by presenting a smooth pattern in East and noisier in West ([Figure 6](#)).

The six Tectono-Sedimentary units are divided as follows ([Figure 7](#)):

TSU1 – Comprised of rollover systems and tilted blocks formed by the frequent listric faults. The rollover systems are well-defined with the differential extension observed in the seismic reflectors. It occurs without a well-defined reflection pattern, slightly chaotic reflectors inside Quissama Seq. II generating a set of anticlines and synclines. There are several top-laps and the entire package is truncated below the Top Macae.

TSU2 – Presents a growth extensional slide wedge, due to the main growth-fault extension, developing an extensional overall prograding pattern. The reflections have a greatly dipping and top-lapping at a negative reflection surface, which could be the Quissama Seq. III or truncated by the Top Macae. The presence of both Quissama Seq. II and III are uncertain in this unit.

TSU3 – Present a minor tectonic influence when compared to other units (TSUs). It is composed by the main growth-fault rooted at the Top of Salt, accommodating syn-tectonic growth strata. The internal reflection pattern is slightly parallel above Quissama Seq. III and toplaping at the Quissama Seq. II.

TSU4 – Is very similar to the TSU3, though structurally-constrained by the outer limit of NNE-SSW and ENE-WSW fault sets, which separate the prograding wedge with minor tectonic influence from the package essentially affected by the main growth-fault system. The reflections pattern has a slight dip downslope strongly compartmentalized by the fault system of the NE-SW set.

TSU5 – This domain is strongly affected by the normal-faulted blocks with uniform extension, creating a stepped pattern in the sedimentary package. The normal faults dip presents a high-angle and are sealed by continuous and parallel seismic reflectors, which we believe to be Outeiro facies sequence.

TSU6 – Highly influenced by high faults and fractures intensity, making interpretation challenging over the whole domain. The establishment of a relationship between fault structures and seismic units is difficult, due to the noisy character. In the northeast sector of the area, the faults and fractures network seems to generate depressions, looking like grabens. This domain, besides having a challenging interpretation has a stratigraphic and structural pattern totally different from the mentioned TSUs.

Conclusions

For this study we suggest a structural zoning of the area in six Tectono-Stratigraphic Units, based on the different structural domains and seismic facies character: (1) TSU1 – rollover and tilted block systems with differential extension, (2) TSU2 - growth extensional slide wedge, (3) and (4) TSU3 and TSU4 – extension by a main growth-fault system, (5) TSU5 – normal-faulted blocks with uniform extension, and (6) TSU6 – highly-faulted and fractured graben area.

The following evidences support our conclusions:

- 1) The structural style of the study area has a strong relationship between the salt-related structures as well as the basement fabric inherited structures.
- 2) The main listric faults are rooted in the salt unit.
- 3) There is an overall structural control of the listric faults, on the Albian strata.
- 4) Rollover and tilted block fault systems increase downslope, in contrast with landward normal-fault blocks that increase updip.

