# Displacement – Length Linkage Model Applied to Footwalls Traps: Examples from the Eastern Llanos Basin of Colombia*

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## Abstract

Low-relief footwall traps on east dipping normal faults constitute a significant number of oil accumulations in the Llanos basin of Colombia. Normal fault systems in this basin are generally formed by discrete fault segments arranged in echelon and separated by relay ramps. The associated footwall traps are in many cases defined in map view as three ways against a normal fault. The structural relief of these traps is related principally to the magnitude of fault displacement. Thus these individual closures associated with discrete fault segments exhibit a simple geometry with the highest structural point (and crest) generally coincident with the maximum fault throw and trap relief tapering toward the fault tips. These fault segments, in some cases, propagate laterally and link forming rather continuous fault systems. This lateral linkage of the discrete fault segments can be inferred by fault throw versus distance diagrams. Results from the application of this methodology validate the displacement-length linkage model (Watterson, 1986) for these footwall traps. This analysis is critical to prevent misinterpretations that might lead to “oversized” footwall traps formed by discrete normal faults separated by saddles (locations of the ancestral relay ramps) and also to infer, via progressive decrease of fault offset toward the fault tips, the presence and dimensions of footwall traps where seismic is absent or of poor quality, due to common problems such as local velocity changes related commonly to fault shadows, associated with the Miocene, mud-prone León Formation, or acquisition problems. Examples of this type of analysis are provided from the central Llanos where these footwall traps have been successfully explored.

## Introduction

The Llanos foreland basin (Figure 1) is the most prolific hydrocarbon basin of Colombia. It covers an area of approximately 200,000 km$^2$. More than 3,500 MMBO of recoverable oil has been documented in this basin. Four giant fields (Caño Limón, Cusiana, Cupiagua, and Castilla) and a significant number of minor fields have been discovered to date. Guyana shield – derived, quartz-rich sands constitute the main reservoirs in this basin. The Late Eocene Mirador sands, in the Cusiana and Cupiagua fields of the basin foothills (Cooper at al., 1995), and younger sands in the Caño Limón field and contiguous Guafita field in Venezuela, stand out for their excellent reservoir quality, deliverability, and recovery factors (Villamil, 2003).

Low-relief footwall traps on east dipping normal faults constitute a significant number of oil accumulations in the Llanos basin of Colombia. Normal fault systems in this basin are generally formed by discrete, east-dipping fault segments arranged in echelon and separated by relay ramps or transfer zones. The vast majority of the associated footwall traps are characterized in map view as three ways against a normal fault. The structural relief of these traps is related principally to the magnitude of fault displacement. Displacement on a single fault surface ideally decreases to zero in all directions from a point of maximum displacement. From data on the maximum lateral dimensions (also known as fault width, the maximum dimension of the fault surface in a direction normal to the slip direction and parallel to the fault trace on map view) and maximum displacements an expression has been derived. The basis of this expression is a fault growth model in which width is proportional to the square root of displacement. The size of a fault trace on map view is always referred to as the length (L) of the fault trace because it is two-dimensional (Walsh and Watterson, 1988). Width/displacement ratios vary systematically with the size of a fault with values of up to ca 30,000, which are characteristic of a single slip event (Walsh and Watterson, 1988), morphology similar to many single normal faults identified in the Llanos basin.

Many papers have investigated the displacement (D) and surface trace length (L) characteristics of normal faults to determine a relationship between the fault displacement and fault trace length finding that faults increase their displacement (D) as they increase their length (L). This systematic relationship has been interpreted in terms of what is known as the fault growth model (Watterson, 1986) [Figure 2].

The goal of this contribution is to systematically analyze the geometry of the central Llanos low relief, footwall traps using the displacement – length linkage model and potentially predict the presence of laterally linked fault segments and their impact in trap integrity.

## Methodology and General Observations

The methodology used in this contribution consisted in:

- Detailed mapping of key horizons and fault planes. Four marker horizons were used for this study: the Carbonera C-5 sand, the Mirador, the Gacheta sand within the Villeta Formation and Ubaque (Figure 1).
- Displacement (D) was measured as offset of a marker horizon measured along the dip of the fault plane. All segments analyzed are east dipping normal faults with low relief footwall traps. General strike of the fault traces is NE-SW.
- Tabulation of displacement (throw) along each fault trace.
- Construction of Displacement (D) – Length (L) plots, Throw-length (T-x) plots or Fault Slip – Distance plots which allow the map-view growth history of the faults by lateral linkage,
- Validation through throw-depth (T-z) plots of the absence of significant fault activity during the sedimentation of key horizons mapped for construction of D-L plots.

The Llanos individual closures associated with discrete fault segments exhibit a simple geometry with the highest structural point (and crest) generally coincident with the maximum fault displacement or throw and trap relief tapering toward the fault tips. In this particular case of a simple normal fault not linked laterally with another one the D-L plot will show an idealized symmetrical bell-shaped displacement profile with decreasing displacement (throw) toward both tip points (Figure 3).

Fault segments, in some cases, propagate laterally and link forming rather continuous fault systems. Extensional faults grow by the process of radial propagation and the linkage of individual faults (Figure 4).

This lateral linkage of the discrete fault segments can be inferred by displacement (fault throw) versus distance diagrams. Results from the application of this methodology validate the displacement-length linkage model (Watterson, 1986) for the central Llanos footwall traps. Inflections in the fault-displacement relationship can be used to determine location and magnitude of transfer zones (Figures 5 and Figure 6).

A fault system that indicates fault linkage by numerous individual propagating fault segments will show an irregular aggregate profile of numerous displacement maxima and minima (cf. Morley and Wonganan, 2000; Corredor et al., 2012) with a multimodal D-L distribution along the fault and minima corresponding to the location of transfer zones (Figure 7 and Figure 8).

Trap integrity in this type of composite closures is heavily dependent on the degree of displacement conservation (Figure 5 and Figure 6). In cases where the degree of displacement conservation is low (Figure 5), i.e. there is a significant difference between actual displacement and simple projected displacement in the transfer zone, trap integrity is low and probably two smaller traps, corresponding to individual fault segments, are viable.

## Selected Examples from the Central Llanos

- Example 1 (Figure 9 and Figure 10)
- Example 2 (Figure 11, Figure 12 and Figure 13)
- Example 3 (Figures 14, Figure 15, Figure 16 and Figure 17)

In the case of individual fault segments, assuming no lateral linkage of faults (as evidenced by unimodal D-L relationship curve) the D-L relationship methodology allows to infer, via decreasing offset toward the fault tips, the presence and dimensions of footwall trap when the seismic cover is of fair to poor quality or there is no seismic cover.

## Conclusions

1. Examples of simple, complete or incomplete, symmetric (unimodal) D-L relationship plots or profiles and irregular (bimodal and multimodal) D-L profiles with displacement (throw) highs and lows have been identified in the east dipping normal faults of the Llanos foreland.
2. Inflections (displacement or throw minima) in the D-L profile can be used to determine location and magnitude of relay zones.

3. The use of displacement-length (D-L) plots is critical to prevent misinterpretations that might lead to "oversized" footwall traps formed by discrete normal faults separated by saddles (locations of the ancestral relay ramps). A bimodal distribution in the D-L plots is indicative of two individual fault segments laterally linked.
4. “Oversized” faults with lengths > 10 km (with low D-L ratios) should be analyzed in detail since they tend to be the product of at least two individual fault segments with a relay zone in between.
5. No evidence was found that the discrete fault segments with an echelon fault array analyzed in this study have any oblique slip component.

