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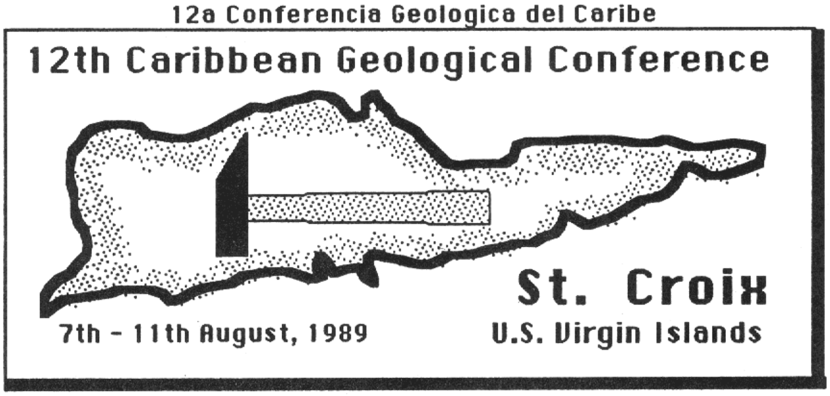

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Edited by

David K. Larue
Department of Geology, University of Puerto Rico
Mayagüez, PR 00708, Puerto Rico

and

Grenville Draper
Department of Geology, Florida International University
Miami, FL 33199
U.S.A.

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STRUCTURAL FEATURES ASSOCIATED WITH THE LOS BAJOS FAULT AND THEIR INTERPRETATION IN THE LIGHT OF CURRENT THEORIES OF STRIKE-SLIP TECTONICS

Llewellyn Tyson
Trinidad and Tobago Oil Company Limited
Pointe-a-Pierre, Trinidad

ABSTRACT

The Los Bajos Fault is a member of a family of NW-SE oriented strike-slip faults present in northern South America. It has an average direction of 113° from north, and a horizontal displacement of roughly ten (10) kilometers. Structural features present along the fault depend on two factors - (1) fault terminii and (2) changes in the direction of the fault:

(1) The northwestern terminus of the Los Bajos Fault is a point of divergence of the former from the Warm Springs (strike-slip) Fault. This area is therefore the site of extensional tectonics, of which the North Soldado Graben is a part. The southeastern terminus of the fault is in a basement-involved reverse fault forming the core of the E-W oriented Southern Range.

(2) Where the direction of the fault trace is less than 113° from north, motion was transpressional, and anticlines developed. These have been somewhat displaced by the Los Bajos Fault, resulting in present day half-anticlines, e.g.the East Soldado, Point Fortin and Los Bajos. Where the direction of the fault trace is greater than 113° from north, motion was transtensional and features such as the Coora and (in part) North Soldado Grabens were formed.

INTRODUCTION

The island of Trinidad is located at the southern terminus of the chain of islands forming the Eastern Caribbean, and is just off northeastern Venezuela. The Los Bajos Fault (refer to Fig. 1) cuts across the island and extends into the shallow sea - the Gulf of Paria - between Trinidad and Venezuela.

The area around the fault has been the focus of intense drilling by oil companies for several decades, because of the occurrence of a giant accumulation along it. This accumulation, of which greater than 800 million barrels of oil have already been recovered, extends over the following areas - East Soldado, Point Fortin, Guapo, Brighton, Forest Reserve, Fyzabad, Palo Seco, Coora and Quarry. The essential results of the geological work by the various companies have been published by Wilson (1958, 1965). In his classical papers, Wilson established:

(1) the magnitude of the strike-slip motion on the fault as being ten (10) kilometers;

(2) the presence of geological structures along the fault on land; and

(3) hypothesized on the relationship between these geological structures and oil entrapment.

In addition, several geologists have published papers pertaining to oil accumulation along discrete parts of the fault. However, there is no publication that studies the Los Bajos Fault in its entirety, i.e. both land and marine areas.

The objectives of this paper are two-fold. In the first place, it is intended to document all of the major structural features along the Los Bajos Fault, and secondly, to interpret these in the light of modern theories of strike-slip tectonics. In this paper the terms "strike-slip", "transcurrent" and "wrench" are used synonymously.

REGIONAL TECTONIC SETTING

Many of the structural elements of northeastern Venezuela extend into Trinidad. For simplicity, these can be grouped into three (refer to Fig. 1):

(1) Belt of low grade metamorphic rocks - this belt extends in an east-west direction across most of northern Venezuela and northern Trinidad. The rocks are predominantly low grade metamorphics including phyllites, schists, slates and marbles. Most of these rocks which are Late Cretaceous in age, crop out just north of the El Pilar Fault.

(2) Middle Miocene fold-thrust belt - this belt which has a width of up to 100 km. consists of a series of NE-SW oriented thrusted anticlines, developed as a result of Middle Miocene tectonism. In surface maps of Eastern Venezuela, this structural style is most conspicuous as the Serrania del Interior, and similarly in surface geology maps of Trinidad as the Naparima-Nariva thrust belt. In both countries the southern portions of the belt are buried under a thick clastic sequence of Late Miocene to Pleistocene age.