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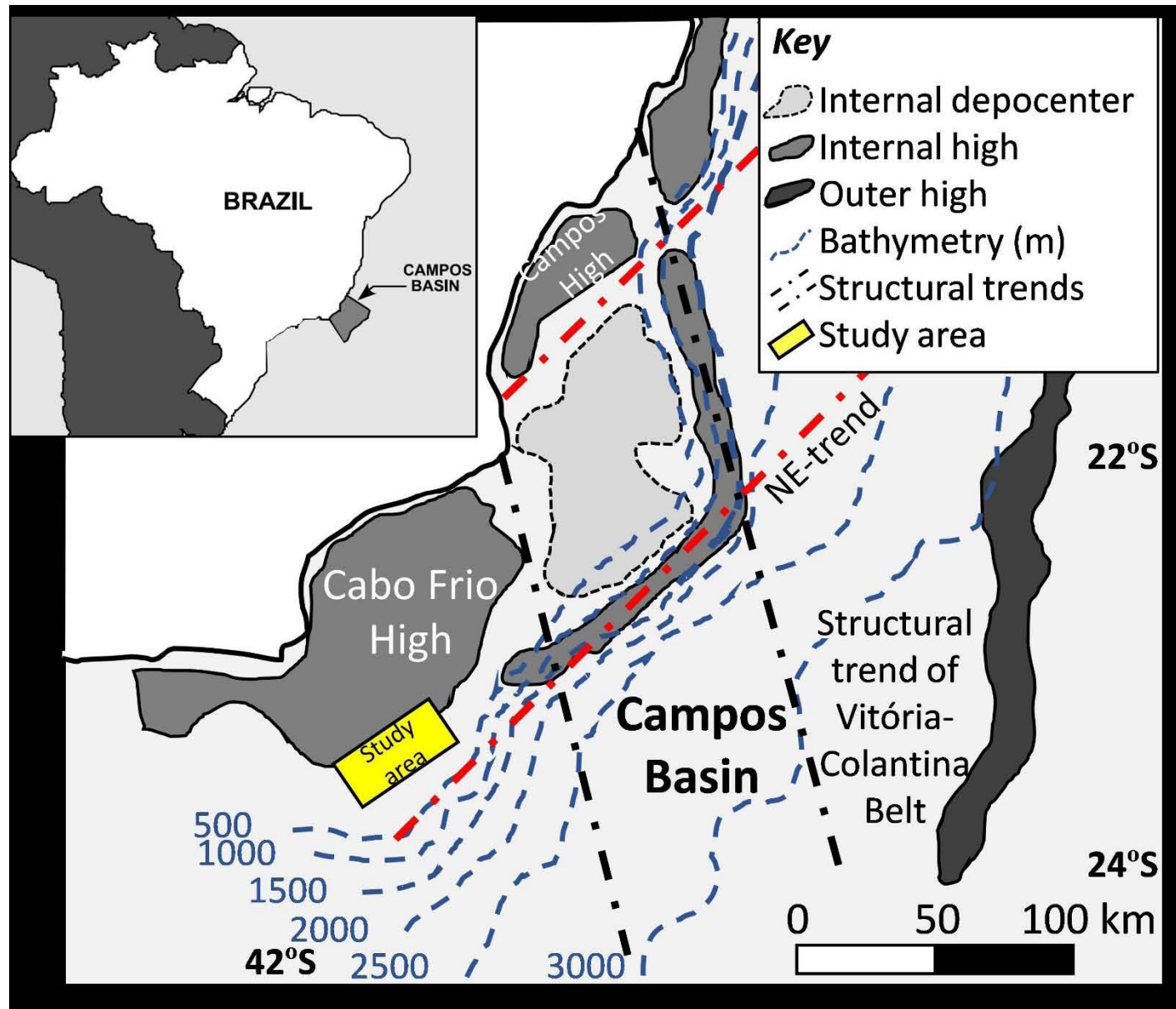


Figure 1. Regional simplified structural map with the main offshore and onshore tectonic trends and domains. It illustrates the main basin depocenters highlighted in light grey and the basement structural highs highlighted in dark grey: Cabo Frio High, Campos High, Vitoria High, Internal and Outer Highs. The main tectonic trends and domains are constrained by NNW-SSE strike (black dashed-lines) related to the Vitoria-Colantina Belt, and NE-SW strike (red dashed-lines) related to the Ribeira Belt. The NE-SW faults are the focus of this study (modified from Fetter, 2009).