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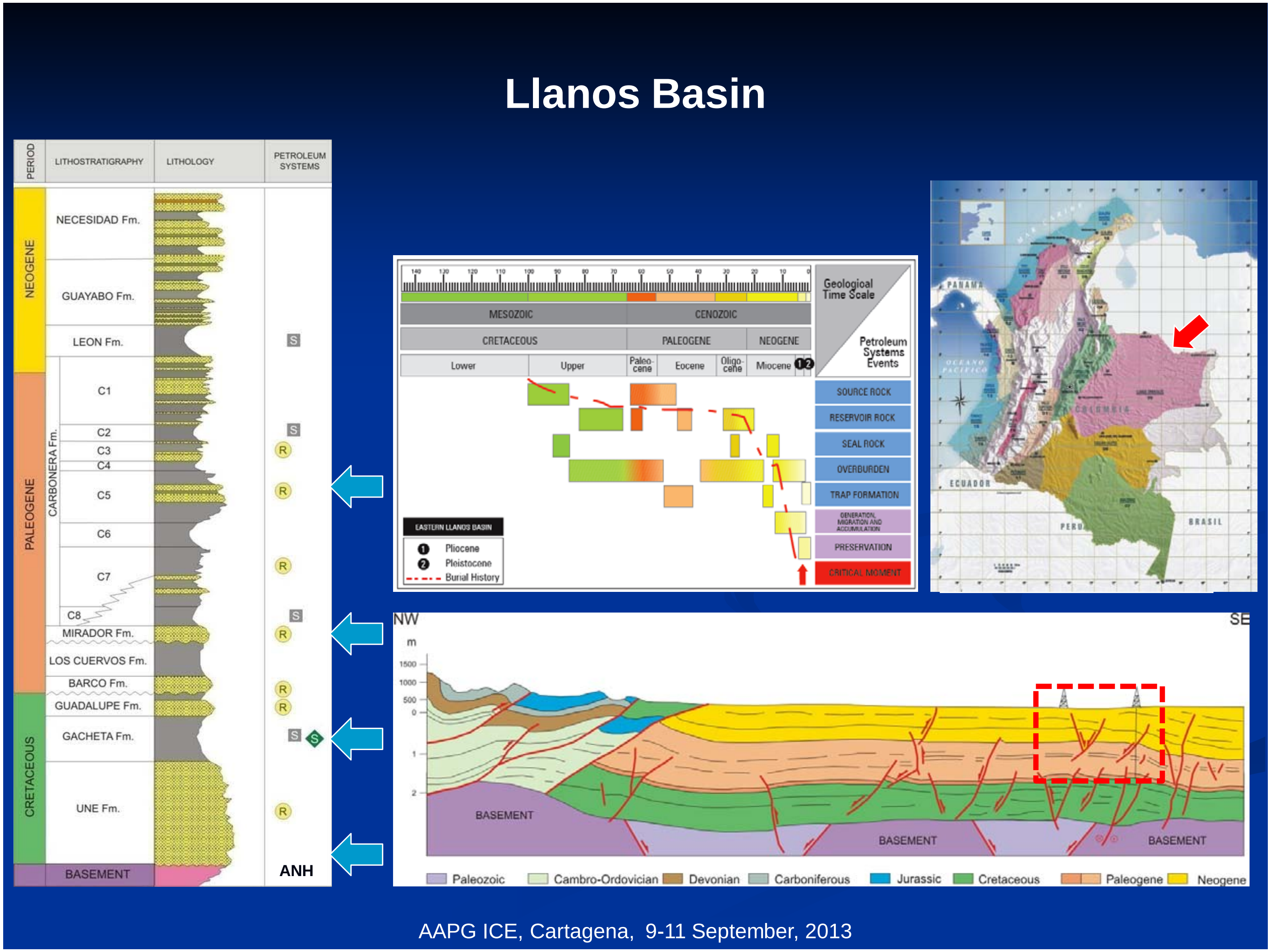
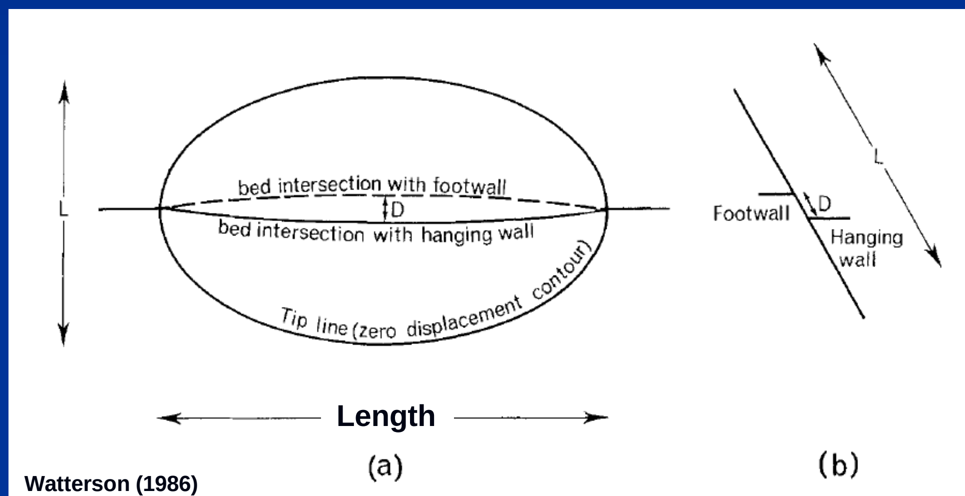



Figure 1. The Llanos foreland basin.

# The relationship between displacement (D) and surface trace length (L)

**The displacement (D) and surface trace length (L, known also as width, W) values of normal faults have a very well defined relationship: faults increase their displacement (D, also known as throw) as they increase their length (L).**




**Geometry of an idealized simple normal fault with elliptical tip line, or zero displacement contour: (a) viewed along normal to slip surface; (b) side elevation. Disposition of an originally horizontal horizon on the fault plane is shown for footwall and hanging wall. L is length (parallel to slip direction), W is width (here renamed as Length) and D is maximum displacement.**

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Figure 2. The relationship between displacement (D) and surface trace length (L).

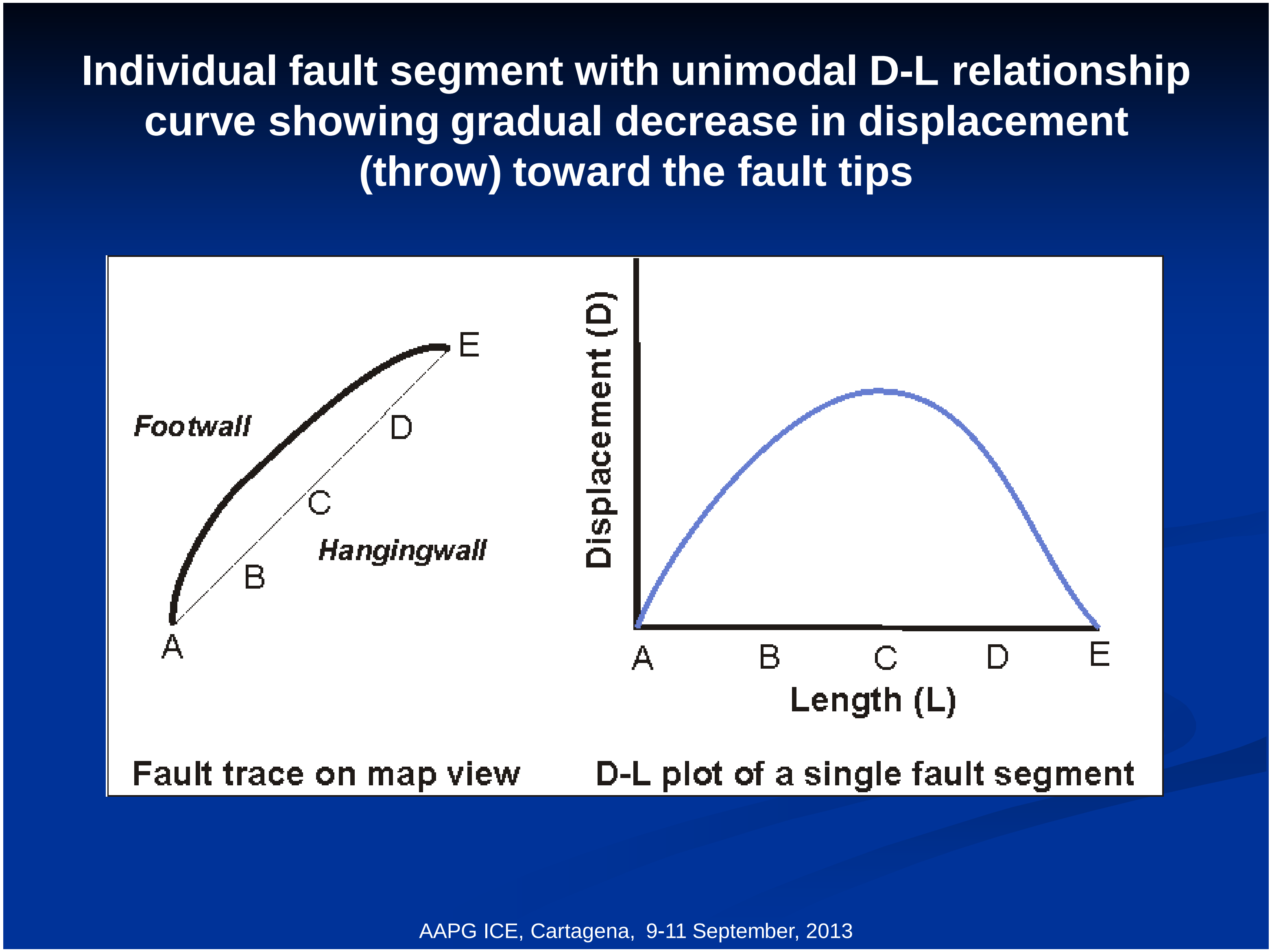



Figure 3. Individual fault segment with unimodal D-L relationship curve showing gradual decrease in displacement (throw) toward the fault tips.