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(3) Belt of strike-slip and associated faulting - This deformation is of Late Pliocene age and is superimposed on the fold-thrust belt. It includes such prominent NW-SE directed faults as the Urica, San Francisco, Soldado, Warm Springs and Los Bajos Faults. All of these terminate in prominent ENE-WSW directed compressional lineaments, including such structures as the Tonoro-El Lirial, the Pedernales and the Southern Range - Galeota Highs.

BASIC CONCEPTS OF STRIKE-SLIP TECTONICS

Before proceeding any further, it is necessary to elaborate on two basic concepts of strike-slip tectonics which impact directly on the remainder of the paper.

The first concept is a model for the development of a strike-slip fault (refer to Fig. 2). This model, which is a synthesis of the ideas of several geologists, illustrates the development of a dextral strike-slip fault. In the first place, as a result of the oblique stresses a line of weakness develops. The latter in reality consists of a series of discontinuous smaller lines of weakness within the basement, arranged at varying angles to each other (Fig. 2(i)). With further compression, left turning or restraining bends become the site of en echelon anticlines in the basement's sedimentary cover. On the other hand, right turning or releasing bends become the site of en echelon synclines in this cover. Hence, at this stage of development a series of en echelon folds and discontinuous faults are characteristic (Fig. 2 (ii)). By the third stage, further compression and extension result in more complex structures - thrusted anticlines, grabens and a through-going fault (Fig.2 (iii)). In the fourth stage (Fig. 2 (iv)), the throughgoing fault results in displaced half anticlines and grabens along it. In more advanced stages of development (not illustrated here), the structural features present along the strike-slip fault become obliterated as a result of uplift and erosion, exposing a very complex shear zone. This latter stage of development is not applicable to the Los Bajos Fault. The salient point to be noted here is that structural features developed along a strike-slip or transcurrent fault depend on the direction of the fault trace. This "snaking" produces restraining and/or releasing bends which correspondingly result in the development of en echelon compressional and extensional features.

The second concept refers to the terminii associated with strike-slip faults developed wholly within continental crust. Such faults, because of the finite nature of continental crust, obey what may be termed a law of conservation of continental crust - i.e. continental crust cannot be created or destroyed by a strike-slip fault, but can be converted from one form to another. Conversion from one form to another dictates that at the respective fault terminii, compression and/or extension occur, complementary to each other. Hence, intra-continental transcurrent faults develop what may be termed a compressional-transcurrent-extensional fault triad (refer to Fig. 3). The "action" of crustal extension at one end is transferred by strike-slipping to the other end, where there is "reaction" in the form of crustal shortening. Within the region, perhaps the best example of this fault triad is the El Tuy-Cariaco Basin (crustal extension) - Urica Fault (strike-slip) - Tonoro- El Lirial High (crustal compression). The El Tuy-Cariaco Basin is well documented by Goddard (1986) and Schubert (1986), while the Urica Fault and Tonoro-El Lirial High have been discussed in an interesting paper by Murany (1972).

LATE PLIOCENE TECTONICS IN THE TRINIDAD AREA

Fig. 4 is a simplified compilation map showing the Late Pliocene structural elements present in the Trinidad area. Three points are of significance here.

Firstly, there are the basement-involved strike-slip faults - Soldado, Los Bajos and Warm Springs - which terminate in the basement-involved reverse faults of the Central and Southern Ranges. This abrupt termination of strike-slip faults and conversion to basement-involved reverse faults by marked change in direction (Stone, 1969), is characteristic of the concept of intra-continental strike-slip fault terminii discussed in the previous section.

Secondly, is the fact that the Los Bajos Fault is a splay of the Warm Springs Fault. This splaying has resulted in divergent wrenching along the latter fault, hence the preponderance of down-to-the-north and down-to-the-south normal faults on either side of the Warm Springs Fault (Fig.4). The N-S line on Fig. 4 is a seismic line, and is illustrated as Fig. 5. In the interpretation of Fig. 5, the two dextral strike-slip faults are shown as well as the (extensional) normal faulting between them.

The third significant point, is the presence of shallow-rooted folds all oriented NE-SW. Some of these folds are shown in Fig. 6, and include the La Brea, Vance River - Boodoosingh, Lot One, Forest, Bernstein and Penal anticlines. The consistent NE-SW orientation of the folds throughout the island further reinforces the idea of a NW-SE directed compression in the Late Pliocene.

STRUCTURAL FEATURES ASSOCIATED WITH THE LOS BAJOS FAULT

The structural features associated with the Los Bajos Fault can be grouped into five (5) categories - (1) the North Soldado Graben; (2) the East Soldado-Point