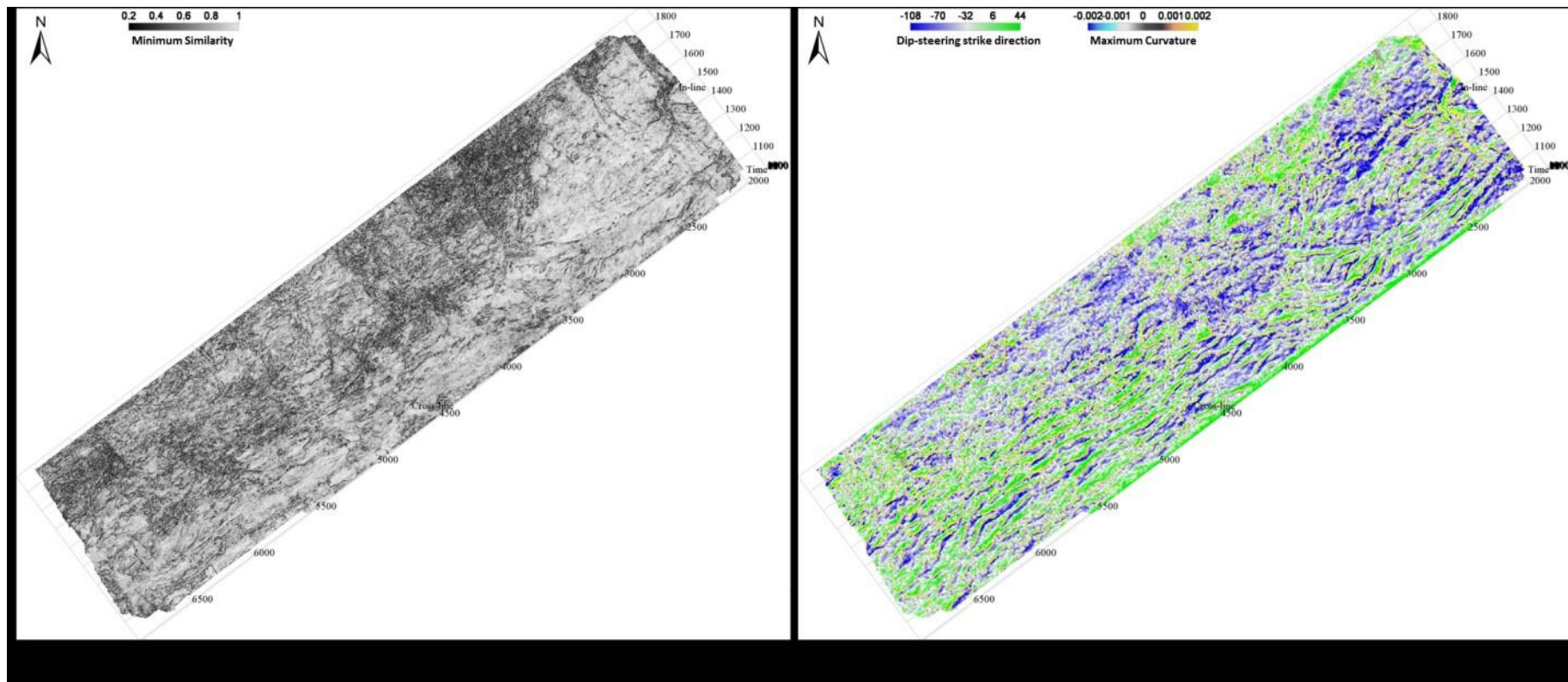


Figure 2. Top Macae Group surface with seismic attributes of (a) steered minimum similarity attribute, and (b) dip-steering filter in the strike direction and maximum curvature attribute, utilized in the structural interpretation of the study area.

