# [PS]Interaction Between Thrust Faults and Strike Slip Faults in Deep Water Fold and Thrust Belts: Examples from the Levant Basin Eastern Mediterranean Sea*

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## Abstract

Deep water fold and thrust belts are commonly found in association with major gravity deformational systems in passive continental margins. Within these continental margin gravity driven systems, an up dip extensional domain is invariably paired with a down dip contractional domain in which there are assemblages of thrust faults, strike slip faults, normal faults and variety of fault related structures, collectively referred to colloquially as deep water fold and thrust belts.

The interactions of thrust faults with strike slip faults, normal faults and other kinds of faults greatly influence the evolution and geometry of the thrust related folds in these deep water fold belts. Understanding the precise nature of the fault interactions is useful in a more fundamental appreciation of the propagation of thrust faults, which, in turn is vital for successful hydrocarbon exploration.

This presentation is based on kinematic observations of fault and fold relationships from a high-resolution 3D seismic survey located in the deep water thrust and fold belt of the Levant Basin. The focus of this study is the influence of strike slip faults on displacement and shortening distribution of thrust related folds along strike. The kinematic data suggests that important variations in thrust fault and fold style relate specifically to positions of thrust fault - strike slip fault branch zone.

We divided the styles of thrust faults into three end members (classes A, B and C) based on their pattern of strike slip fault bounding. Class A folded thrust is bounded by only one side by a strike slip fault, Class B is bounded on both sides by strike slip faults of different sense of shear and Class C is bounded by strike slip faults of same sense of shear.

We compared summed displacement and total shortening of the thrusts faults along strike in order to have a mathematical relationship of both parameters along isolated segments and branched zones. We conclude by proposing models to explain timing relationship between the thrust faults and their strike slip counterparts within the study area in a chronological order.

# Interaction between Thrust Faults and Strike Slip Faults in Deep Water Fold and Thrust Belts: Examples from The Levant Basin Eastern Mediterranean Sea.

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## I. 0 INTRODUCTION

Deep water fold and thrust belts are commonly found in association with major gravity deformational systems in passive continental margins (Rowan et al. 2004). Within these continental margin gravity driven systems, an up dip extensional domain is invariably paired with a down dip contractional domain in which there are assemblages of thrust faults, strike slip faults, normal faults and variety of fault related folds, collectively referred to colloquially as deep water fold and thrust belts. Understanding the precise interaction between the thrust faults and strike slip fault is useful in a more fundamental appreciation of the complexities of fault propagations, which in turn is vital for successful hydrocarbon exploration.

This study is based on kinematic observations, displacement and shortening distribution of examples of thrust related folds segmented or bounded by strike slip faults from a high resolution 3D seismic survey located in the deep water thrust and fold belt of the Levant Basin. The main focus of this study is the interaction between thrust faults and strike slip faults which defines deformation in the study area.

### 1.1 Aim and objective

✓ To give a brief structural overview of the study area.

✓ Describe the displacement and shortening distribution of the segmented thrust fault and fold respectively.

✓ Outline the several end member thrust fault -strike slip fault interaction.

✓ Discuss the timing relationship of the thrusted folds and strike slip fault.

### 2.1 Structural frame work and Main stratigraphic units

✓ Extensional domain of 5-14 km net extension.

✓ Translational domain of medium to low strain.

✓ Contraction zone of shortening greater than extension.

✓ Shortening and tectonic transport is in ENE direction, oblique to that of the extensional domain.

✓ The main stratigraphy in the area is divided into 3 main units :Pre-Messinian, Messinian and Nile derived overburden. Detailed stratigraphy of the Messinian and Plio-Quaternary deposit is shown in Figure 3.
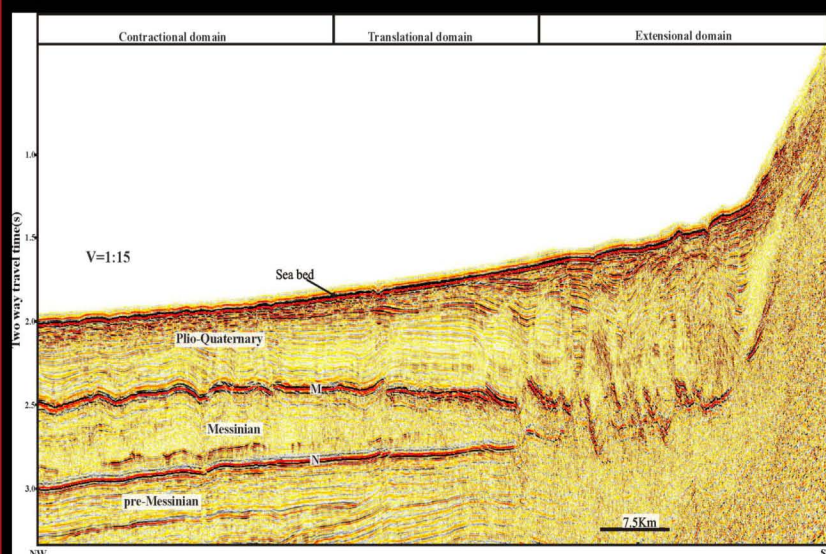


Figure 2: Seismic profile showing the main stratigraphic units and structural domains of the Levant Basin. The location is shown in Figure 1.0.

### 2. 2 Stratigraphy

✓ The crust is either oceanic or continental overlain by 14km sediments.

✓ Pre- Messinain is made of clastics and Carbonates, overlain unconformable by the Messina salt of approximatly 1600m thick.

✓ Messinian salt is bounded by the M and N reflection which pitches out unto the continental slope (Figure 3).

✓ The salt interval is the fault detachment layer and it is characterized by prominent internal reflection which have been divivided into M50-M24 (Bertoni and Cartwright 2005) Figure 4 .

## 2.0 REGIONAL GEOLOGY

✓ It represents an area of complex tectonic environment, which includes the Nile Cone, Eratosthenes Seamount, Cyprus Arc and Syrian Arc.