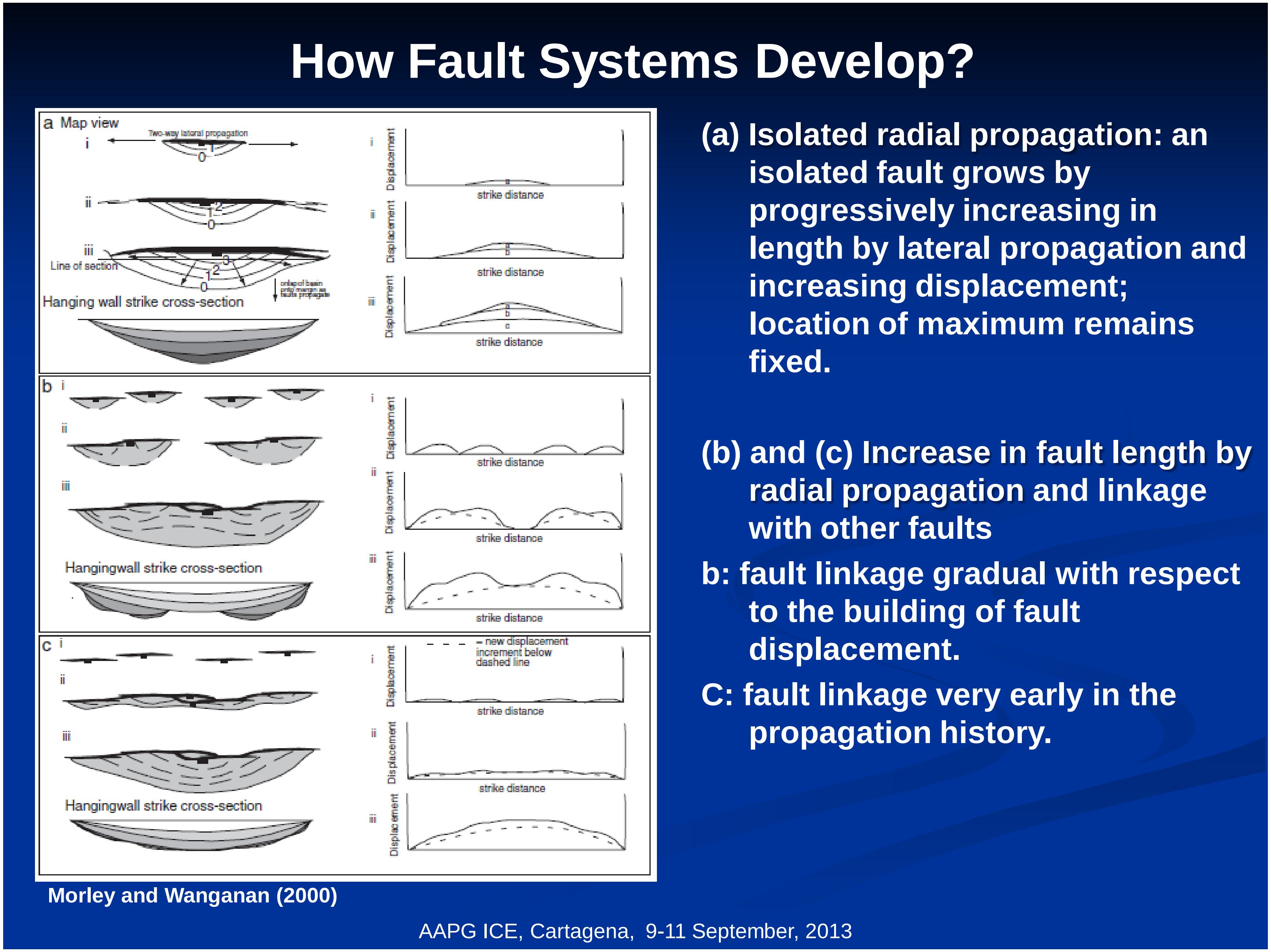



Figure 4. How fault systems develop.

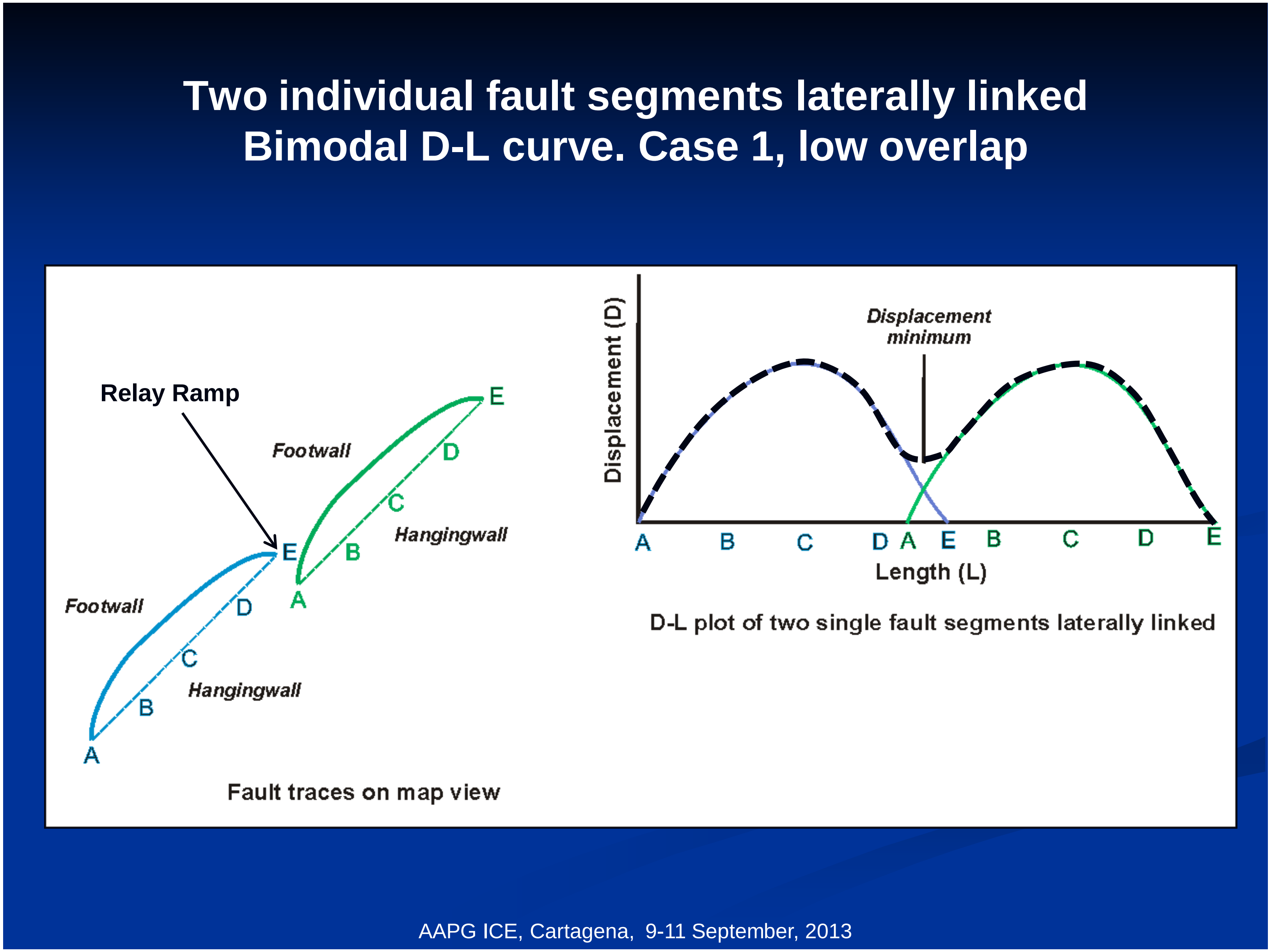



Figure 5. Two individual fault segments laterally linked bimodal D-L curve. Case 1, low overlap.