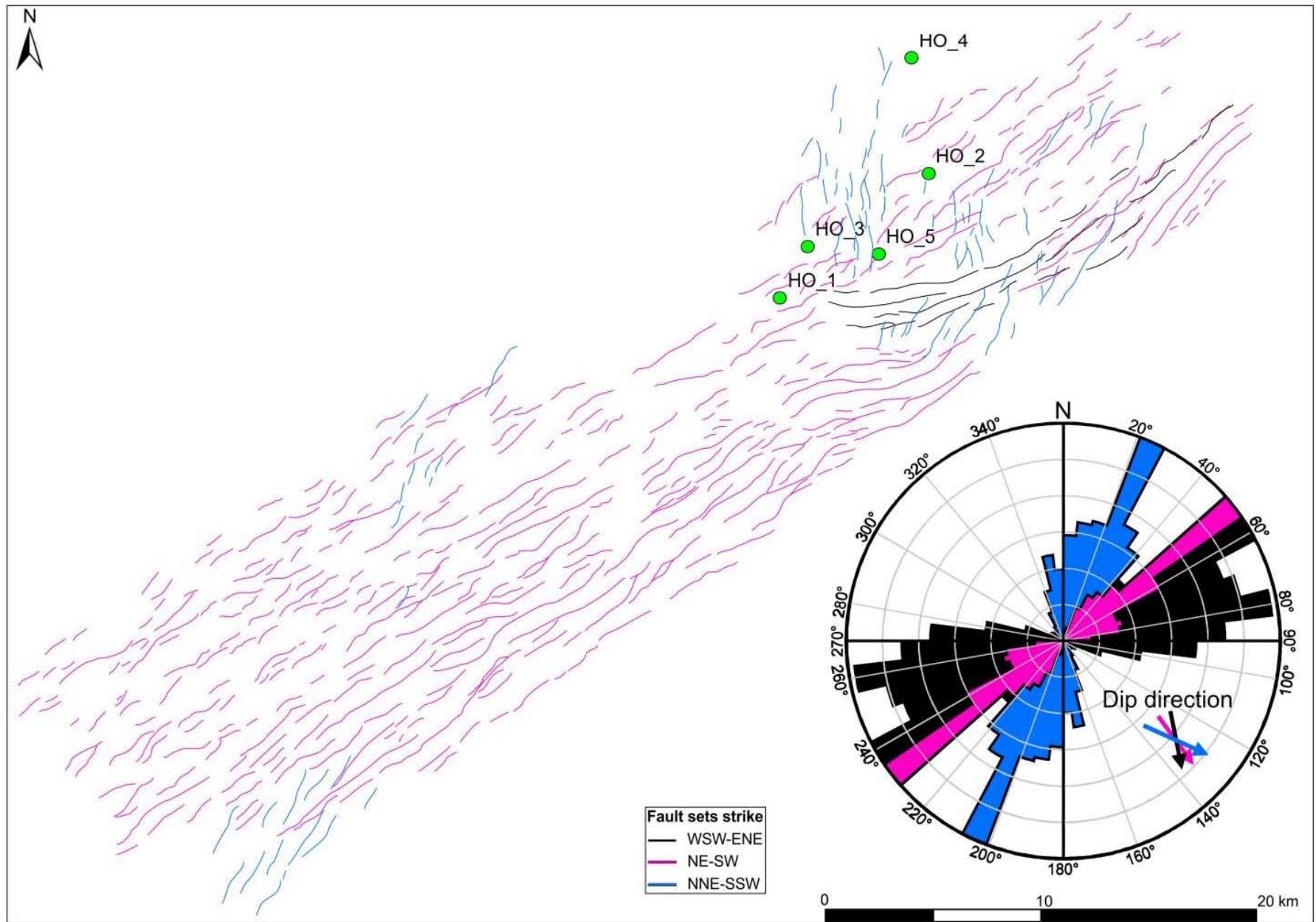


Figure 3. Fault surface lineaments strike direction and rose diagrams showing the azimuth for each fault set: (1) WSW-ENE comprised of the easternmost portion of the area, (2) NE-SW widespread over the whole area, and (3) NNE-SSW occurring both in the East portion and in the Southwest portion of the area.