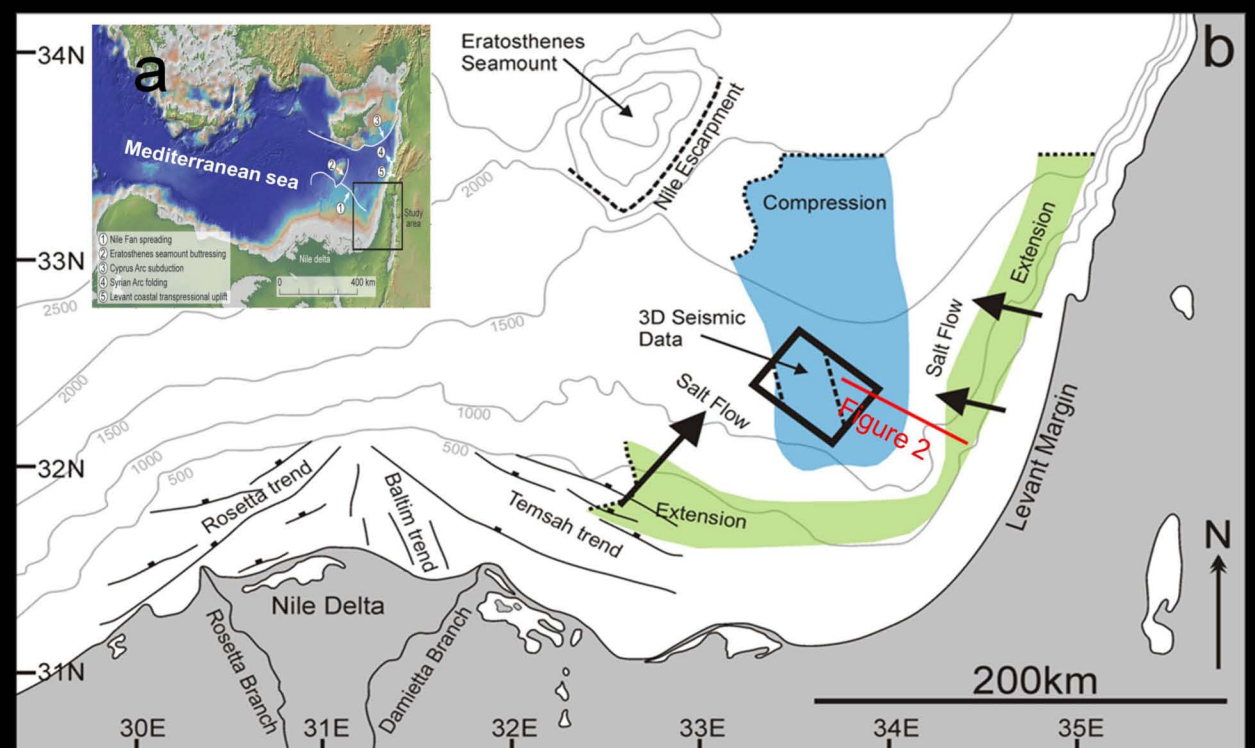✓ The Levant Basin is located towards the easternmost part of the Mediterranean sea, north of Israel.



Figure 1: Location map of the study area. 1a (inset) shows the area of interest in the Eastern Mediterranean and sources of far – field compression surrounding the Levant Basin ; image from GeoMap App. 1b shows the setting of the Nile Delta and the location of the seismic survey used in this study. The area covers a portion of the eastern Nile deep sea fan which is currently undergoing thin-skinned compression. The zone of compression within the Levant basin is driven by the gravitational collapse of both the Nile Delta and the Levant Margin. Figure adapted from Clark and Cartwright 2009, Gradmann et al., 2005;

✓ The salt layer is overlain by the Plio-Quaternary deposit (PQ) which is where the structures described in this study ramps. It is mainly derived from the Nile delta( Figure1 ). Average thickness of PQ is about 800m, divided into PM1 PM2 and PM3( Clark and Cartwright 2009, 2012).

✓ PM1 and PM2 are pre-Kinematic layer while PM3 is composed of syn and post kinematic sediments .
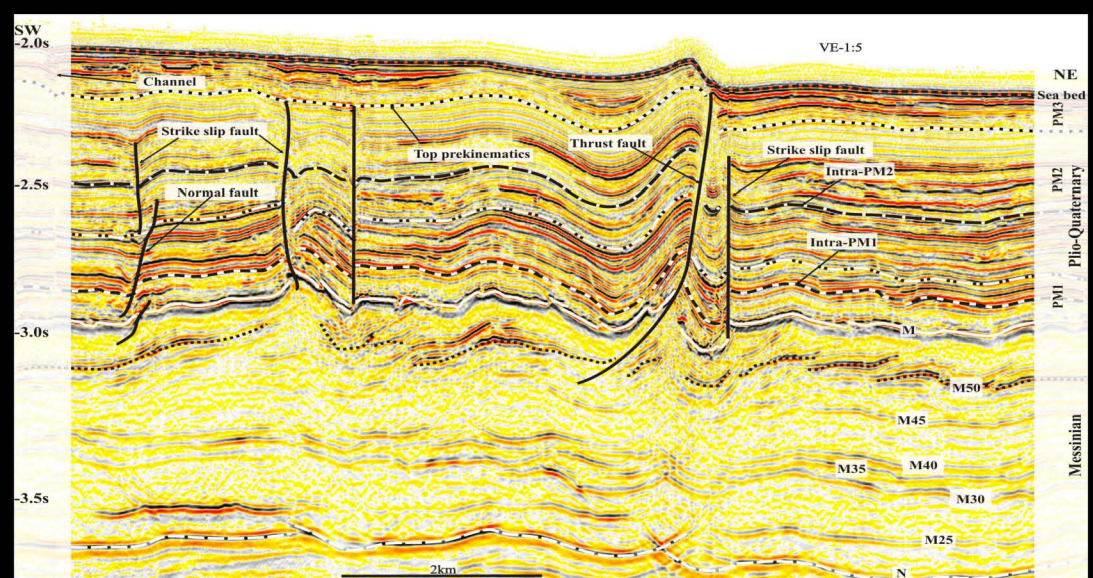


Figure 3: Section within the data set showing the detailed stratigraphy and structural elements within the data set. Inline shown in Figure 4.

# 3. 0 DATA SET AND METHODOLOGY

✓ Gal C covers an area of about 1,450 km$^2$ within the southern area of the contractional domain, deep water Levant.

✓ The average bathymetric gradient of the survey is c. 0.45$^0$ towards N-NE, and water depth ranges between 1000 m to 1400 m.

✓ The data was processed to near zero phases using SEG normal polarity.

✓ The data was migrated using a single pass 3D post stack time migration, which was used to generate a 12.5 m by 12.5m grid at sampling interval of 1ms.

✓ The post-Messinian sediment has a dominant frequency of 50Hz which decreases with depth. Its vertical and horizontal resolution has been estimated to be 10 m and 40 m respectively.

✓ The Messinian layer has a variable unit having its maximum frequency and velocity within the Messinian unit is 30Hz and 4200ms$^{-1}$ respectively.
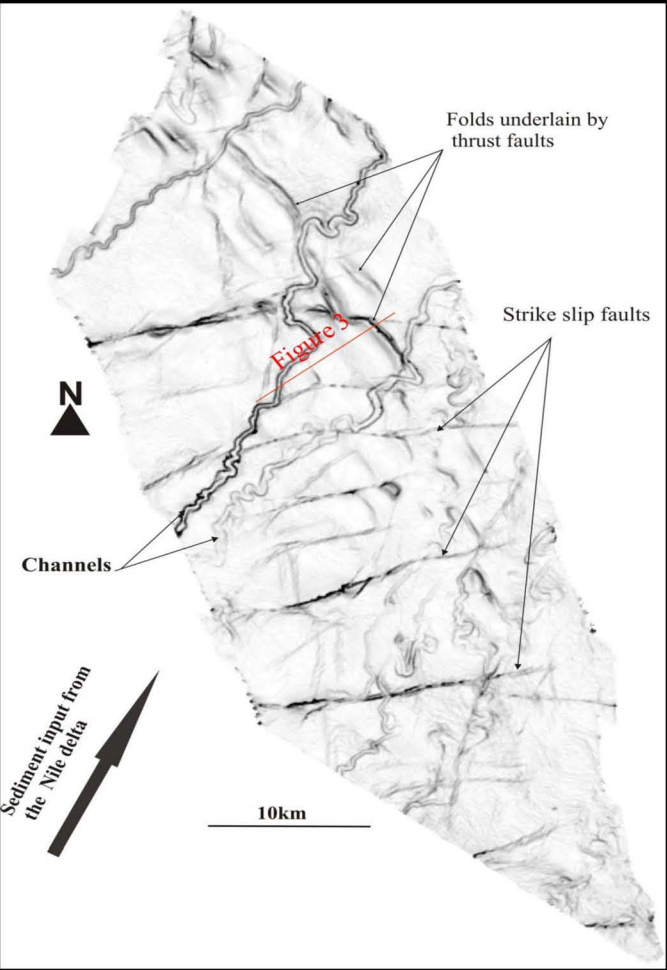


Figure 4: Time dip seabed map of the data set used for this study (Gal C) showing the main features within the area.