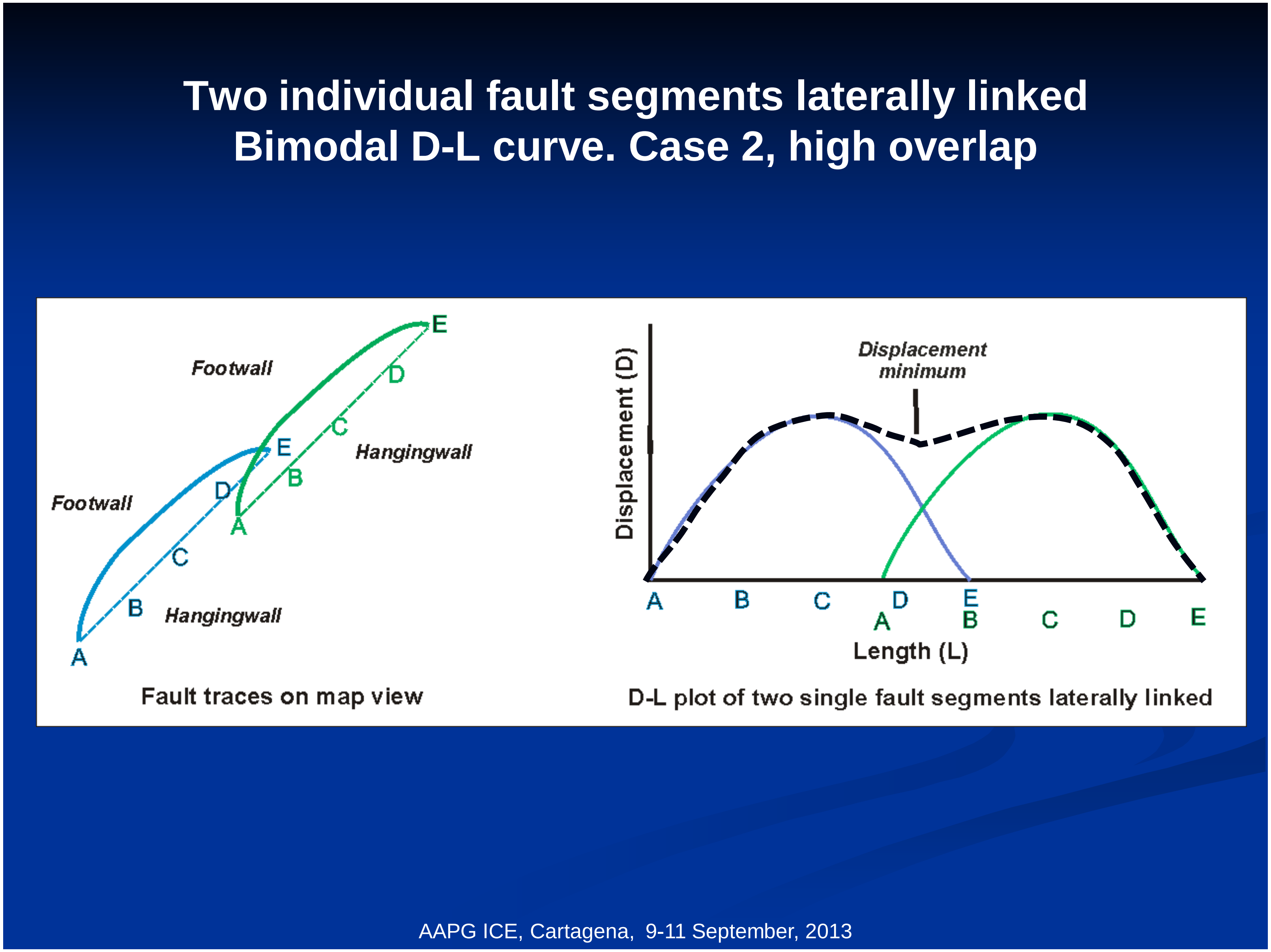



Figure 6. Two individual fault segments laterally linked bimodal D-L curve. Case 2, high overlap.

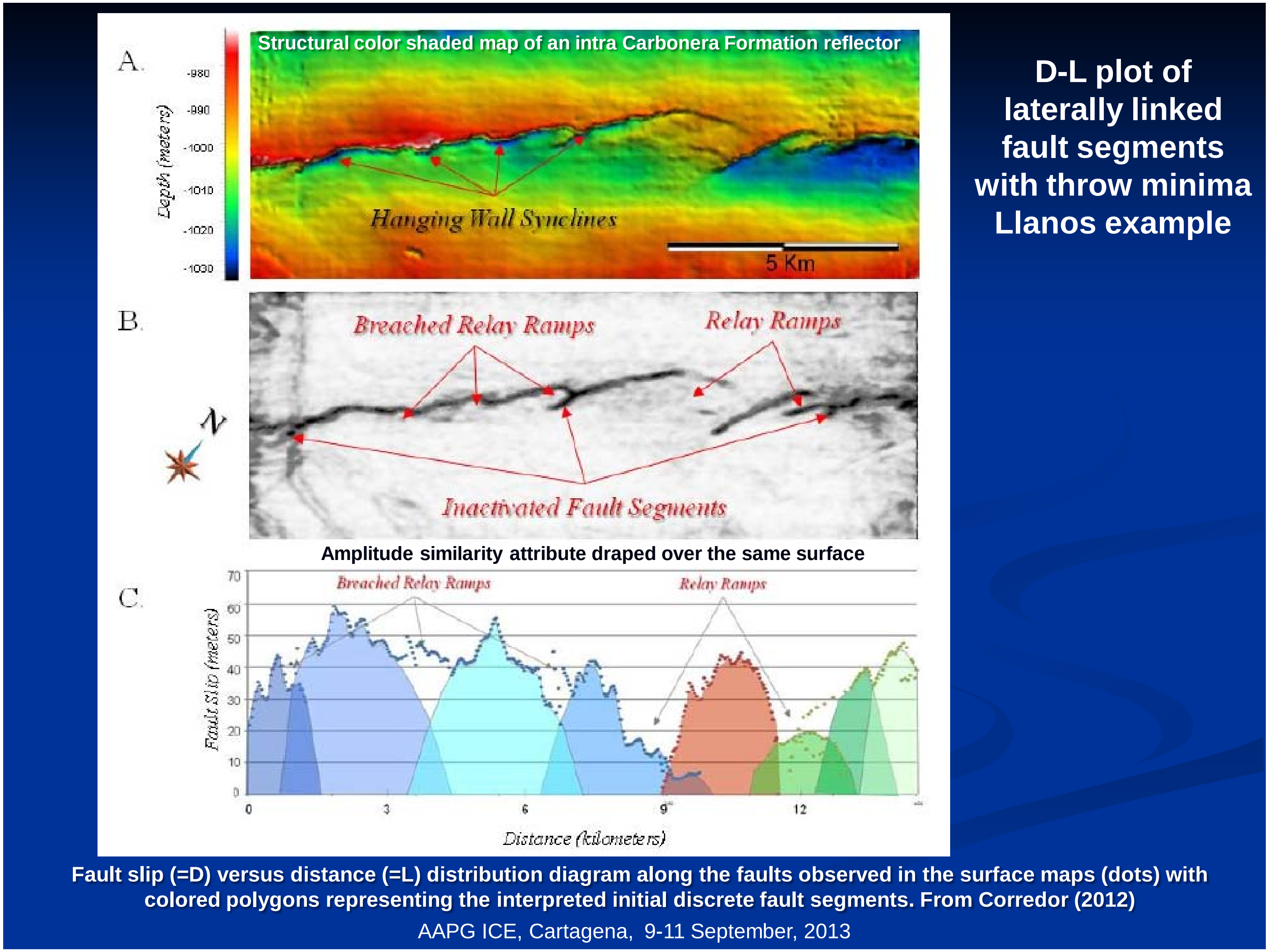
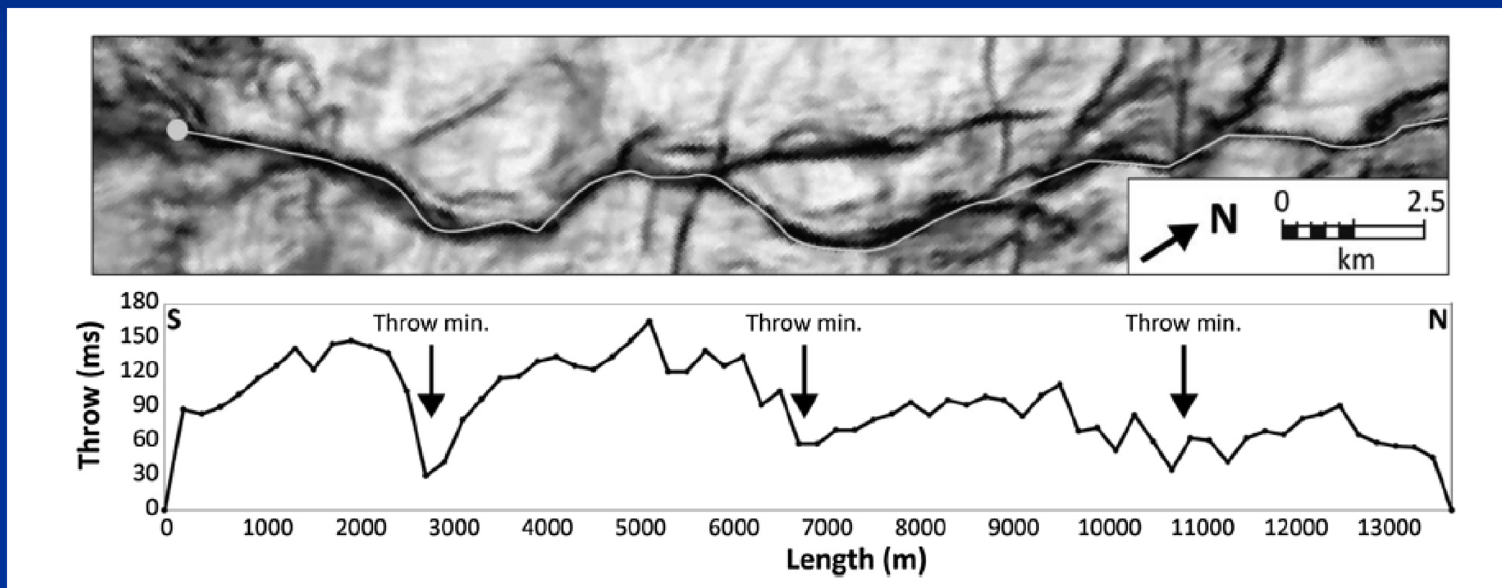



Figure 7. D-L plot of laterally linked fault segments with throw minima Llanos example.