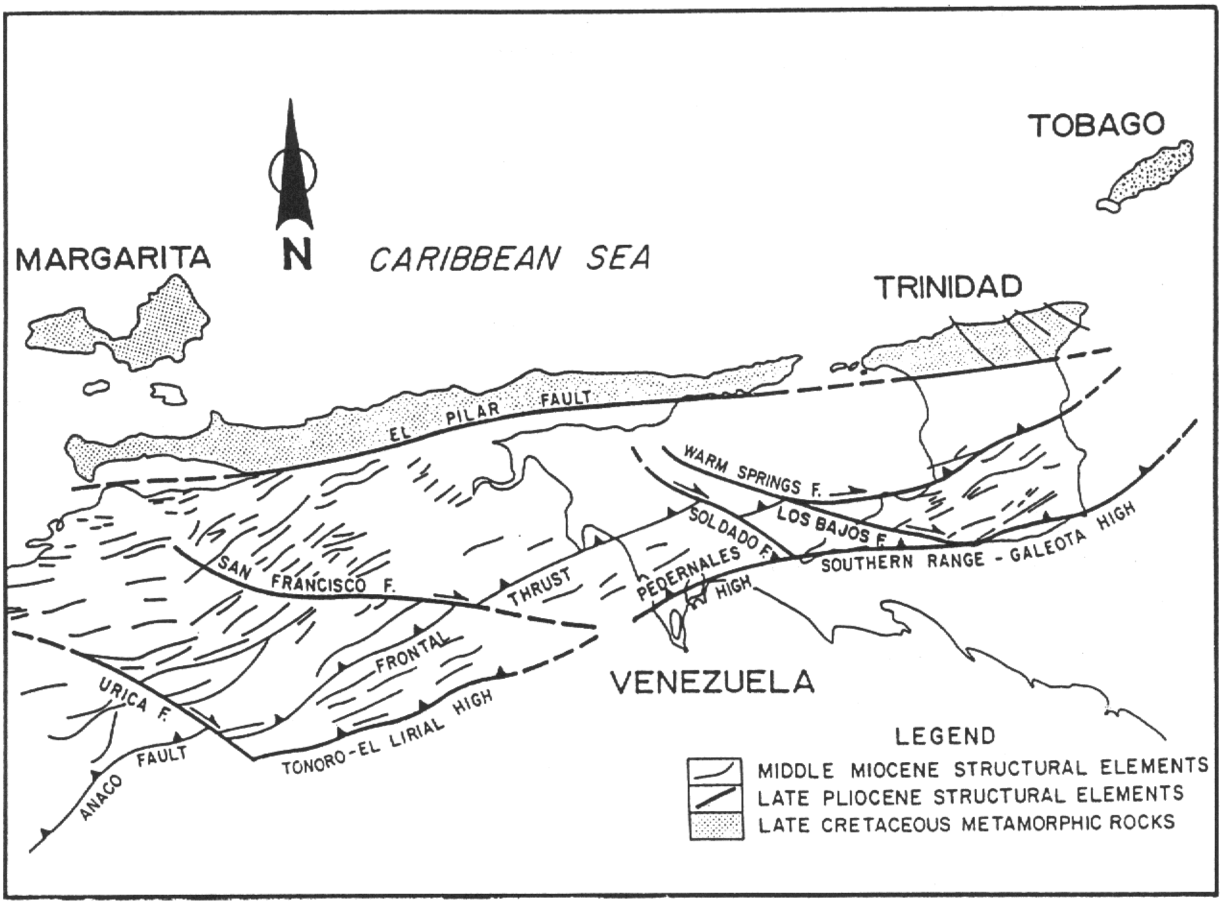

Fig. 1. Location of Los Bajos Fault in relation to the major structural elements of N.E. South America (modified after Salvador and Stainforth, 1965)

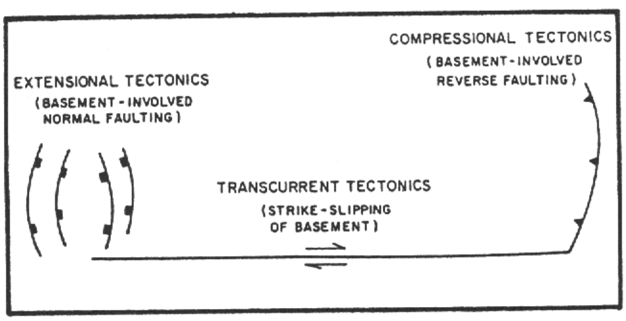

Fig. 3 Model of an extensional - transcurrent - compressional fault triad developed within continental crust