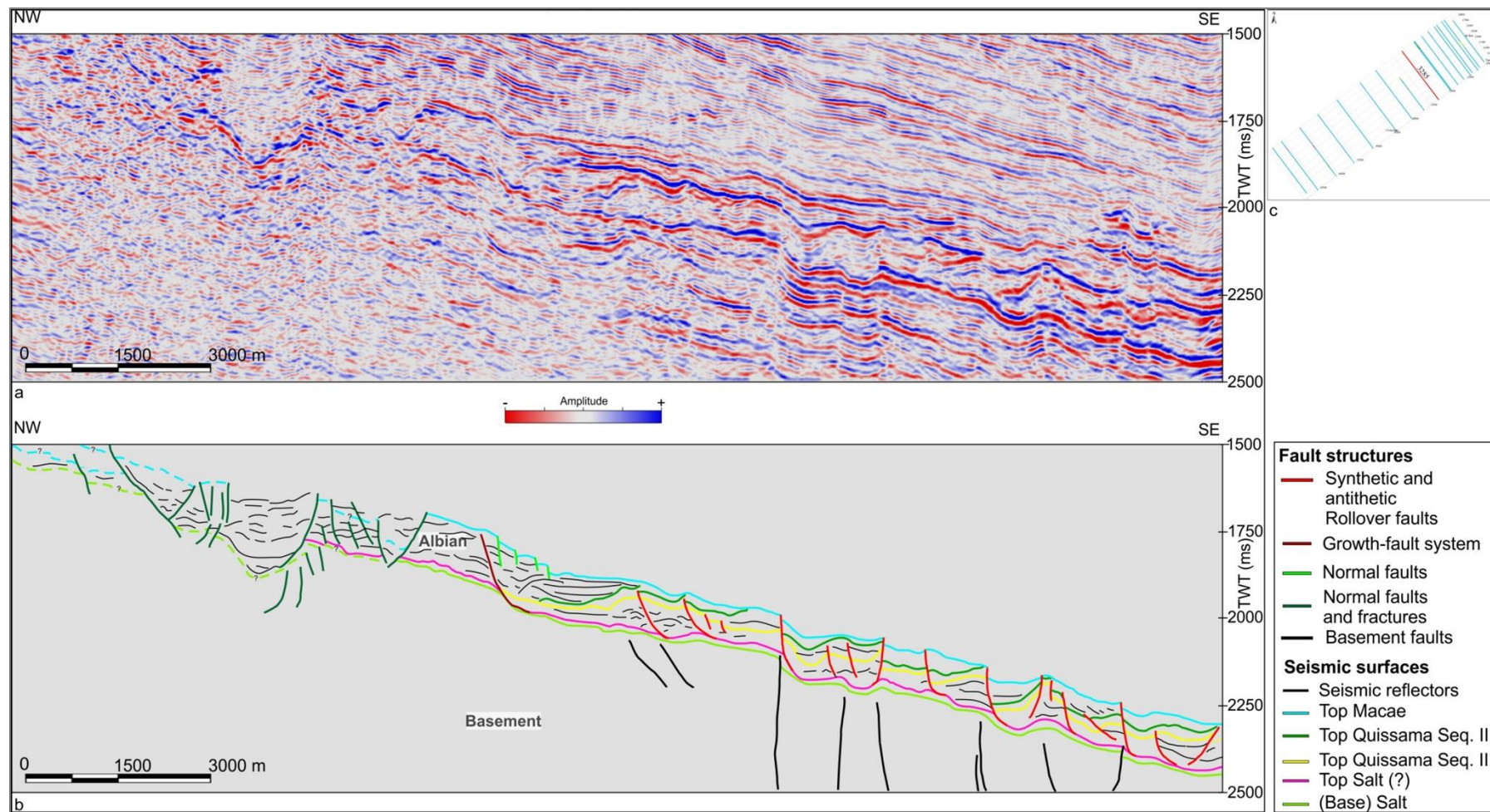


Figure 4. (a) Seismic dip cross section, and (b) general geological interpreted dip cross-section of the Albian interval. It is possible to see the overall pattern of faults and fractures as well as its geometric relationship with the strata. Normal faulted-blocks are updip, and the composite growth-fault system is downdip.