# D-L plot of laterally linked fault segments with throw minima North Sea example




**Tvedt et al. (2013)**



Figure 8. D-L plot of laterally linked fault segments with throw minima North Sea example.

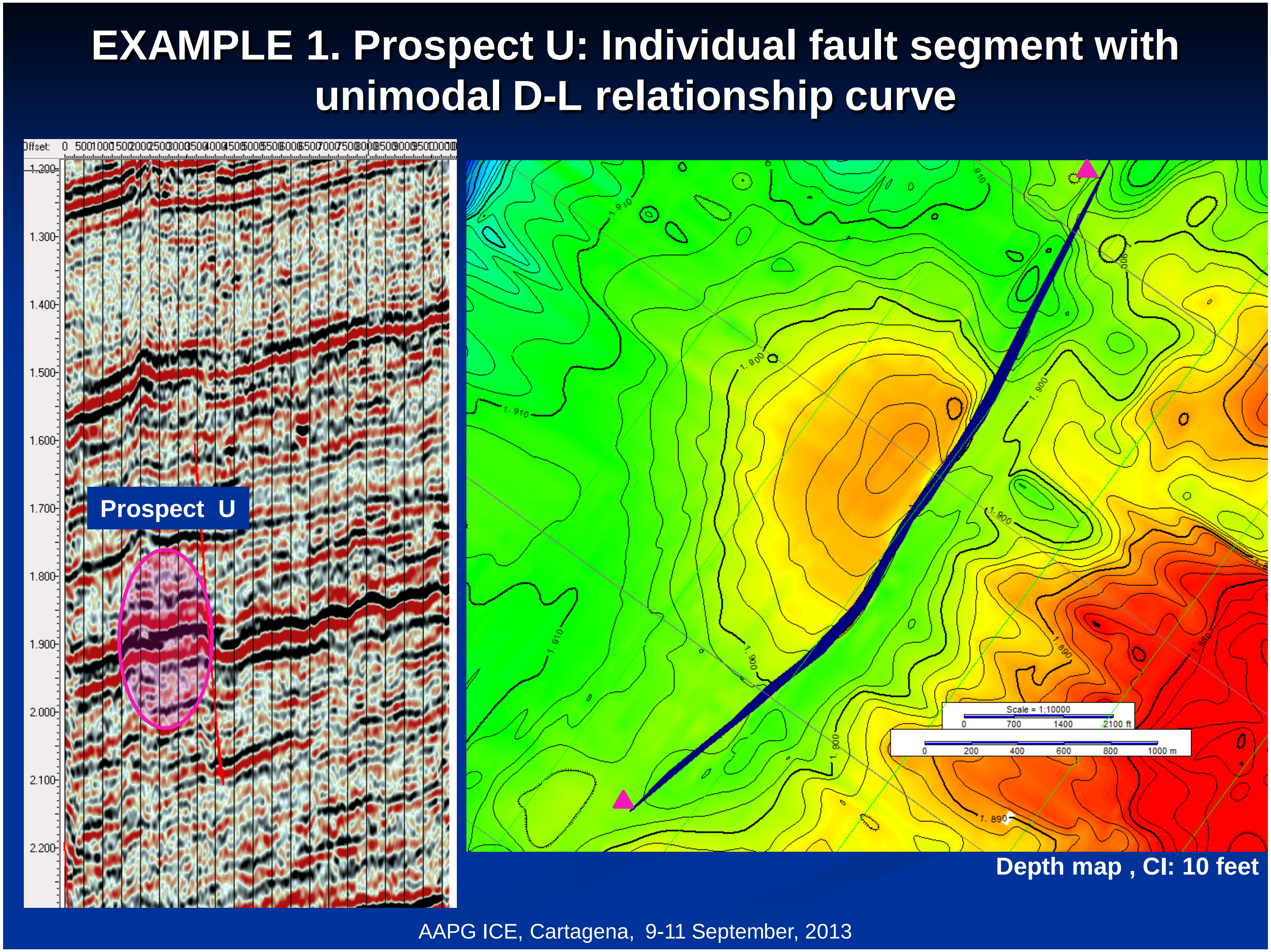



Figure 9. Example 1. Prospect U: Individual fault segment with unimodal D-L relationship curve.

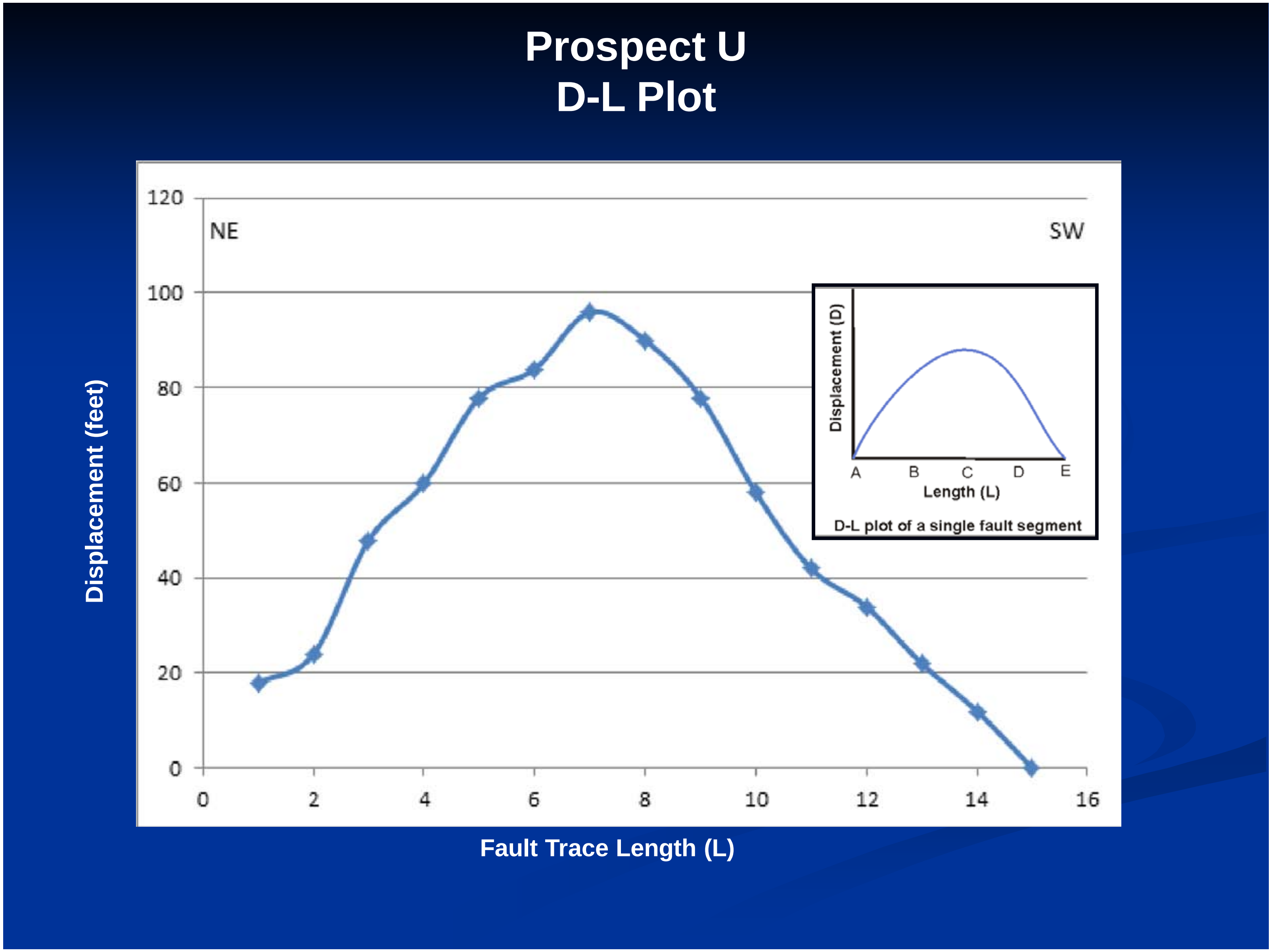
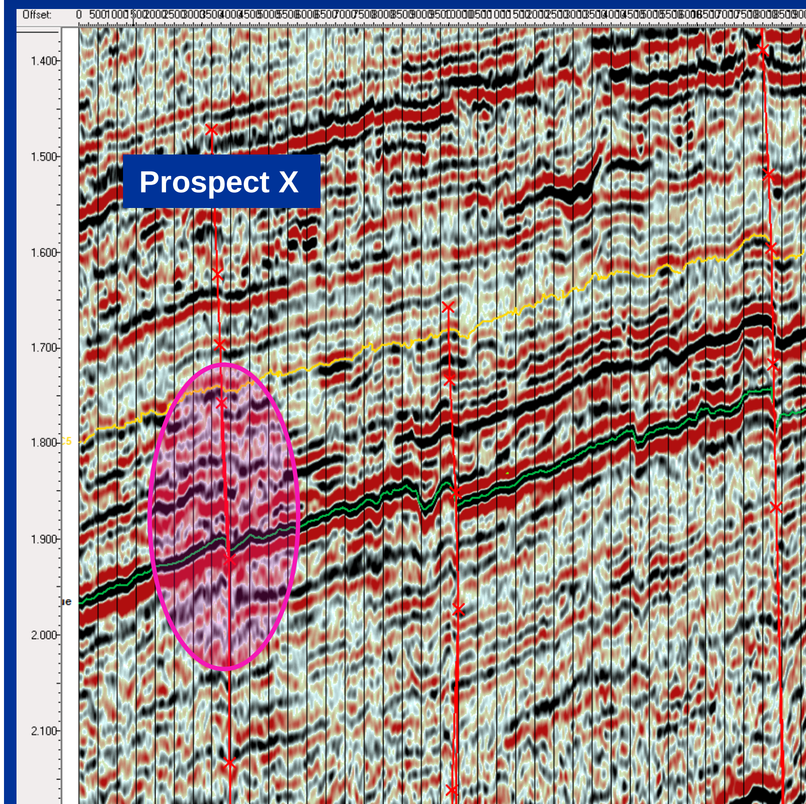



Figure 10. Prospect U D-L Plot.