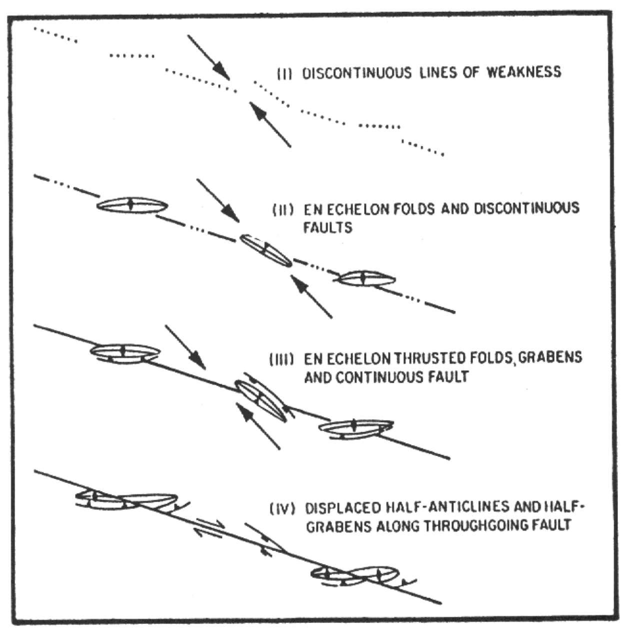

Fig. 2. Model of development of a wrench fault

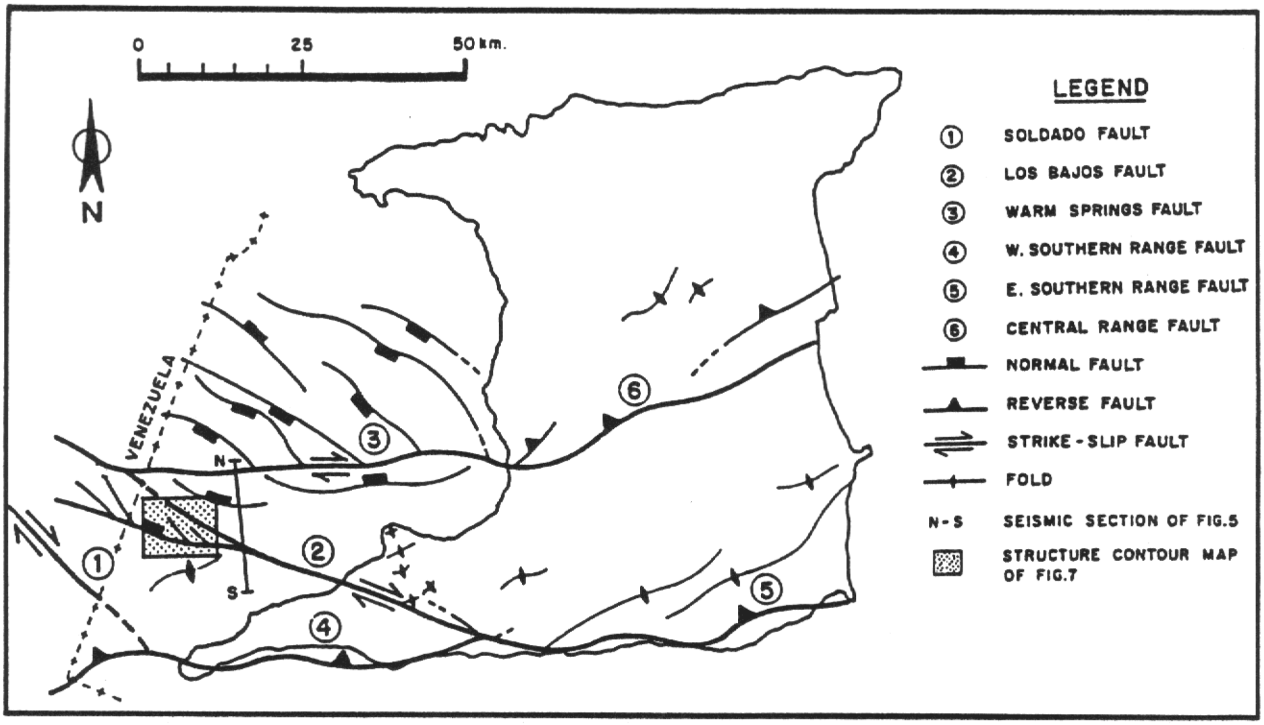

Fig. 4. Compilation map showing Late Pliocene structural elements on land and in the Gulf of Paria, Trinidad