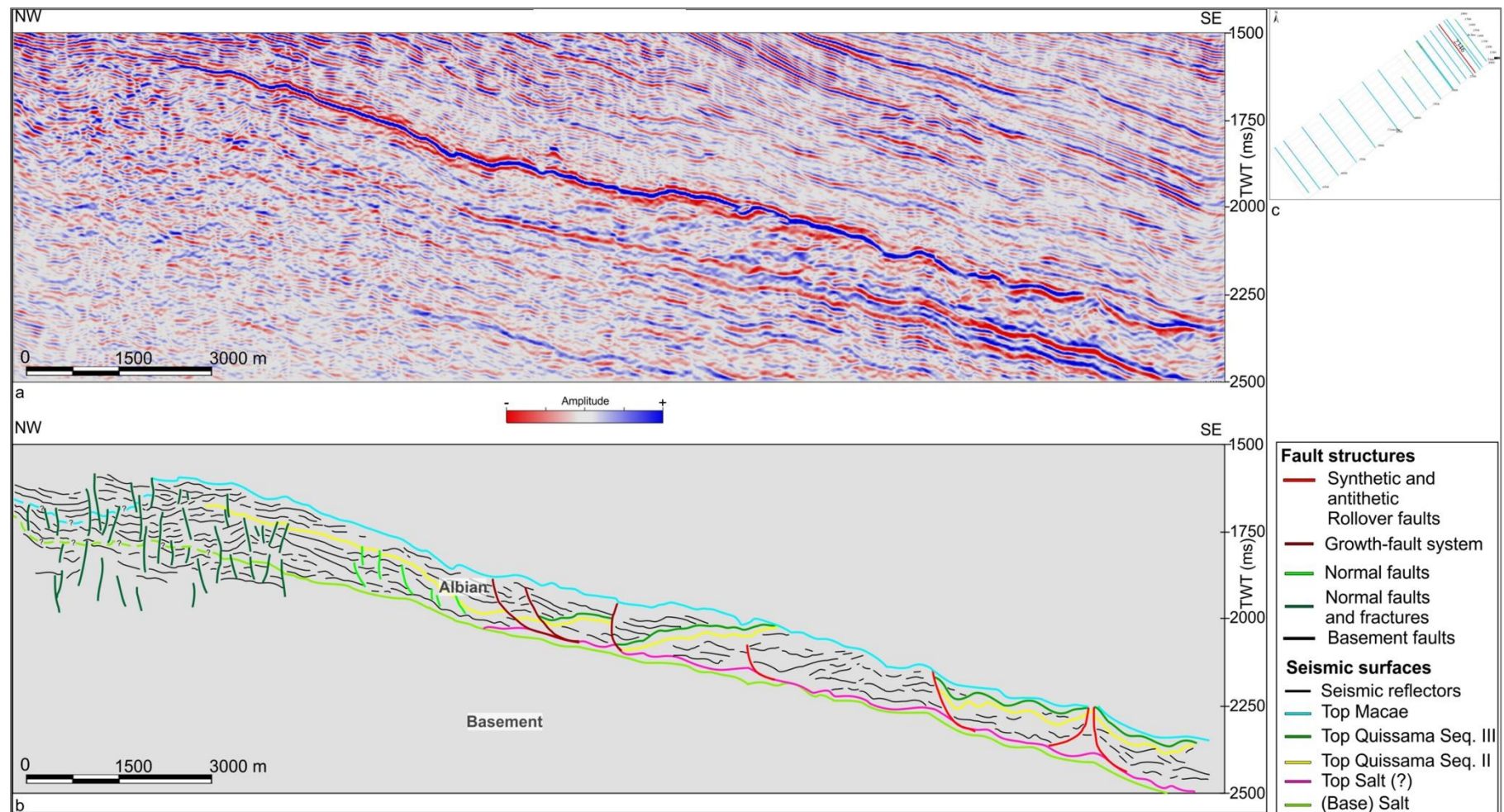


Figure 5. (a) Seismic dip cross-section, and (b) geological interpreted dip cross-section of the Albian interval. It is possible to see the faults and fractures pattern and its geometric relationship with the strata. It is possible to see the interpreted updip sector highly faulted and fractured generating a depression similar to a graben.