# EXAMPLE 2: Prospect X, “oversized trap" originally mapped as a single fault segment

## Strong Bimodal L-D Relationship Curve

- **Originally mapped as a single fault segment, then turned into two linked fault segments with low overlap and therefore a high risk of trap integrity and trap size reduction.**




**Depth map , CI: 10 feet**

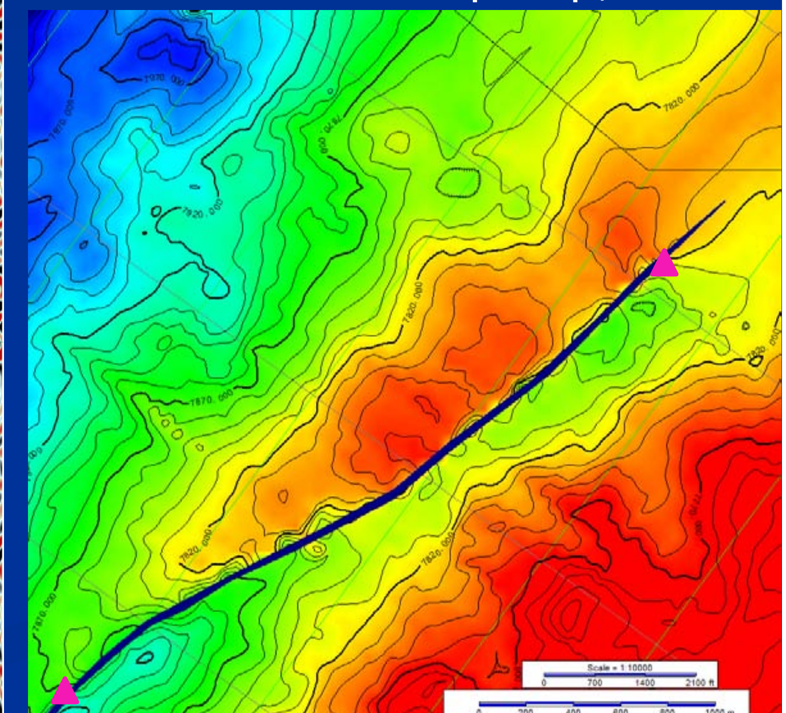


Figure 11. Example 2: Prospect X, “oversized trap" originally mapped as a single fault segment.

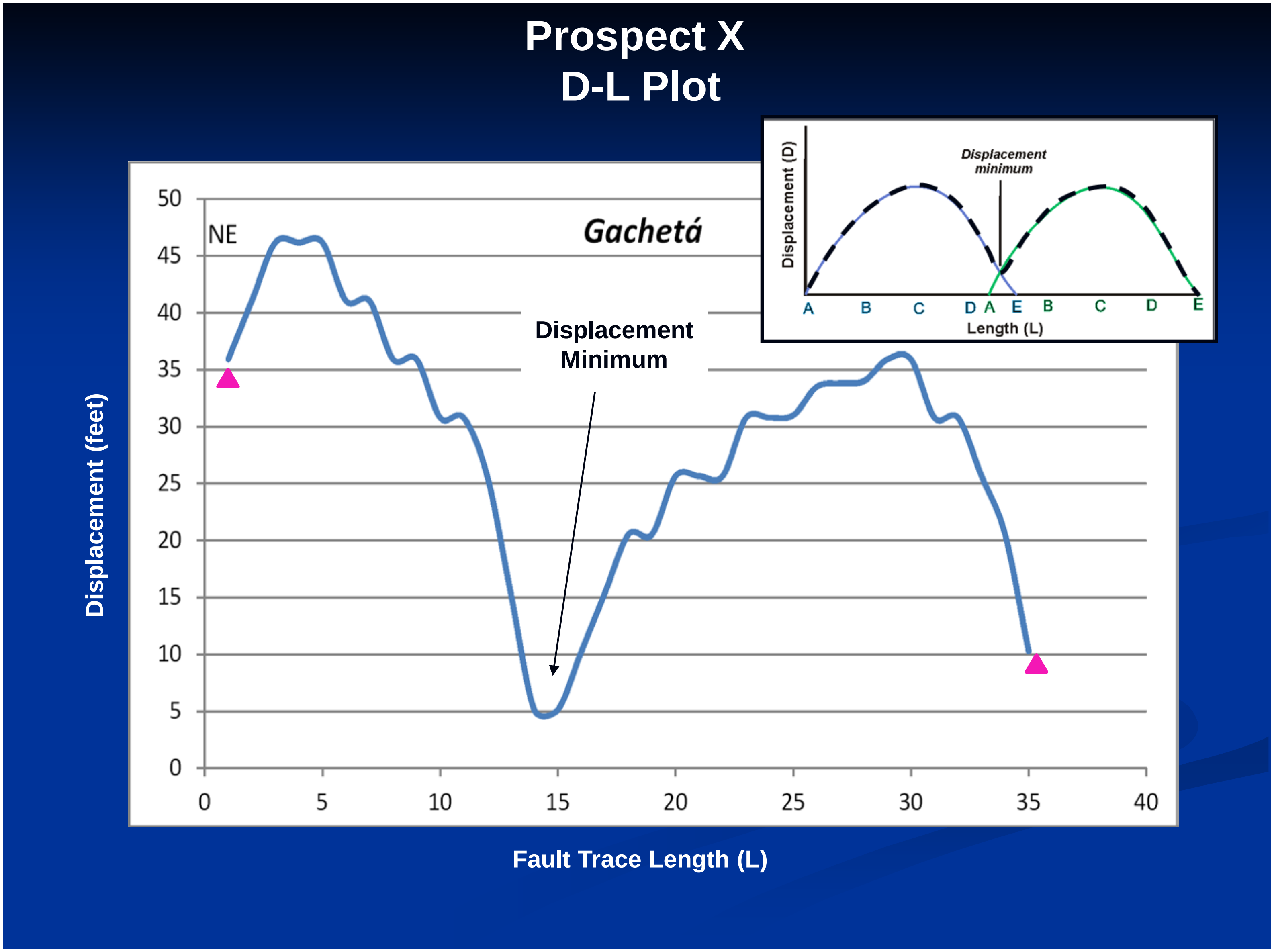



Figure 12. Prospect X D-L Plot.