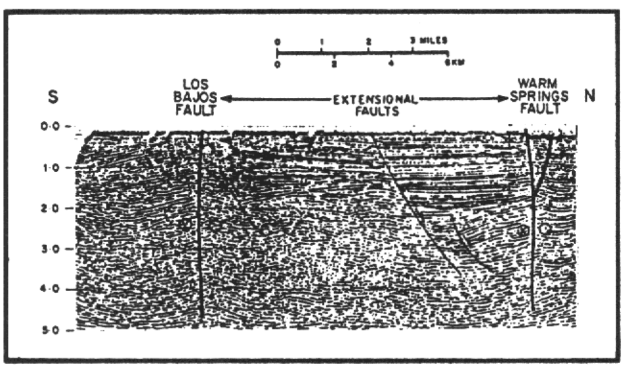

Fig. 5. N-S seismic section across Warm Springs and Los Bajos Faults

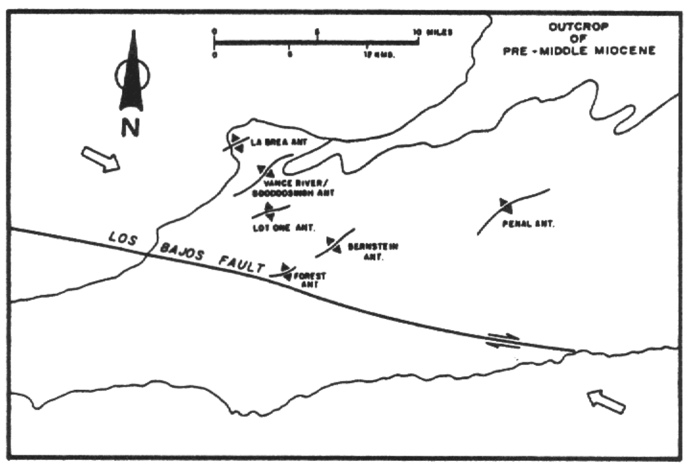

Fig. 6. Map showing shallow - rooted folds in SW Trinidad

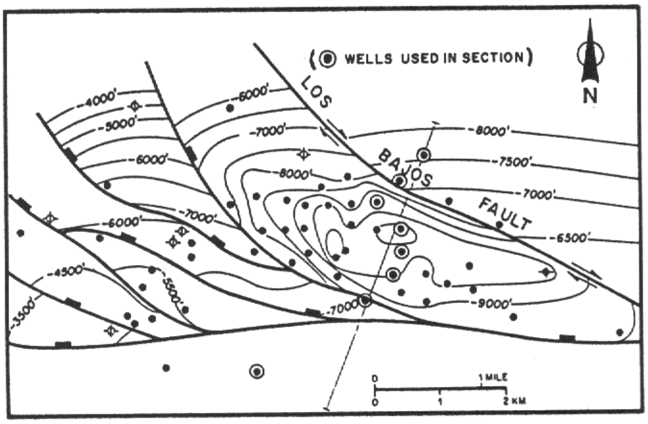

Fig. 7. Structure contour map on top Nariva FM. to illustrate the North Soldado Graben

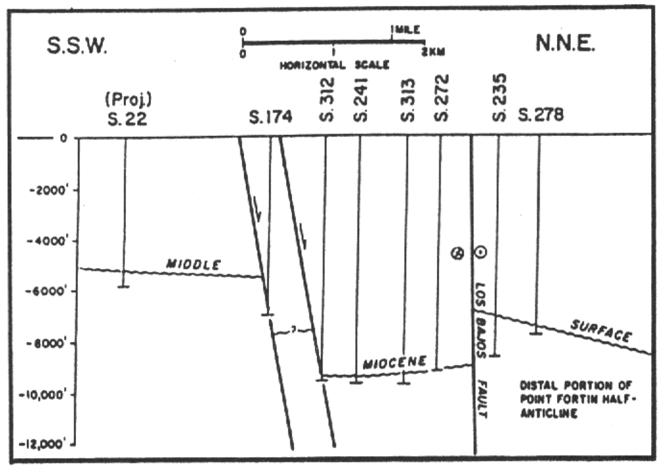

Fig. 8. Structural cross-section across the North Soldado Graben

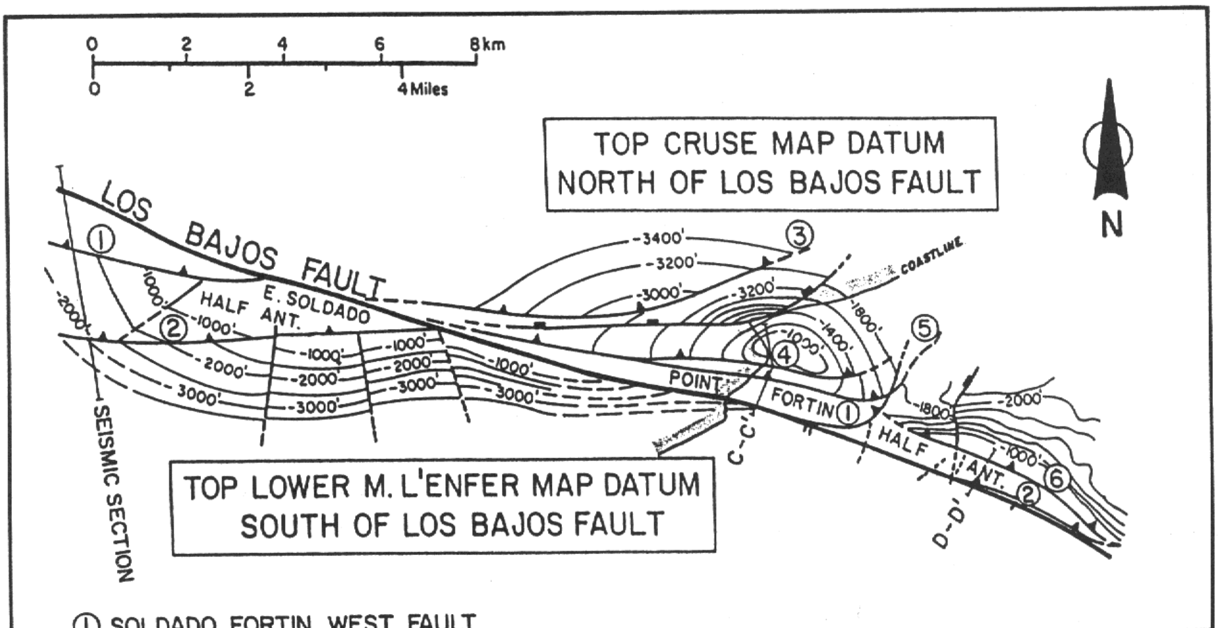

Fig. 9. East Soldado - Point Fortin Anticlinal complex to show interpretation of the major thrust patterns

