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Seismic expression and internal order of gravitational fold-and-thrust belts in Brazilian deep waters

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INTRODUCTION

The deep/ultra-deep water realms of most Atlantic continental margins, especially those of the facing margins of West Africa and Brazil, are dominated by huge, gravity-induced, compressional fold-and-thrust belts, developed above either salt or shale detachments; engulfing huge volumes of shales and turbidite sandstones in spectacular deformation. They are part of linked systems of extensional provinces, located updip in the continental shelf/upper slope, characterized by listric normal faults and rollover structures, and systems of compressional provinces, located downdip in the continental lower slope/rise, distinguished by huge folds, reverse and thrust faults. The latter assemblage is termed *Gravitational Fold-and-Thrust Belts* (GFTB). Extension due to gravitational gliding of sedimentary masses piled up in the higher regions of the tilting (flexural bending by thermal cooling) continental margin is compensated by contraction in the less tilted, subhorizontal lower regions of the most external limits of the stretched continental crust.

The sliding of huge masses of recently deposited, slightly indurated sedimentary rocks takes place along well defined, seismically evident, closely-spaced detachment zones, nucleated in plastic beds with regional distribution; salt or thick laminated shales. The detachment zones provide the linkage between the extensional and compressional provinces. When in significant volumes, the plastic beds may be involved in the folding, giving rise to huge diapir-nucleated folds. The nature of the detachment zone is the main factor determining the structural style of the associated GFTB. They may be of two strikingly different types: (a) salt-detached/salt-cored foldbelts, e.g. the Perdido and Mississippi Fan foldbelts (GOM) (Trudgill *et al*., 1999), and (b) shale-detached/shale-cored foldbelts, e.g. the Mexican Ridges (GOM) (Trudgill *et al*., 1999), Amazon Cone (Silva and Maciel, 1998) and Niger Delta (Hermann, 1998) foldbelts.

Since the gliding and consequent contraction occur during reasonably long periods of time (they are definitively not catastrophic events), and in deep water realms (most probably they were never subaerially exposed), syntectonic sedimentation is the rule, creating very complex stratigraphic patterns of localized unconformities, tilted and folded onlaps, thinning/thickenning of beds and awkward stratigraphic relationships between coeval strata deposited above and below time-transgressive unconformities. Minibasins developed between growing anticlines, that had served as traps for turbidite sands, may later be inverted by growing diapirs or by transportation into an actively folding region.

The potential of these compressional structural closures for petroleum exploration seems to be very high. Structural closures are usually four-way and in the order of tens of square kilometers, vertical reliefs in the order of hundreds of meters. Tens/hundreds of meters of laterally confined porous turbidite sandstones are encased within shales in the hearts of the anticlines. Initial concerns regarding migration of hydrocarbons from deep-seated source rocks, through the plastic beds of the detachment zones, upwards into the turbidites located atop and surrounding the positive structures, seem to wade out as the first results of wells drilled in such frontier plays become public. Successfull wells were drilled in the deepwaters of the GOM and the Niger Delta. Detachment seems to preferentially take place in weakened, highly pressurized organic-rich shales located in optimally situated oil windows. Reverse/thrust faults that splay upwards from the detachment zones into the folds serve as migrating routes for the ascending, released hydrocarbons. When salt is the lubricant media, salt windows are required to allow migration from subsalt source rocks.

INTERNAL ARCHITECTURE

Few attempts have been made in order to understand the internal geometry and chronological development of the faults and folds that constitute the GFTB's. The first published accounts come from the Gulf of Mexico, most noticeably the Perdido Fold Belt (Trudgill *et al*., 1999) and from the Brazilian continental margin (Zalán, 1998). Our observations from Brazilian examples seem to indicate that there is a predictable pattern of gradually developing structural styles in time and space within the GFTB's. A three-domain model is here proposed for an ideal, complete, fully developed GFTB, detached in shale sequences, presenting or not shale-cored anticlines. This tripartite model works better in shale-detached GFTB's, because deformation is more varied and more coherently distributed in space than in salt-detached/salt-cored GFTB's. The latter seem to be constituted by successions of monotonous detachment folds (salt-cored anticlines and intervening synclines), symmetrical/slightly asymmetrical, faulted or not, without the development of thrust faults and fault-related folding that constitute the typical signature of shale-detached GFTB's.