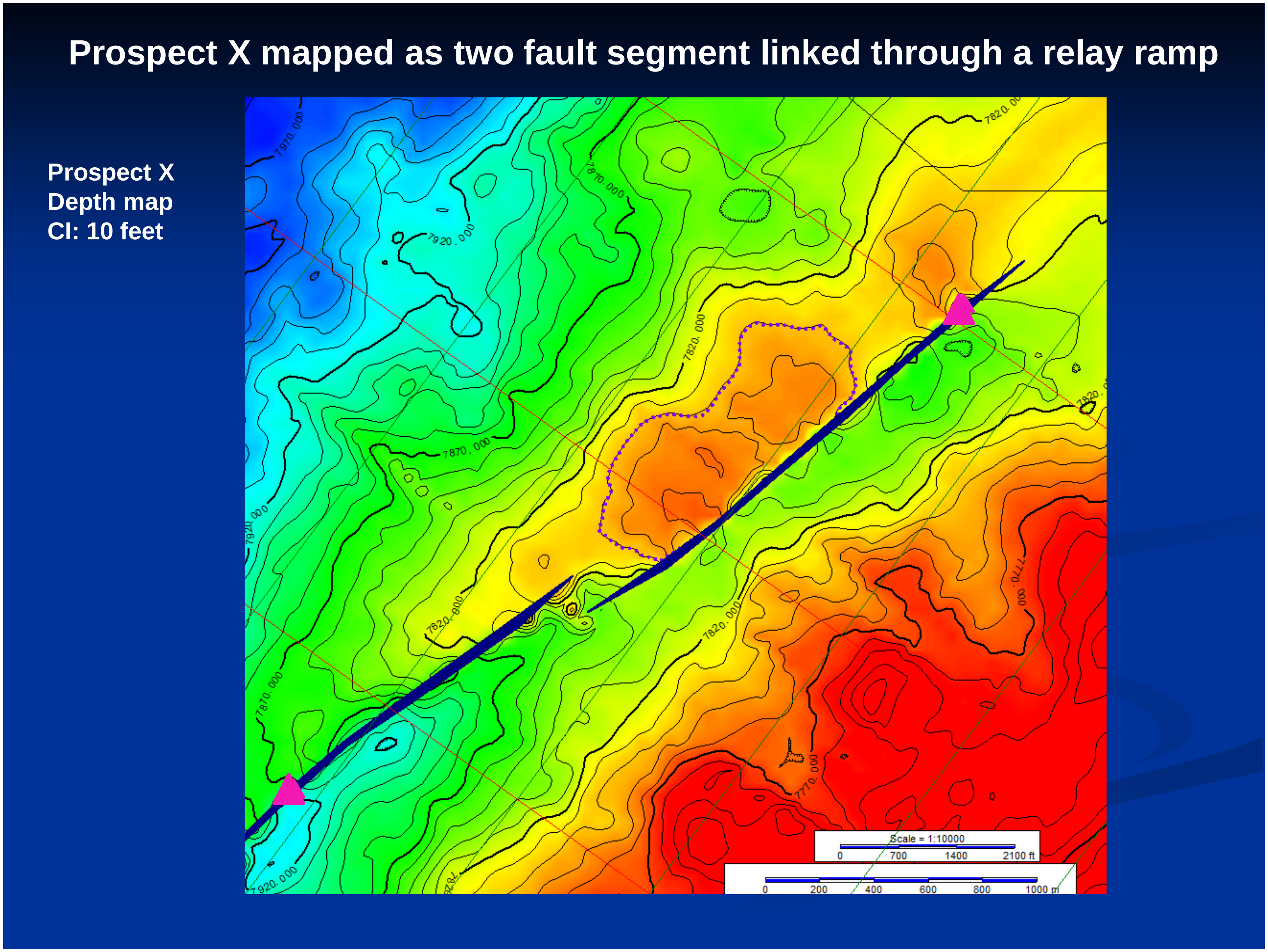



Figure 13. Prospect X mapped as two-fault segment linked through a relay ramp.

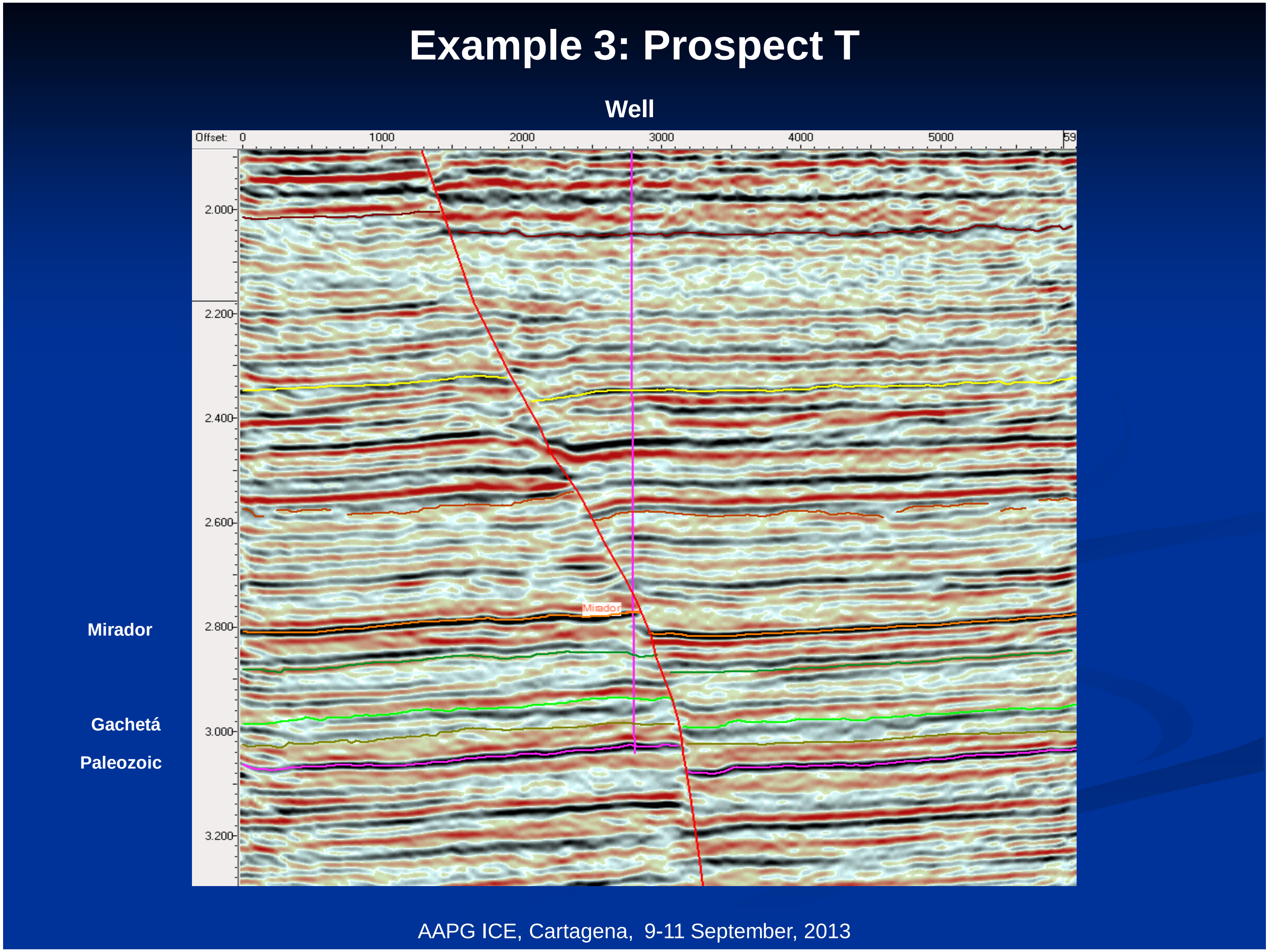



Figure 14. Example 3: Prospect T.

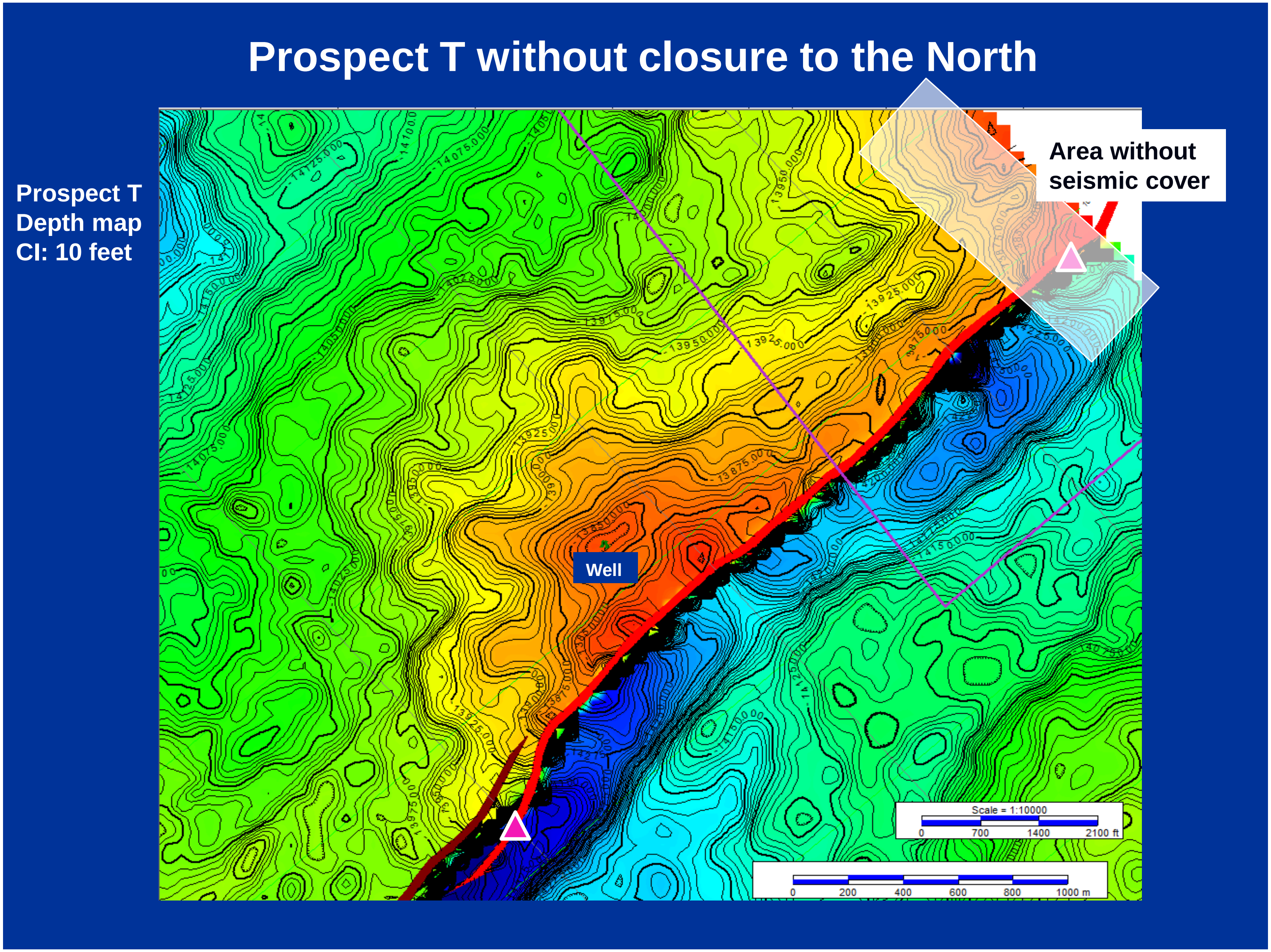



Figure 15. Prospect T without closure to the North.