## 3.2 Method

✓ Displacement was used in place of throw and heave.

✓ Fig 9 shows a plot for the 3 parameters of a fault segment for comparison.

✓ Error from sampling interval, faults drag, variable fault dip is less than 10%.
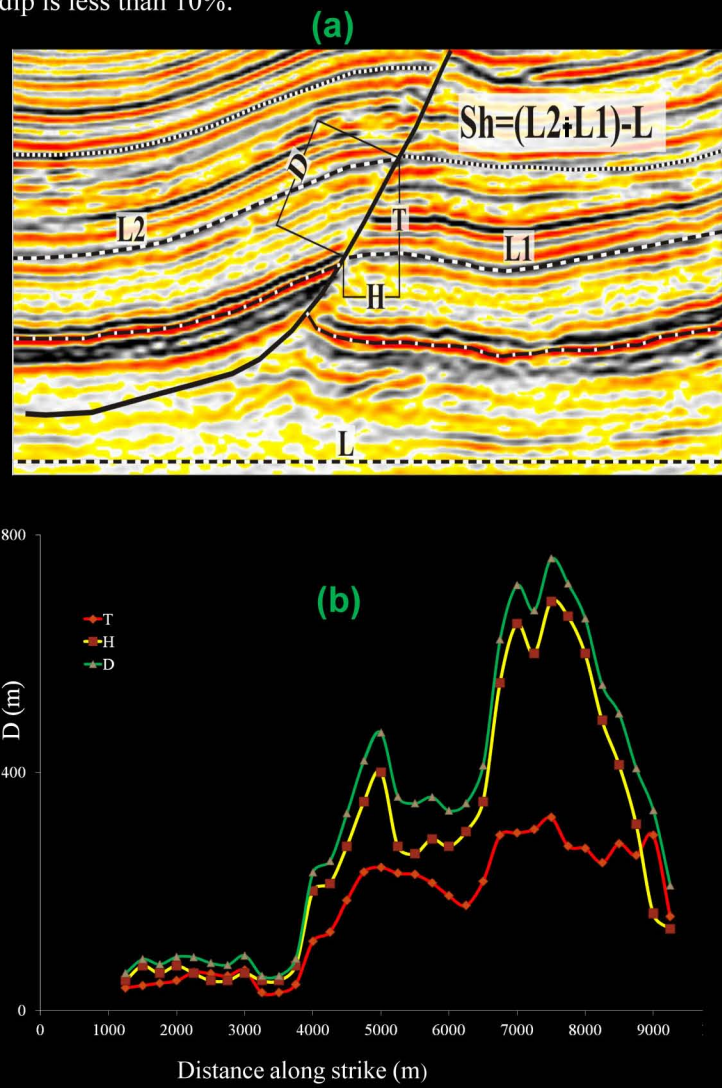


$$Sh = (L2+L1) - L$$



Figure 6 : (a) Methodology for cal calculating slip (Displacement, heave and throw) and shortening. (b) Plot showing the relationship between displacement, heave and throw along strike of a given thrust. H- Heave, T- Throw, D- displacement, L- Total un deformed length, L1- Footwall length, L2- Hanging wall length, Sh- Shortening.

## 3.1 Structural overview

✓ Deformation in the area is a product of the combination of 2 post-Messinian gravity driven systems. (1) Gravitational collapse of the basin ward spreading Nile cone to the southwest (Gradmann et al. 2005, Netzeband et al. 2006) (2) Deformation induced by the tilting of the Levant margin to the south east, which involved the entire Plio-Quaternary overburden detaching in the Messinian sequence (Cartwright et al. 2012) ( Figure 1a).

✓ The zone is characterized by thrust related folds commonly striking to NW-SE., detaching within the salt layer shown in Figure 6.

✓ Over 90% of the thrusted folds are either segmented or bounded by conjugate sets of strike slip faults whose bisectrix is almost orthogonal to the folded thrust.

✓ Unbounded TF have Dmax/L less than 0.02 (Figure 5d).

✓ Strike slip faults striking 030$^o$ are dextral faults while those striking 110$^o$ are sinistral faults both of which may show considerable change in orientation along their width.

✓ Both thrust faults and strike slip faults variably detach within the top Messinian interval (Figure 3 and Figure 5c).
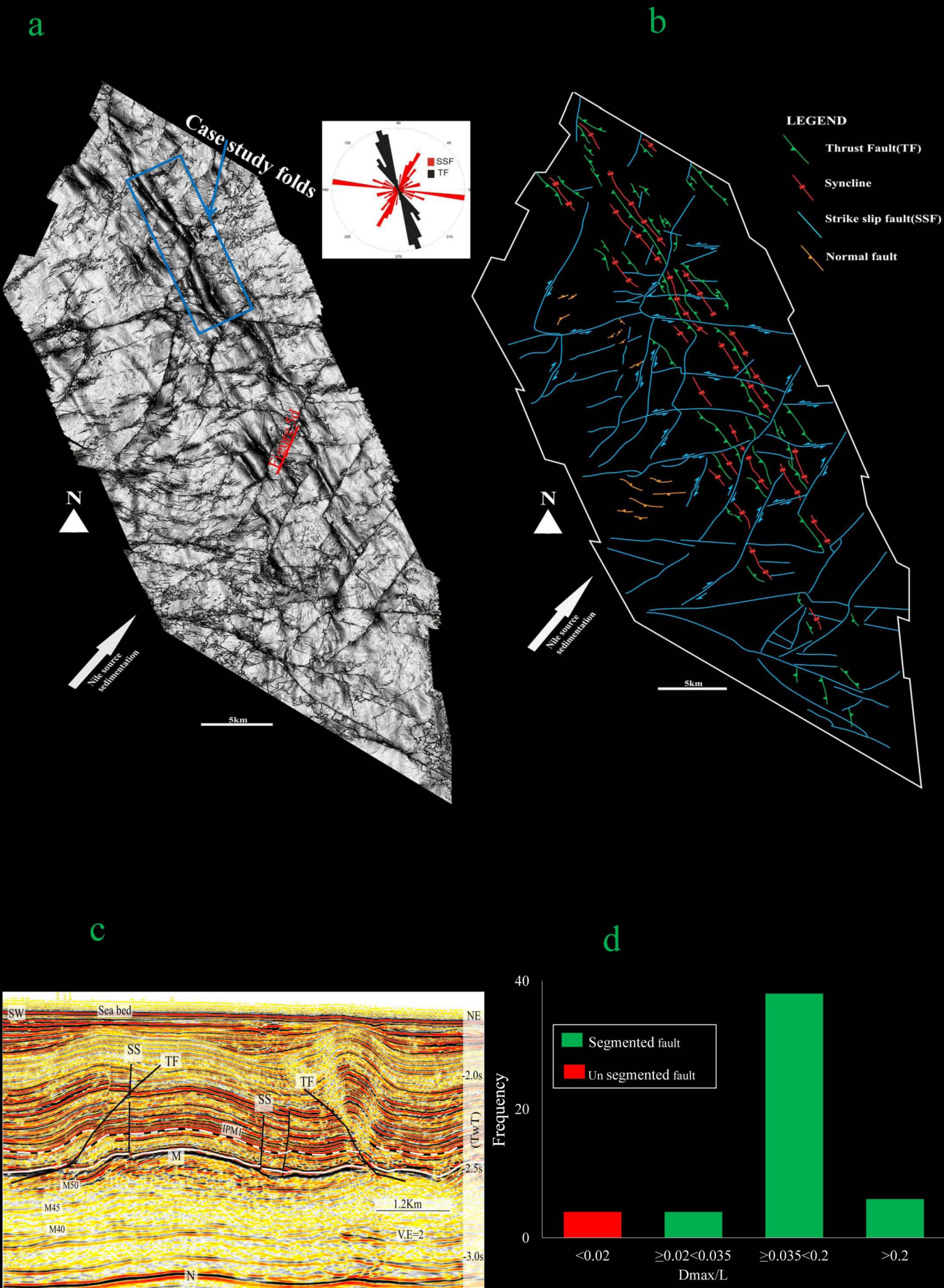