Figure1 illustrates the derived ideal model of a fully developed shale-detached GFTB. This model was conceived after the interpretation and analysis of several such GFTB's that occur all over the Brazilian deep waters. One of them in particular, the "PM" foldbelt, can be considered a geological wonder since it displays with reasonably high seismic resolution the complete development in time and space of a large, long-lasting slide in Tertiary siliciclastic sediments (Figure 2). All possible elements that could possibly exist in a tectonic environment such as this can be discerned: from the last listric normal fault of the extensional province in the west, with its associated rollover structure, via discrete regions dominated by detachment folding, closely-spaced high-angle thrusts, widely-spaced lower angle thrusts (each of these two with characteristic styles of folding), until the eastern end of the entity when the termination of the detachment zone dies up into a section of non-affected sub-horizontal strata.

Coming from the internal parts of the extensional province, after the last listric normal fault, the first signs of compression can be found within its associated rollover structure (Figure 1). The fold is slightly tightened by the buttressing effect of the contracted pile ahead. Wrinkling occurs at its base, just above the detachment zone, and gradually spreads with increasing strain forward (in the direction of movement) and upward into the allochtonous pile of sliding sediments. The compressional province presents **three** different structural domains***:*** ***Domain I*** is the realm of detachment folding, represented by short wavelength, high amplitude, symmetrical and/or slightly asymmetrical anticlines and synclines, that can be weakly faulted or not by reverse faults. If diapirism is to occur this is the domain where this phenomena will emerge with great intensity. The nuclei of the anticlines can be filled with low density plastic material that will tend to diapirically grow upward, greatly enhancing the vertical closure of the folds. In salt-dominated systems this is the prevailing domain. The foldbelt attains its maximum topographic relief in ***Domain I***. A noticeable increase in reverse faults, with the destruction of the monotonous succession of detachment folds marks the transition to ***Domain II***.

The next two domains are dominated by thrust faults and related folding and the topographic relief is significantly lower than in the previous area. ***Domain II*** is characterized by intense, closely-spaced, imbricate high-angle thrusts without much stepping (or reverse faults). Fault-propagation folding dominates. A nice example of a snake head anticline can be seen in the middle of Figure 2. ***Domain III*** presents widely-spaced, imbricate, low-angle thrusts with marked ramp-flat geometries. Fault-bend folding dominates. Good examples can be seen in Figure 2, where the eastern termination of the foldbelt displays several well-developed fault-bend folds. Duplexes can develop within ***Domain III***.

Although the boundaries between the extensional and compressional provinces, and in this between the compressional domains, are of transitional nature, they are generally narrow, reasonably easy to point out. The order of appearance of these domains, from the internal parts of the slide outward into the foreland, is usually repeated among the GFTB's. The completeness may be broken by the absence, or extreme narrowness, of one or even two domains, but inversions of the order here described have not been observed in the analyzed examples. All combinations among the three domains have been observed, but the order of spatial occurrence seems to be maintained.

The contractional process seems to develop gradually from the foreland towards the hinterland (extensional province). As the frontal parts of the sliding allochton loose drive for a series of reasons (volcanic ridges, changes in slope) they come to a halt and are compressed by the coming rest of the allochton, which still has movement drive in the steeper slopes. Contraction takes place via faulting and associated folding; the style they develop and propagate towards the hinterland seems to be reflected in the spatial distribution of the three domains. As the folds grow high erosion takes place. A transgressive erosional surface develops also from the foreland to the hinterland. As this process is submarine sedimentation takes place simultaneously with the contraction; thus, coeval sediments are deposited ahead and upon the inactive folds in an onlap pattern, and in the back of the allochton in a conformable pattern, until active folding takes place and the transgressive unconformity continues its gradual development above them (Figures 1 and 2). Similar mechanism (growth-folding) was described in an orogenic foldbelt in California (Medwedeff, 1989).

It is interesting to notice that in terms of topographic relief and structural styles GFTB's resemble truly orogenic foldbelts, e.g. the Canadian Rocky Mountains and the Andean orogen (Figure 1). ***Domain I,*** with its highest topographic relief and maximum structural complexity, would represent the Rocky Mountains and the Cordillera Oriental. ***Domains II*** and ***III***, with their intermediate topographic relief, imbricate sets of thrust faults and associated folding would correspond to the Foothills and the Piedmonte. The subdued plains in the foreland would correspond to the Alberta Basin and the Llanos. This coincidence may be simply due to the fact that, regardless of the driving mechanism, the compression of piles of sediments follow some general and repeatable geometric rules, giving rise to overall similar orogens.