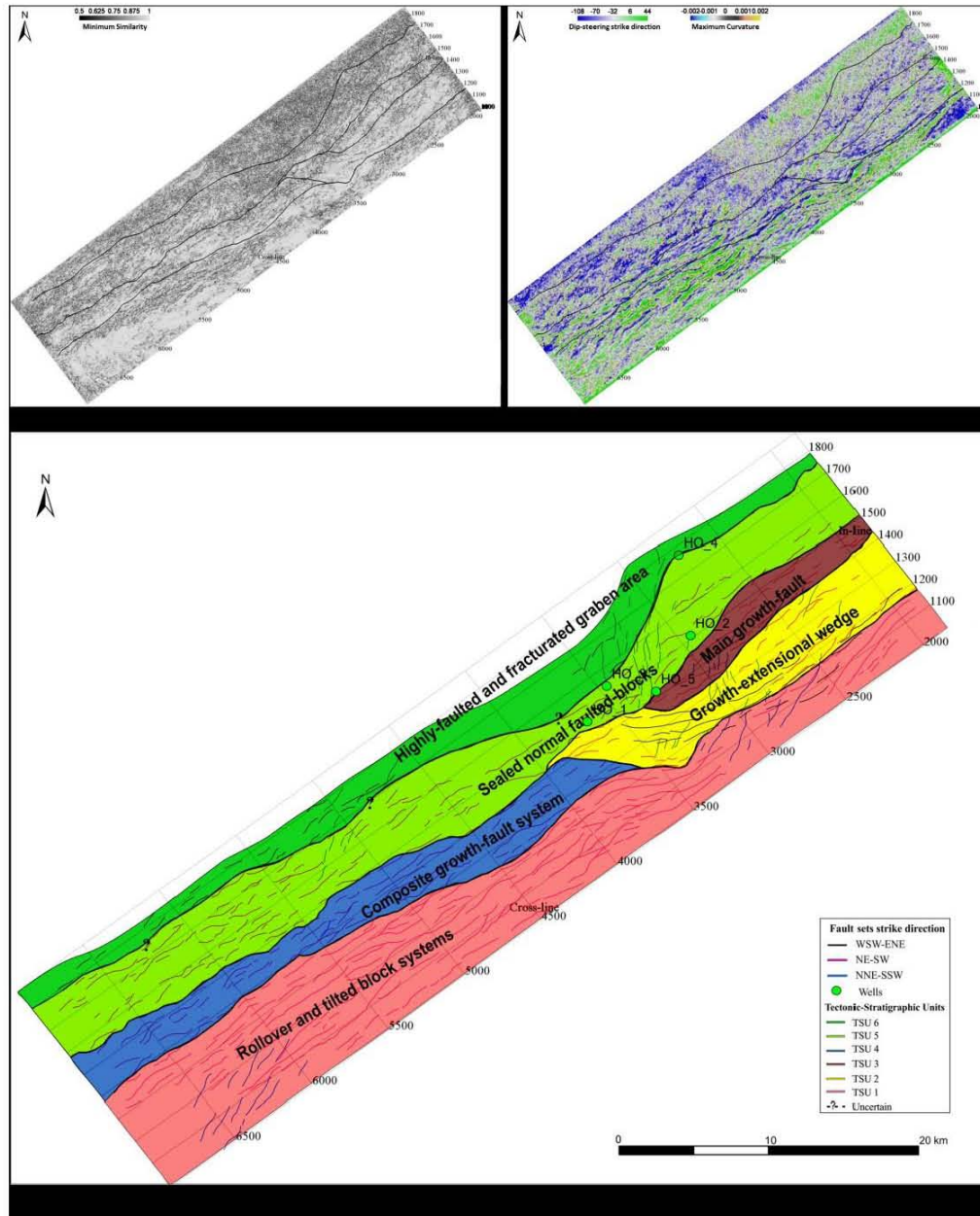


Figure 6. Time-slice at 2296 ms of (a) steered minimum similarity attribute, (b) dip-steering filter in the strike direction and maximum curvature attribute, with (c) a proposed division of the study area in six different domains, defined as Tectonic-Stratigraphic Units (TSU1 to TSU6). These domains are associated mainly with the rollover structures formed by listric and growth faults, the tilted blocks formed by the normal faults and the seismic facies.