Figure 5: Deformation within the post Messinian layer . (a) Time dip map of IPM1 horizon (b) Time structural map showing the distribution of the structural element IPM1 . (c) Cross section taken from Figure 5a showing the structural style and sub stratigraphic unit s within the data set. (d) Ratio of maximum displacement to length(Dmax/L) of over thrust faults within the data set.

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## 4.0 RESULT

The result presented in this study , is based on kinematic observations, displacement and shortening distribution of the case study thrust related folds highlighted on the time bathymetric map (Figure 5a).

### 4.1 Case study structures

✓The thrust related folds are labelled T1-T8, those lager than 4km are the main thrust fault (T2, T4, T6 and T8) while the smaller ones are minor thrust fault. The main strike slip faults are labelled ssa, ssb, ssc and ssd (Figure 8).

✓Seismic lines across the main thrust related folds are numbered a1-a6,with the exception a7 which is a cross line at the tip of ssa which marks the north western and south eastern limits of T2 and T6 respectively (Figure 8b).

✓Notice how the main thrust (T2,T6 and T8) appear be one and same structure segmented by strike slip faults.

✓ One of the main question for this study is, are these thrust faults segmented by the strike slip faults or are they individual thrust faults which propagated towards the strike slip fault?

✓Generally, strike slip fault displacement using channel offset does not match with thrust faults offset.

✓ ssb has a displacement of about 0.2 km using channel offset close to where it branches the southward and northwards ends of T6 and T8 respectively, while the separation distance along both the south west dipping faults (T6 and T8) is about 4km.

✓ Similarly, ssa has a separation distance of more than 2km close to its tip using separation distance between SE and NW ends of T2 and T6.

✓Figure 9.1d shows a cross section (cross line a7) at the tip of ssa, which is characterized by limited deformation.
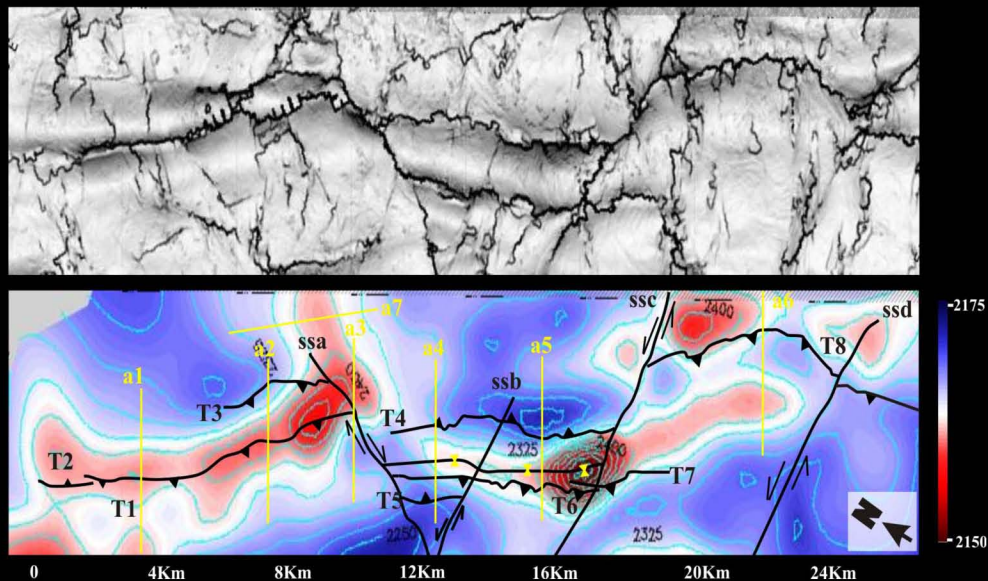


Figure 8.0: (a) Time dip attribute map of the case study thrust related structure along a key horizon with the unit PM1(IPM1) immediately above the M reflection, see Figure 3 and 5c for statigraphic location. (b:) Time structural map of the of the case structures along 1PM1.

### 4.3 Kinematic packages.

✓The sections below (Figure 10) are magnified from the green rectangular boxes at back limb of the main thrust related folds ( T2,T4,T6 and T8) shown in Figure 9. They clearly show prominent the kinematic packages for recording fold onset.

✓T2,T4 and T8 commonly show prominent onlapping horizons below and above IPM3 up to almost the sea bed, which implies the folds are still active (Figure 10 a, c and d).

✓T6 only show onlapping units which are most evident below IPM3, which are unconformably overlain by post kinematic deposits indicating the fold was last active at the deposition of the IPM3(Figure 10 b).

## 4. 2 Internal geometry of the folds.

✓Figure 9 shows seismic sections along the main thrust faults, position of cross lines are shown in Figure 8.0b.

✓Rectangular boxes on the sections are kinematic packages magnified in Figure 10.

✓All the main thrust faults detached at the top of the Messinian.

✓T2 dips $038^0$ SW and it is cross cut at its NW end by ssa, as shown on cross line a3.

✓T6 dips $036^0$ SW similar to T2 and both thrust are sheared at their tips by ssa (Figure 8).

✓T4 is a divergent thrust to T6 and it has an average dip of $033^0$.

✓T8 is also similar to T2 and T6 and it dips $038^0$ SW.