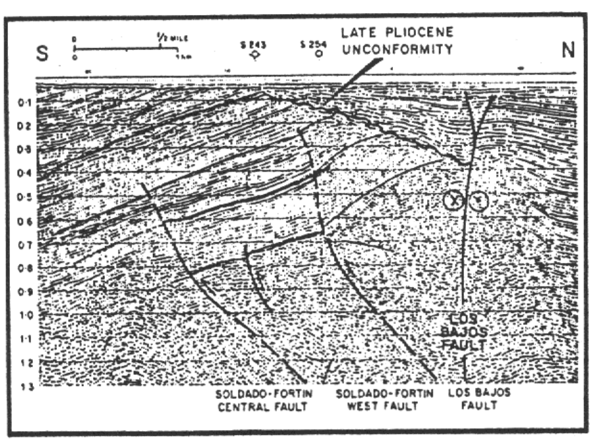

Fig. 10. N-S seismic section across the E-Soldado half anticline

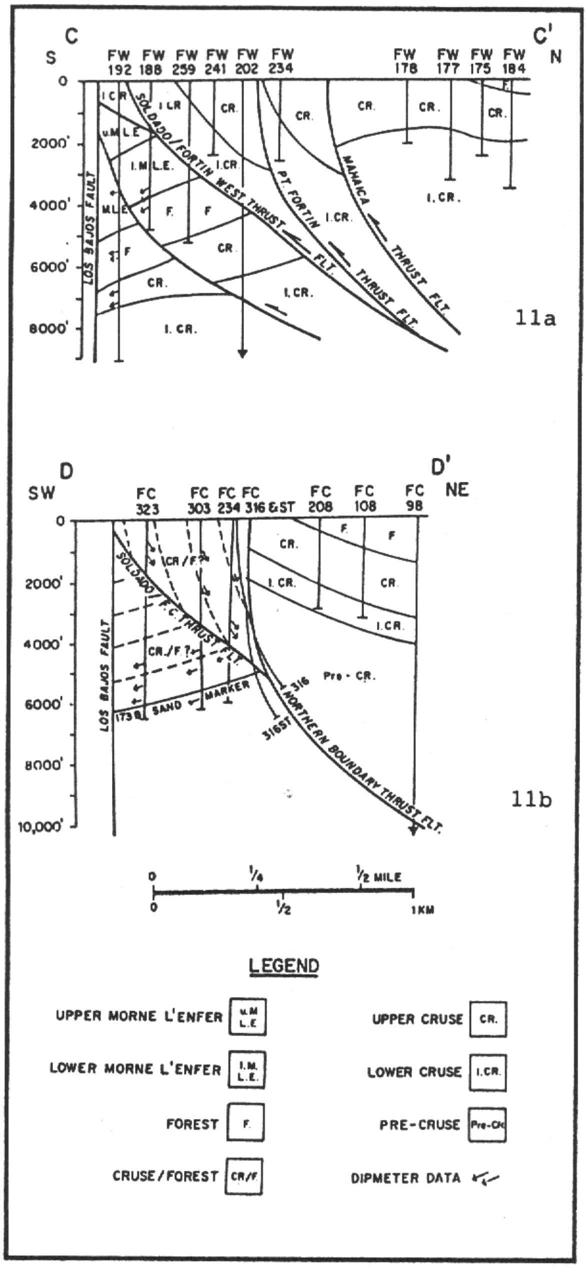

Fig. 11 Structural cross-sections
(a) Point Fortin West C-C'
(b) Point Fortin Central D-D'

Note : All reverse faulting always directed from North.

Fortin Anticline; (3) the Coora Graben; (4) the Los Bajos Anticline; and (5) the Southern Range Basement Reverse Fault. Each of these will now be described in detail.

(1) The North Soldado Graben - This asymmetrical graben structure is located between the WNW-ESE oriented Los Bajos Fault and an E-W trending major normal fault (refer to Fig. 7). Splaying off this normal fault in a NW-SE direction are a series of smaller normal faults, all of which are downthrown to the north or north-east. Consequently, there is a progressive, stepwise downfaulting as is illustrated by the structure contour map on the Middle Miocene datum of Fig. 7. For instance, in the west the datum is at a subsea depth of -3500' and is downfaulted in a stepwise fashion to -10,000' subsea in the axis of the graben. This pattern of faulting is also supported by the SSW-NNE oriented structural cross-section of Fig. 8. The style of faulting in the central Gulf of Paria (refer to Fig. 4) - i.e. down-to-the-south normal faults north of the Warm Springs Fault and down-to-the-north normal faults south of the said strike-slip fault - suggests that the North Soldado Graben is but a part of this larger extensional faulting system.

(2) The East Soldado - Point Fortin Anticline - This feature is really an anticline which has been cut and displaced significantly by the Los Bajos Fault. The East Soldado half-anticline is a complex half-flower on the south side of the Los Bajos Fault (refer to Fig. 9). Associated with this positive half-flower are two major reverse faults, the Soldado Fortin West and Soldado Fortin Central Faults. These two reverse faults are quite clear from the seismic line in Fig. 10. The most uplifted part of this half-anticline has been truncated to form a Late Pliocene unconformity surface, and then onlapped by post - Late Pliocene sediments.

The Point Fortin half-anticline on the northern side of the Los Bajos Fault, is even more complex. There are several reverse faults (refer to Figs. 9, 11) including the Fortin Marine, Mahaica, Point Fortin and Northern Boundary Reverse Faults, as well as the displaced portions of the Soldado Fortin West and Soldado Fortin Central Reverse Faults present in the East Soldado half anticline. The structural cross-section C-C' of Fig. 11a shows the pattern of reverse faulting associated with the western portion of the Point Fortin half -anticline. The basic pattern of faulting is the same in the central and eastern parts of the anticline (refer to cross section D-D' of Fig. 11b), with overthrusting from the north. However, in the central and eastern parts the faulting is much simplified, with only the Northern Boundary and Soldado Fortin Central Reverse Faults being present.