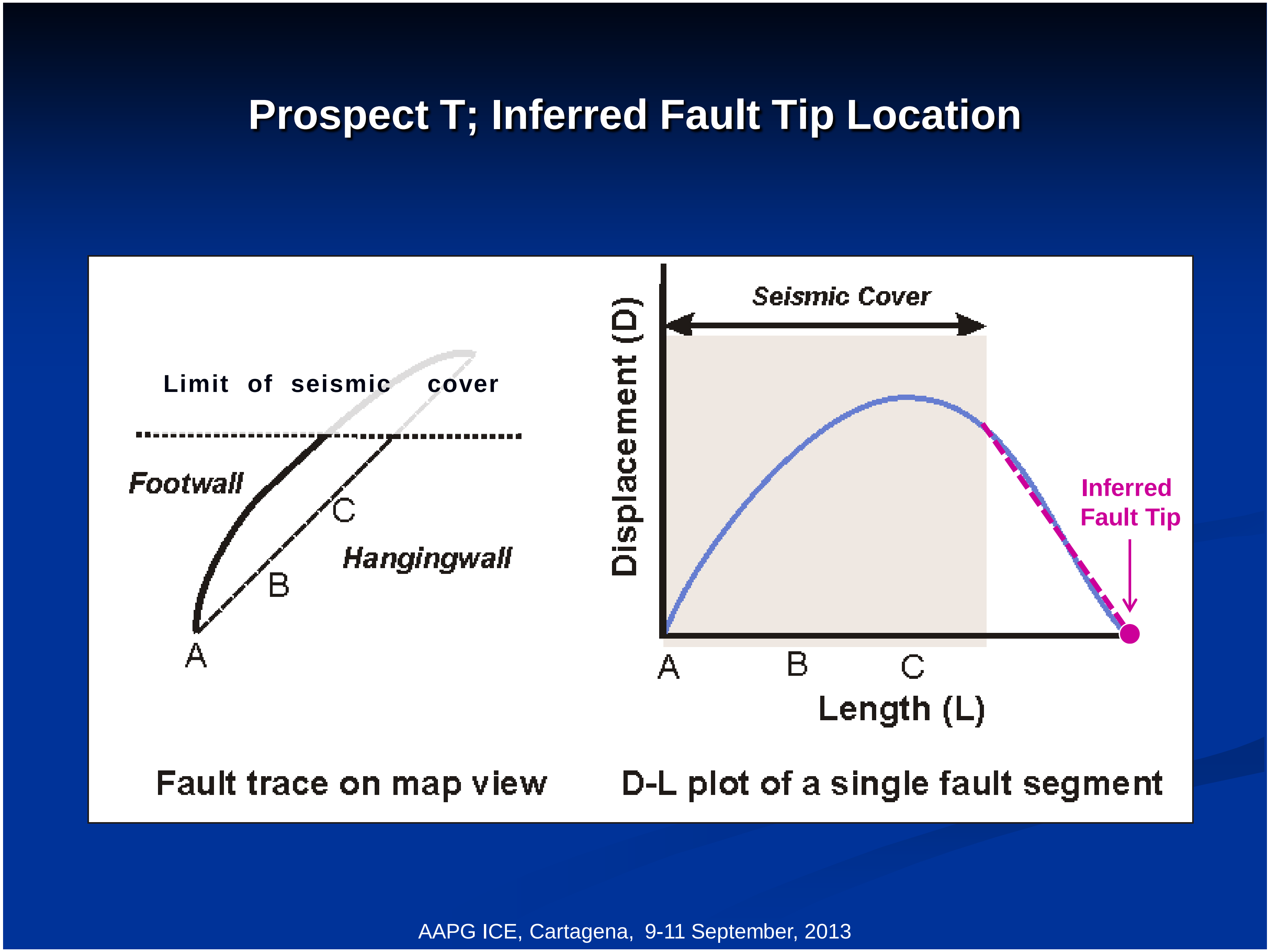



Figure 16. Prospect T; Inferred Fault Tip Location.

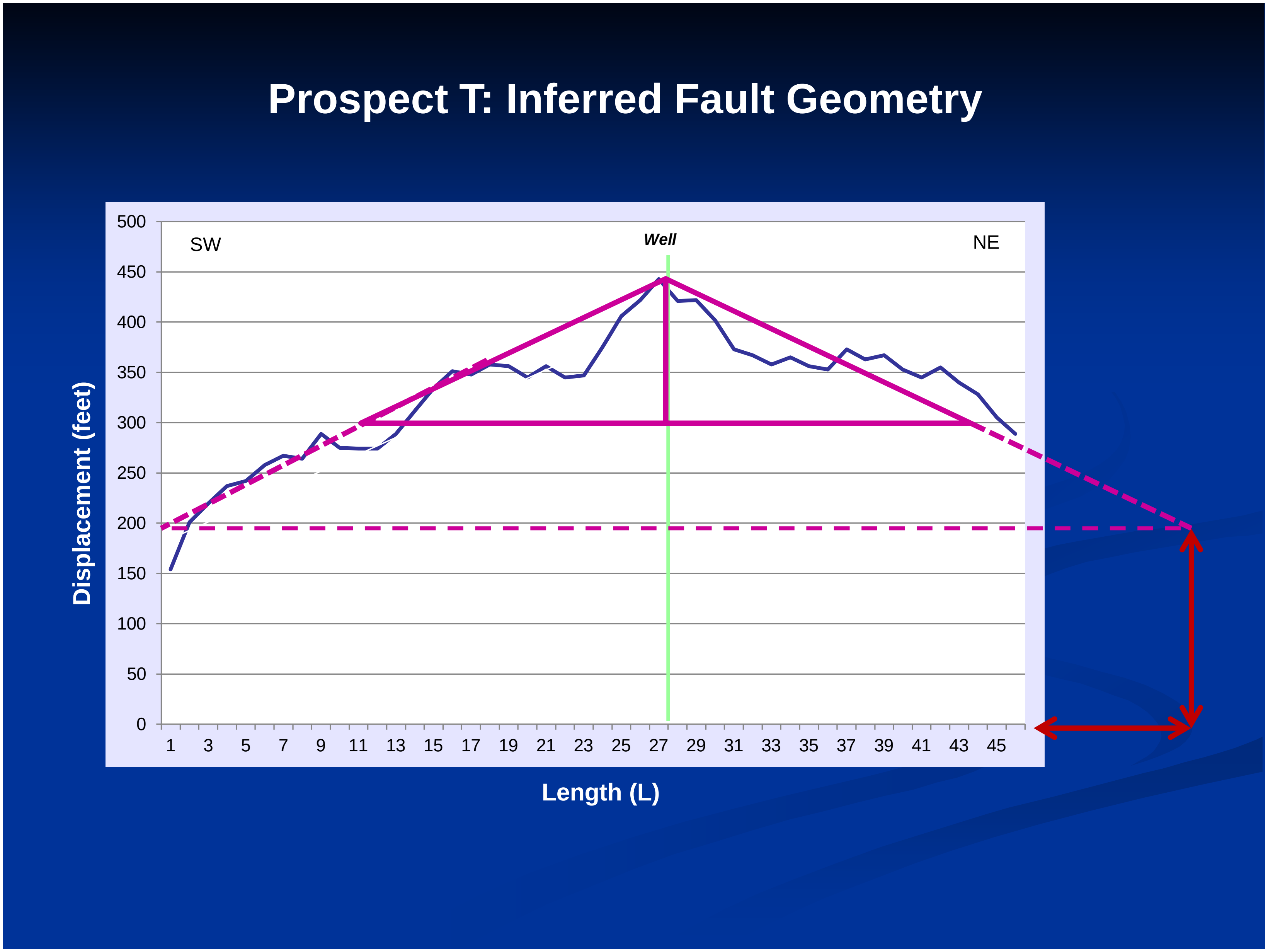



Figure 17. Prospect T: Inferred Fault Geometry.