✓Figure 9d shows the insignificant deformation at the northward tip of ssa, close to where it branches T2 and T6.
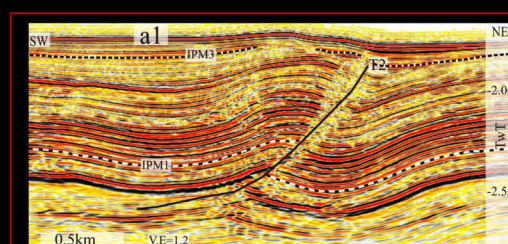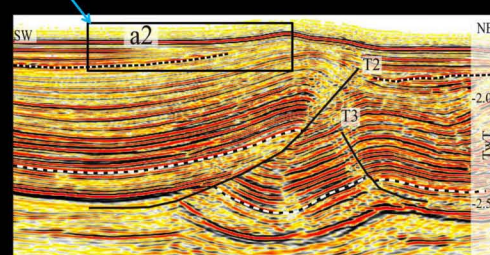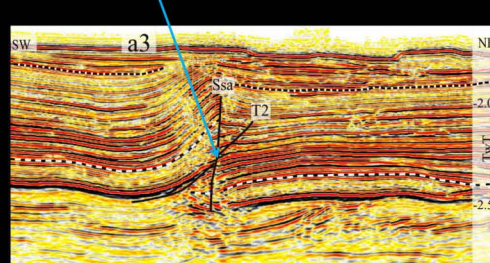


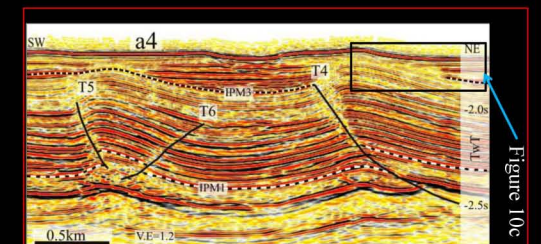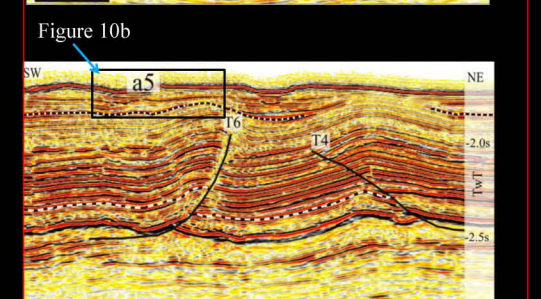Figure 9a: Seismic sections along T2. Cross line a1-a3 from Figure 10b.

Figure 9b :Seismic sections along T6 and T4. Cross line a4 and a5 from 8b.
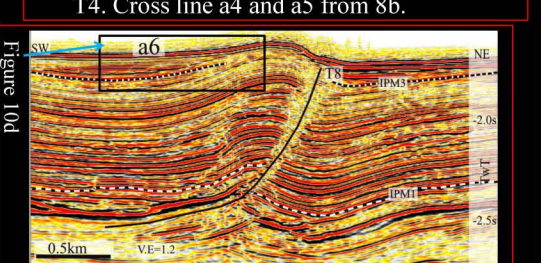
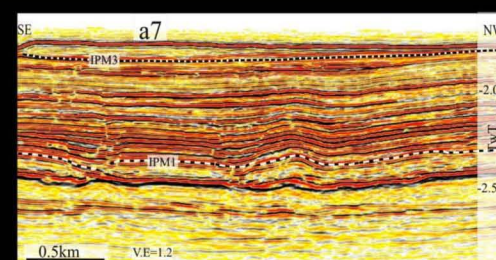Figure 9c: Seismic sections across T8. cross line a7 from 10b.



Figure 9d: Seismic sections close to the tip of ssa. Notice that its almost un deformed.
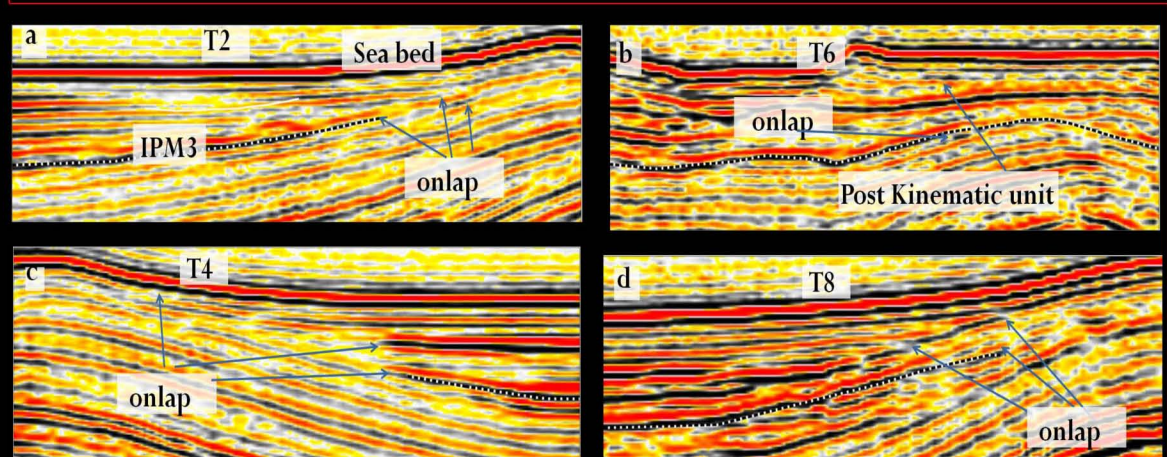


Figure 10: Sections showing sedimentary packages above back limb of the main thrust related folds (T2, T4, T6, and T8).

# 4. 4 Displacement distribution.

✓The plots are individually characterized by several minima and maxima some of which are more than the error limit which may be attributed to segment by linkage (Cartwright et al 1995), lithological contrast (Mouraka and Kamata 1983).

✓Many of the D-W irregularities, occur where SSF intersects TF.

✓3 distinctive classes of profile may be identified (Type 1, Type 2 and Type 3).

✓ Type 1 is simple symmetry or a C type plot (Mouraka and Kamata 1983, Nicol 1995, Bauldon and Cartwright 2008). Maximum displacement is at or close to the centre.

✓ Type 2 has its maximum displacement away from the center. In this case study, maximum displacement tends to be towards where it intersects strike slip fault.