A simplified palinspastic reconstruction of the East Soldado - Point Fortin anticline is shown in Fig. 12. This "best fit" was achieved by a restoration movement of the northern side of the fault by roughly four (4) miles. In this reconstruction there is a fairly good match-up of the displaced portions of the Soldado Fortin West and Soldado Fortin Central Reverse Faults. The very complex nature of the reconstructed anticlinal structure, with at least six (6) significant reverse faults, suggests that it was an area of intense compression. Furthermore, it can be deduced that this compression was directed from the northwest, which complements the idea that NW-SE directed oblique compressive forces were responsible for the development of the Los Bajos Fault.

(3) The Coora Graben - The Coora Graben is a triangular structure composed of down-to-the-southwest normal faults, subparallel to the Los Bajos Fault (refer to Fig. 13). The structure contour map is drawn on the Coora silt, an easily correlatable marker from well logs. The faults converge with the Los Bajos toward the south-east, but because of a lack of well data their behaviour towards the northwest is not known. Fig. 14 is a N-S cross-section along the line illustrated in Fig. 13, and shows the typical grabenal nature of the area, with the normal faults converging with the Los Bajos Fault at depth.

(4) The Los Bajos Half-Anticline - This structural feature shows up on Kugler's surface geology map (refer to Fig. 15) as a half-anticline, truncated to the north by the Los Bajos Fault. In the core of the structure is the older Cruse Formation, surrounded by the progressively younger Forest and Morne L'Enfer Formations respectively. The structural cross-section Fig.16a, shows a single reverse fault as the cause of the upturning of strata to form the Los Bajos half-anticline. On the other hand, further west along the same structure, this single reverse fault has splayed into a series of smaller reverse faults, as shown in Fig. 16b.

(5) The Southern Range Basement Reverse Fault - Whereas the Los Bajos Fault trends in a NW-SE direction, the Southern Range Basement Reverse Fault has an E-W trend. This remarkable change in direction is responsible for the "death" or "termination" of strike-slip motion on the Los Bajos Fault. The strike-slip motion is "consumed" by basement-involved reverse faulting along the Southern Range Fault, which continues offshore as the Galeota Ridge. Basement-involved reverse faulting along the Southern Range is accompanied by the development of an asymmetrical basin on its southern, underthrust portion (refer to Figs. 17 and 18). This asymmetrical basin is the E-W trending Columbus Channel Syncline. In the latter, as much as 3000 metres of post-Late Pliocene age sediments have accumulated. The tremendous uplift associated with the Southern Range Basement Reverse Fault is best illustrated by Fig.18.
The core of this structure is diapiric, and straddles the southern coastline of the island.

ORIGIN AND INTERPRETATION OF STRUCTURES ASSOCIATED WITH THE LOS BAJOS FAULT

Two types of structural features are associated with the Los Bajos Fault. Firstly, there are those associated with the terminii of the fault - the North Soldado Graben and the Southern Range Basement Reverse Fault. Secondly, there are those resulting from the "snaking" or changing of direction of the fault - the East Soldado - Point Fortin Anticlinal Complex, the Coora Graben and the Los Bajos half-anticline. The former features are of much greater magnitude than the latter.

(1) Structures associated with fault terminii :

(a) The North Soldado Graben - The origin of this feature is perhaps linked to two factors. Firstly, it is in the area of the divergence of the Los Bajos and Warm Springs Faults. This area is therefore the site of extension and subsidence, as illustrated by the normal faulting pattern in the Central Gulf of Paria (refer to Fig. 4). Put into perspective, the North Soldado Graben then, is simply one of the down-to-the-north, major normal faults present on the south side of the Warm Springs transcurrent fault. Secondly, and of lesser importance, it owes its origin to the fact that the Los Bajos Fault undergoes a directional change from WNW-ESE to NW-SE in the area just north of the graben (refer to Fig. 7).

(b) The Southern Range Basement Reverse Fault - This represents the southern terminus of the Los Bajos Fault, equivalent to the compressional end of the extensional-transcurrent-compressional fault triad illustrated in Fig. 3. This "killing" of a strike-slip fault by compression, suggests that the Southern Range Reverse Fault and its extension offshore as the Galeota Ridge, must be basement involved. The Tonoro-El Lirial and the Pedernales Highs in Venezuela, as well as the Southern Range-Galeota High in Trinidad are thought by the author to represent present day expressions of an old fundamental fault. Furthermore, the author suggests that it is along this fundamental fault that the compression associated with each of the Late Pliocene strike-slip faults - Urica, Soldado and Los Bajos - is absorbed.