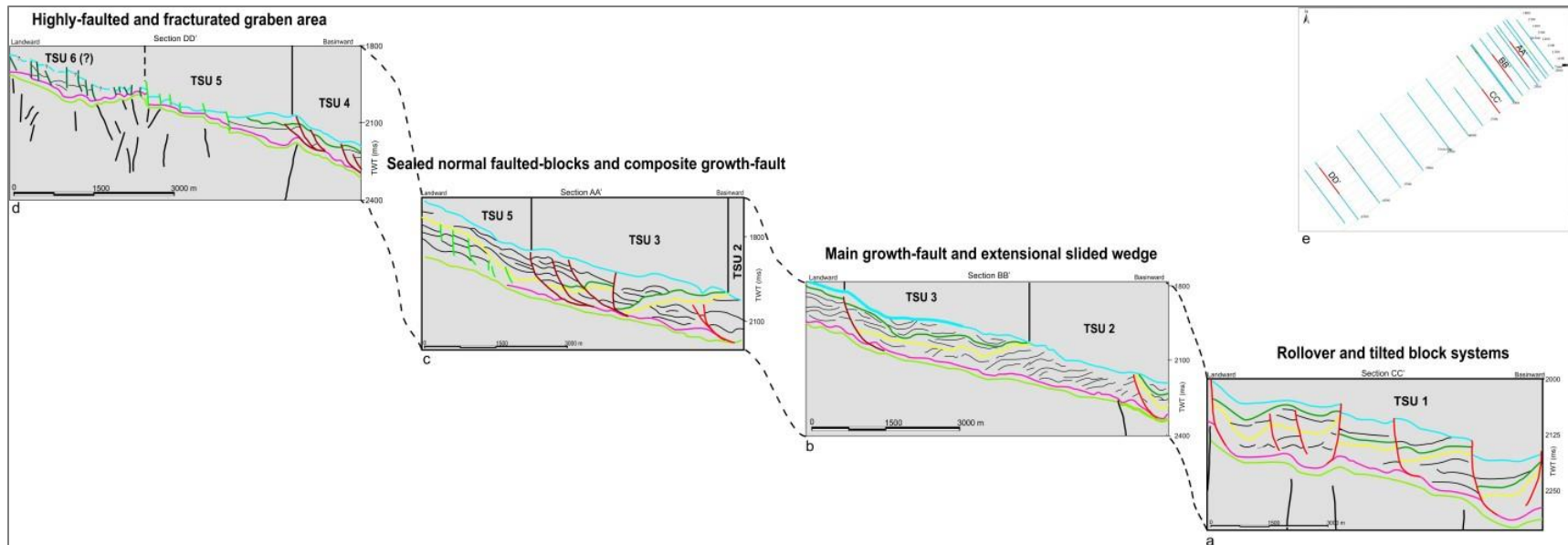


Figure 7. Tectono-Stratigraphic Units in schematic dip cross sections: (a) the rollover and tilted block systems increasing downslope in TSU1, (b) the large slided extensional wedge defined in the TSU2, (c) the main growth-fault that separates TSU3 from TSU5, very similar to the TSU4 configuration, and (d) the landward normal-faulted blocks in the TSU5, and the high intensity of faults and fractures featuring the TSU6.