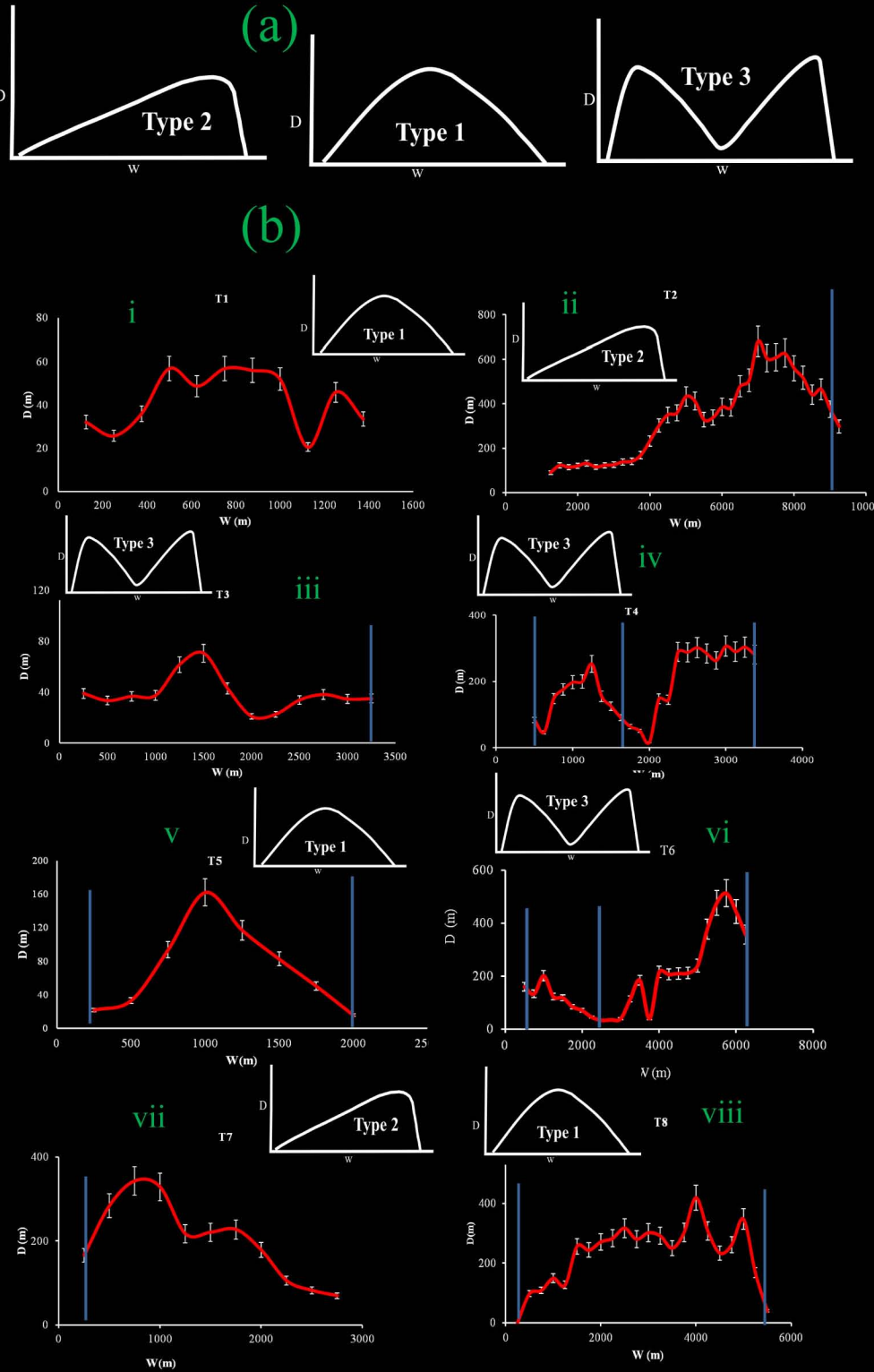✓Type 3 shows multiple asymmetry and has its minimum displacement at the centre.



Figure 11: (a) Sketch of the 3 types of D-W profile geometries observed in this study (Type 1, Type 2 and Type 3). (b) Profiles of displacement along width of thrust faults within the case study structure (i-vi). The white bars represents 10% error limit. The blue line represents strike slip fault.

# 5.0 DISCUSSION

## 5.1: Thrust related fold and strike slip interaction

✓From the result presented in this study several end members can be identified within the case study folds (Figure 13).

✓5 end member thrust related folds (TRF) - strike slip fault (SF) interaction (Class A-F) are possible to occur in zones characterized by network of TRF-SF. 4 out of these end members were observed within the structure described here.

✓ Class A - TRF free from strike slip faults. An example of this type of structure is the T1 (Figure 13 a).

# 4.4 Shortening versus displacement.

✓Comparison between shortening (Sh) and summed displacement (SD) is useful in defining timing between folding and faulting (Suppe 1983).

✓The geometry of the summed displacement and shortening (Figure 13b) are strikingly similar with only a minor differences in irregularity.

✓This similarity relationship between total shortening and summed displacement indicates that folding and faulting are contemporaneous which supports the model of Suppe (1983) for the evolution of fault propagation fold.

✓Also notice trend in continuity between T2 and T6 where they branch ssa at about 10,000m. T2 show a small decrease at branch zone while T6 shows an increase appearing as both structures were one and same faults pre-dating ssa.

✓ while T8 and T6 shows no continuity at 1700m where they both intersected ssc. They both decrease in displacement at intersection zone.
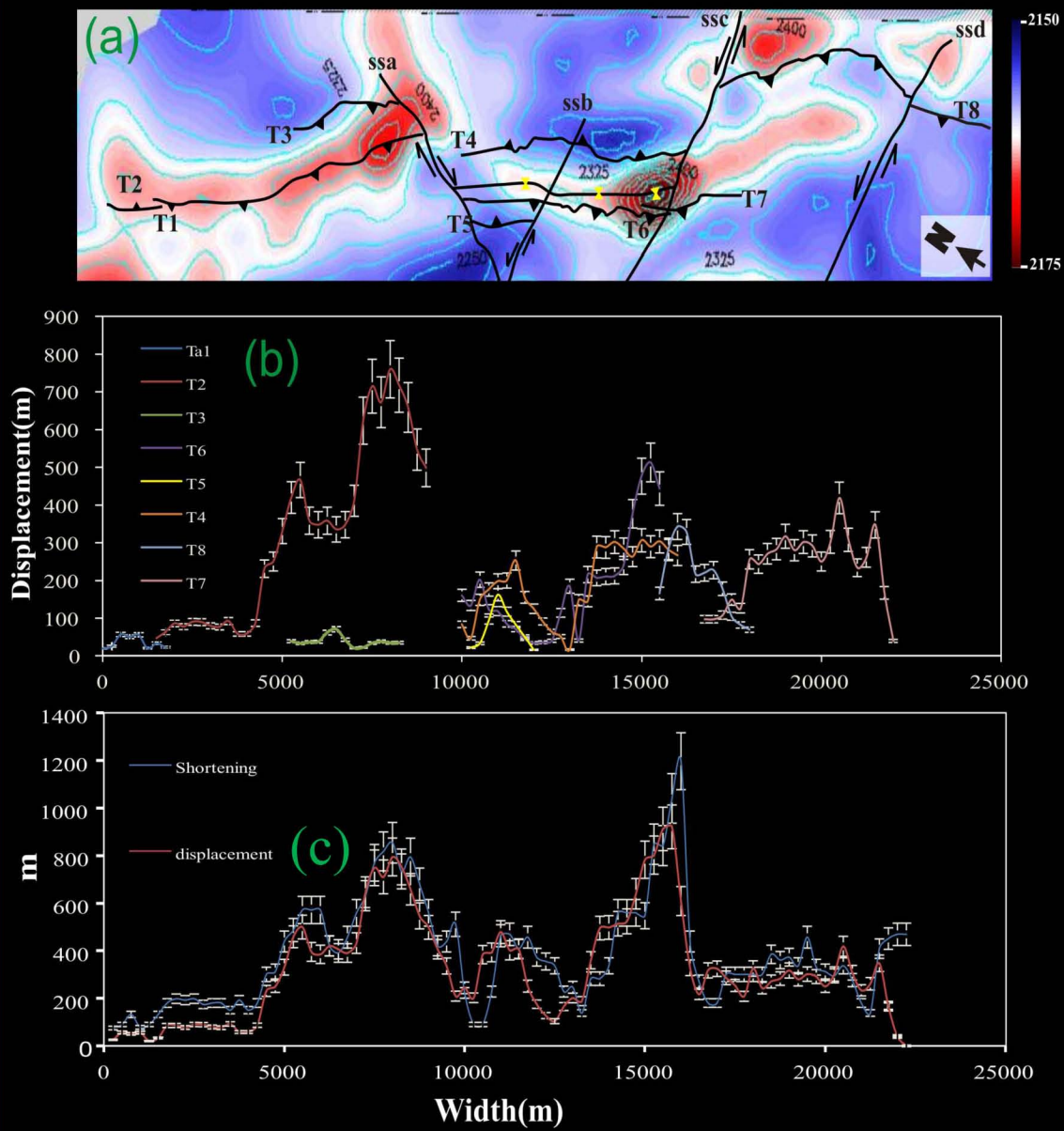


Figure 12: Displacement and shortening plots along strike. (a) Structural time map showing the case study structures. (b) Individual plots of the thrust faults. (c) Plot of the summed displacement of the thrust faults and total shortening of the folds.