CONCLUSIONS

Gravitational fold-and-thrust belts provide high potential exploratory opportunities in frontier deep and ultra-deep waters. Best structural four-way closures will be associated to detachment folds in ***Domain I*** and fault-bend folds in ***Domain III***. Multiple pay accumulations can be expected in repeated reservoirs associated to thrusts in ***Domains II*** and ***III***. This base model could serve as a guide in order to predict the location of such petroleum traps.

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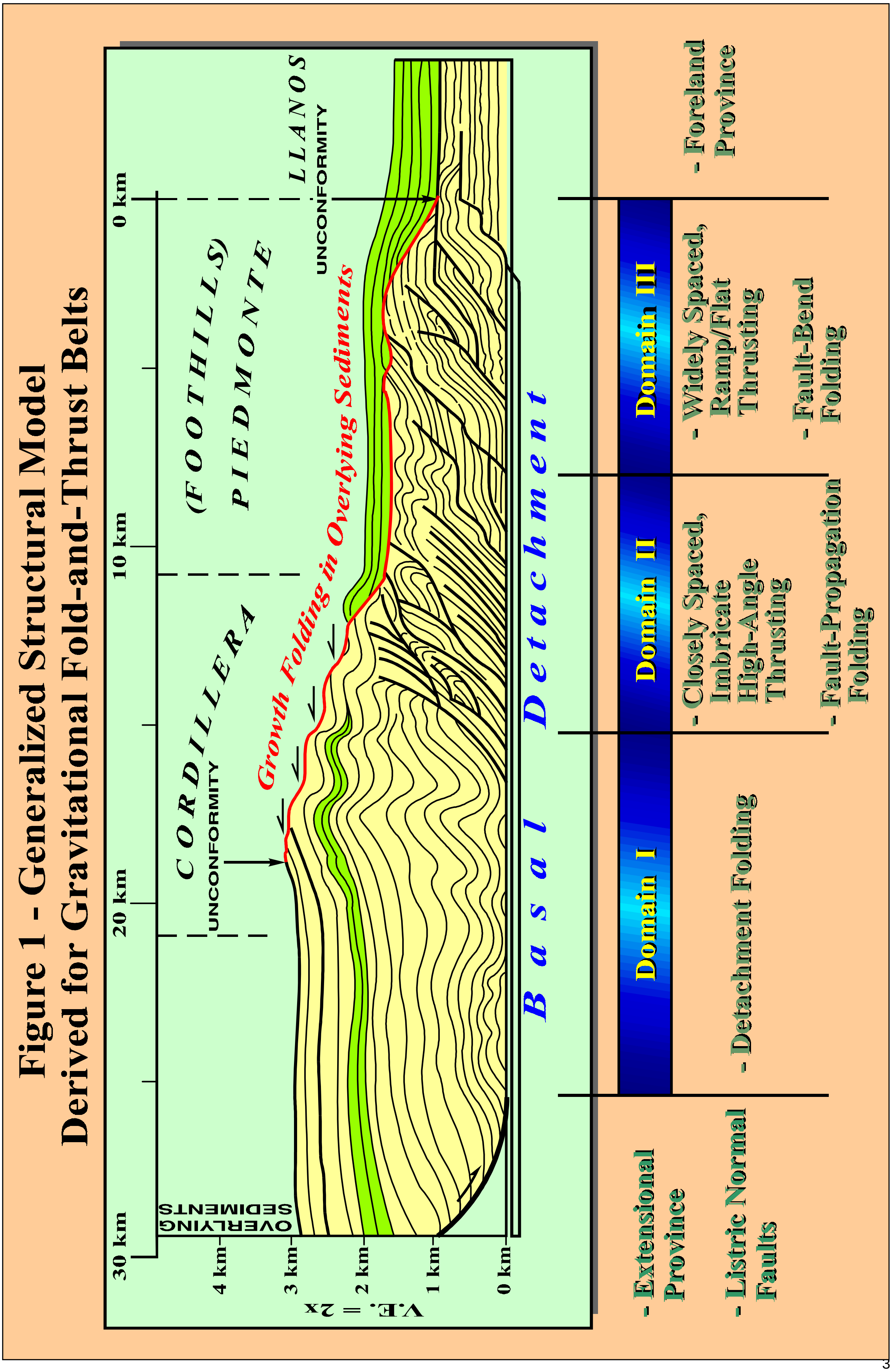