✓Class B – These are TRF bounded or sheared at only one end. T2 and T7 fall within this category.

✓Class C- TRF that have been bounded at both tips by strike slip faults striking at same orientation. A typical example of this is T8.

✓ Class E-TRF bisected or cross cuts by a pre-existing SSF. This is observed at the tip of T2 (Figure 9a). This may also be a possible relationship in the case of the central zones of T6 and T4 intersecting ssb (Figure 8).

✓Class D- These are another set of TRF bounded at both ends by strike slip faults striking at different orientation. In most cases these strike slip faults intersects at angle an angle whose bisectrix are almost orthogonal to thrust faults. T5 displays this kind of end member interaction.

✓Class F- TRF cross cutting SSF. This may also be a possible scenario for the central zone of T6 and T4, where both thrust faults intersected SSb.

✓ Some of the end members can occur together for instance T6 and T4 shows the Class D, class C and either Class E or Class F.
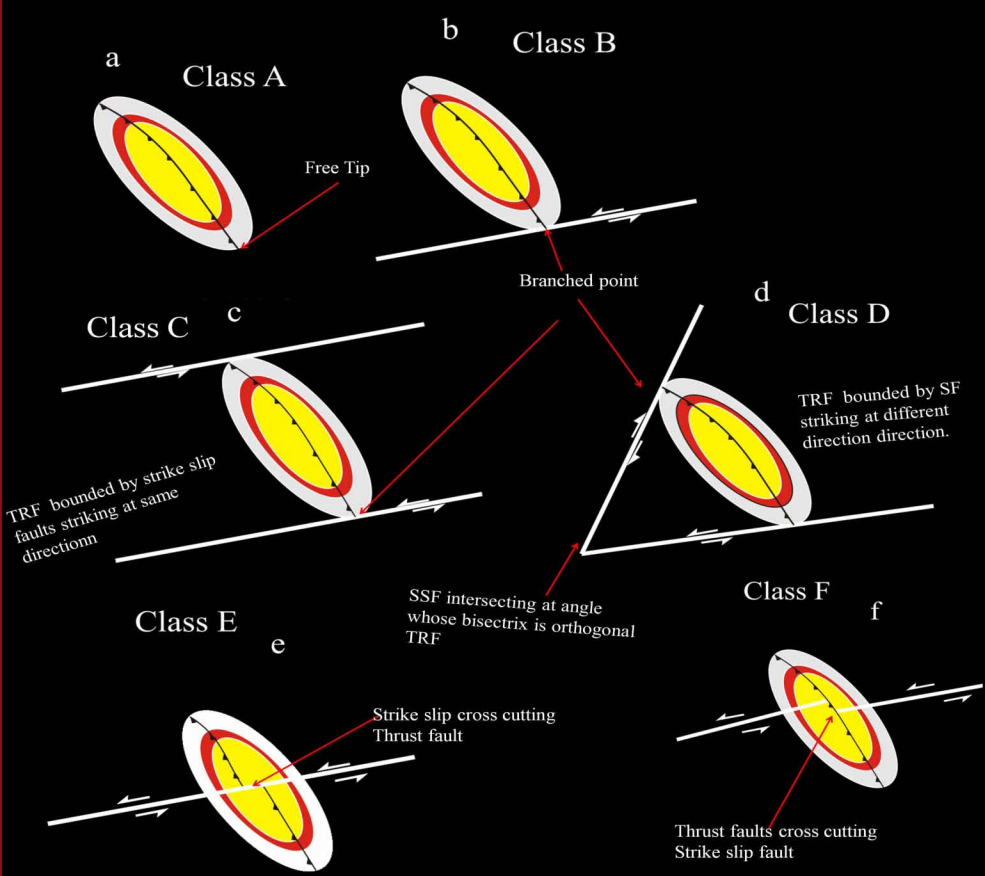
Figure 13: Diagram illustrating the different end member interactions between thrust faults and strike slip faults (class A-F). The different types are labelled a-f.

Labels within figure: Class A (a), Class B (b), Class C (c), Class D (d), Class E (e), Class F (f). Free Tip. Branched point. TRF bounded by strike slip faults striking at same direction. SSF intersecting at angle whose bisectrix is orthogonal TRF. TRF bounded by SF striking at different direction direction. Strike slip cross cutting Thrust fault. Thrust faults cross cutting Strike slip fault.

## 5.2: Relationship between end members and displacement geometry.

✓Previous work has shown several d-x (d-w for this study) profiles, some of which are compatible with our result.

✓The C type profile indicates that the faults propagate freely without interacting with any medium any intervening medium. This is almost compatible with T1 which shows no notable strike slip intersection(Figure 8).

✓The C type profile which is similar to our type 1 profile covers a range of end member interaction in this study ( Class A, Class C and Class B), which indicates that the C type profile does not hold strictly for isolated faults.

✓The asymmetric type profile (Figure15D and E) is similar to the type 2 profile which has been interpreted as faults which have been tip restricted. The class B end member faults (T2 and T7) fall within this category(Figure 11).

✓The closest profile geometry to type 3 is the elliptical with taper (Figure 14E). This is indicative of faults which laterally propagates pass barrier. The central strike slip branch zone of T4 and T6 may be explained by this scenario.



Figure 15: Displacement distribution geometry from previous work (A- E)

Labels: A Standard profile (C type) (Mouraka and Kamata 1983); B M type profile (Mouraka and Kamata 1983) Change in lithology; C Assymetric(tip restricted) (Nicol et al.1995, Manighetti et al. 2001); D Assymetric (double restricted) (Manighetti et al. 2001) Barrier Barrier; E Elliptical with taper (Manighetti et al. 2001) Barrier Barrier Barrier.

## 5.3: Relative timing between thrust faults and strike slip faults.

3 models can be used in explaining whether T2,T6 and T8 are all one same structure before segmented by strike slip faults or whether they are thrust faults which have been tip restricted to propagation (Figure 8). t1 - t2 represents sequence in time.

### 5.3.1 : Thrust fault pre-dates strike slip fault

✓ This models shows that thrust fault was inactive as strike slip runs through it.

✓It may explain the displacement continuity of profile geometry of T2 and T6, it may also support cross cutting at tip of T2.

✓There are 3 main observations within the case study folds which does not support this model. (1) If this model is true, the displacement of ssc using channel segmentation would be compatible with that of the separation distance between T8 and T6. (2) It is unrealistic for ssa to have a displacement of more than 2km at tip, using the fold offset (T2 and T6) without transferring any notable deformation close to its tip see (Figure 8 and 9d). (3) kinematic packages show that T6 is no longer inactive while T2 and T8 are still emerging thrust folds.
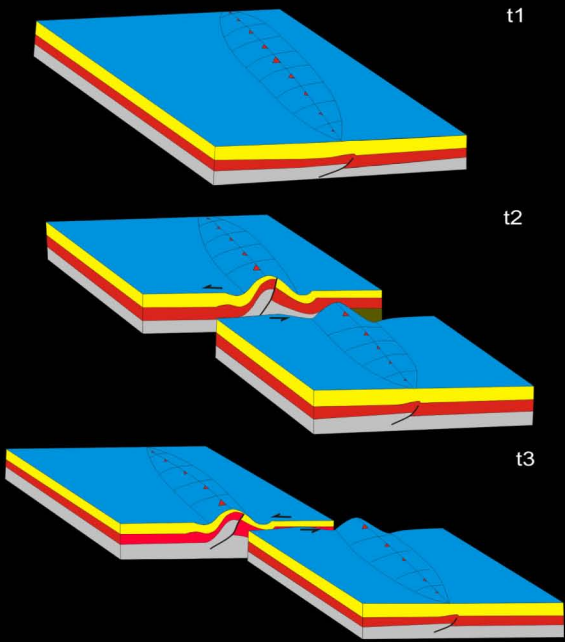
### 5.3.2 : Thrust fault post-dates strike slip fault

✓This model shows that SF was in active as the thrust faults laterally propagated towards it (t1-t3) .

✓There is a shift of maximum displacement from the centre as their propagation is laterally impeded by the strike slip fault.

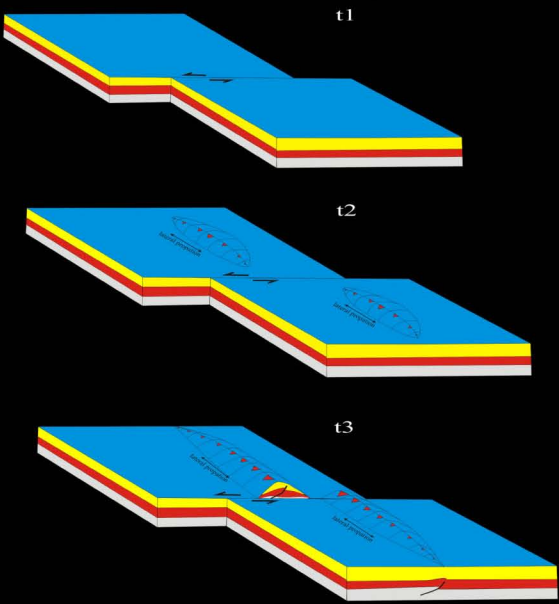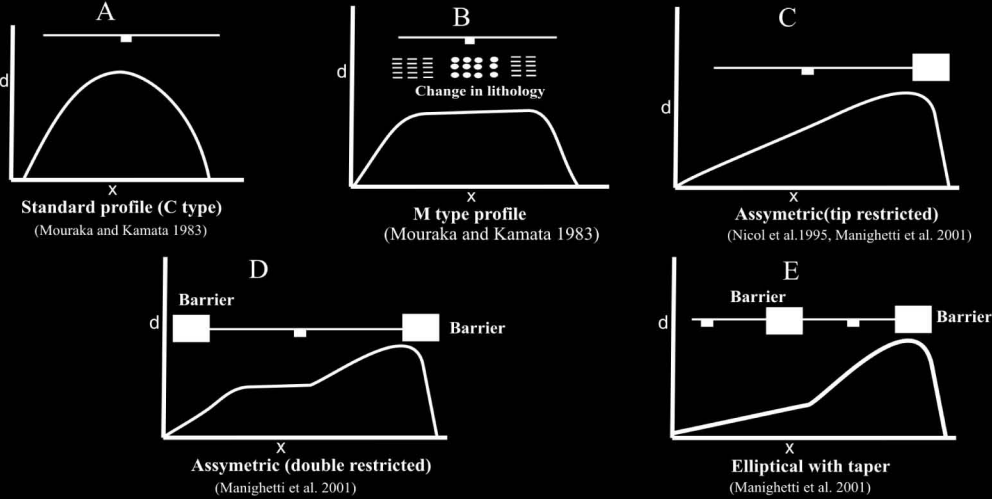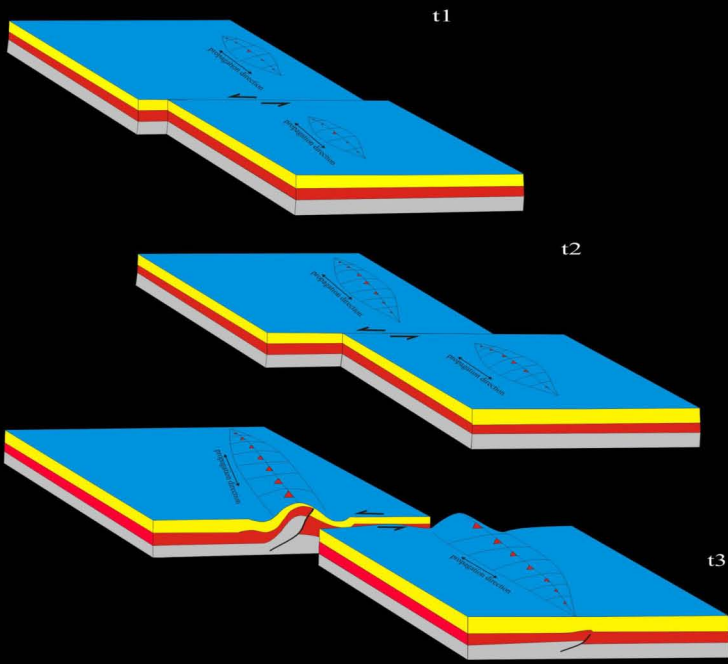✓The only problem with this model is that it those not explain the cross cut observed at the tip of T2 .

### 5.3.3 : Both thrust fault and strike slip faults are coeval.

✓This model is the most probable out of the 3 models whether the structures initiated at same source or the thrust faults gradually propagated towards the active strike slip fault.

✓In this model thrust faults propagated towards active strike slip fault, due to intense straining at the branch zone, strike slip faults may form branches (splays) which may cross cut lateral thrust fault tip.



Figure(16a) model illustrating thrust faults pre-dates strike slip fault propagation.



Figure (16a) model illustrating thrust faults post-dates strike slip fault propagation.



Figure(16c) model illustrating coeval relationship.

## 6.0 CONCLUSION

✓This study document a number of thrust related folds within deepwater water fold and thrust belts segmented or bounded by strike slip faults. Five (5) end members identified include: - Class A, B, C, D, E, and F.

✓The displacement distribution geometry described include Type I (Class A, C & D), Type II (Class B), and type III (Multiple classes), the classes are not restricted to the different displacement geometry.

✓Relative timing models between thrust faults and strike slip faults may include (1) Thrust faults pre-dates strike slip fault, (2) thrust faults post dates and, (3) both faults are coeval. This study supports the third model.

✓This study also shows that fold shortening is contemporaneous with fault displacement.

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