Figure 1 - Generalized Structural Model Derived for Gravitational Fold-and-Thrust Belts

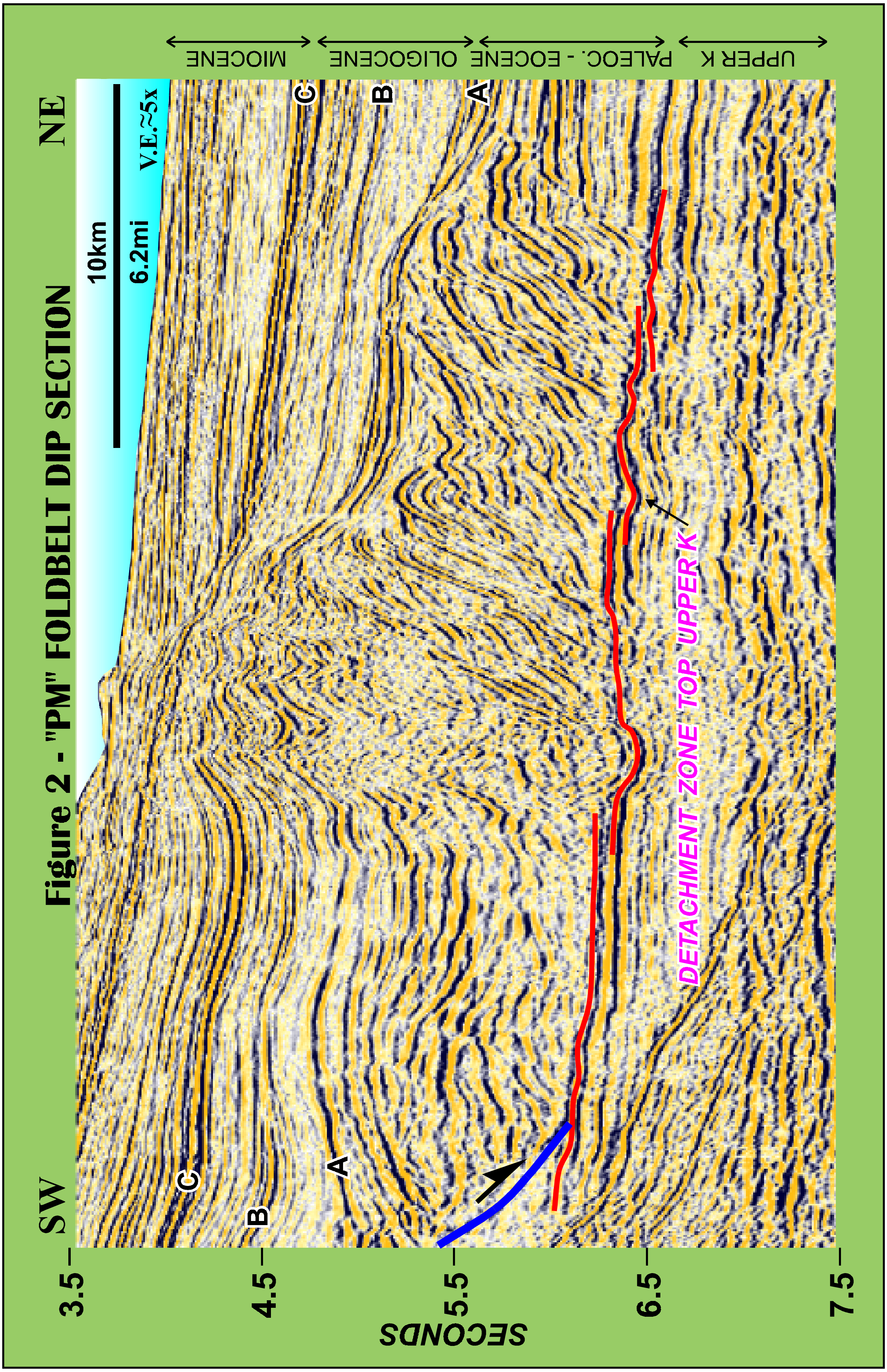

Figure 2 - "PM" FOLDBELT DIP SECTION