(2) Structures resulting from the changing of direction ("snaking") of the Los Bajos Fault :

Fig. 19 is a plot of the direction from north of the Los Bajos Fault (over 0.3 mile unit intervals) on land, starting from the coastline at Point Fortin, and proceeding southeastwards. The graph shows that

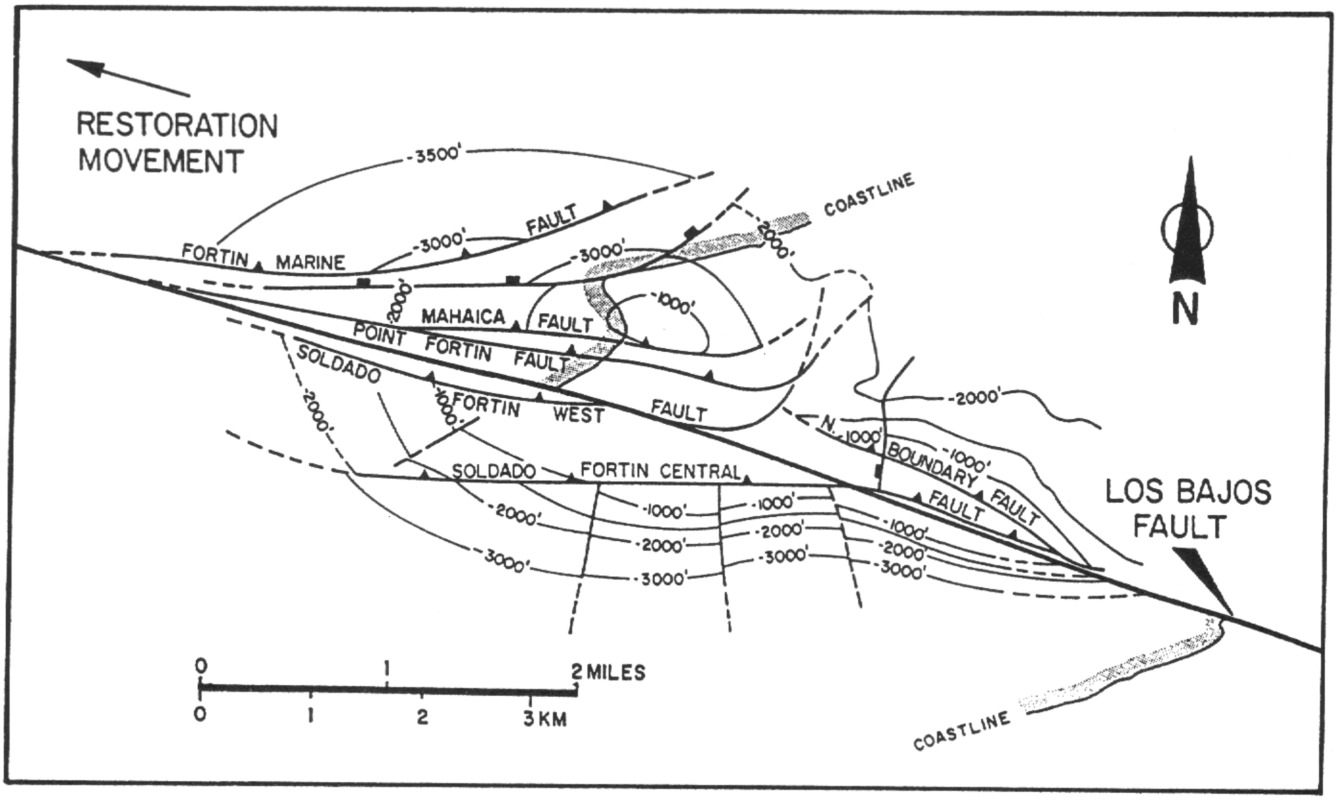

Fig. 12. Simplified palinspastic reconstruction of E. Soldado-Point Fortin anticlinal complex

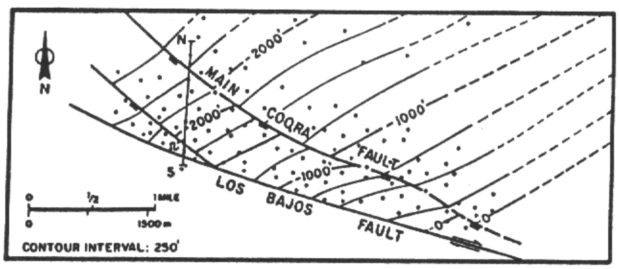

Fig. 13. Structure contour map showing the Coora Graben (modified after Nath 1979)

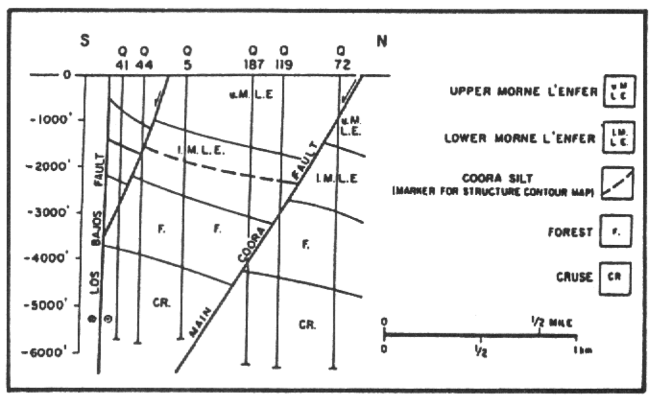

Fig. 14. Structural cross-section across Coora Graben (modified after Wilson 1958)

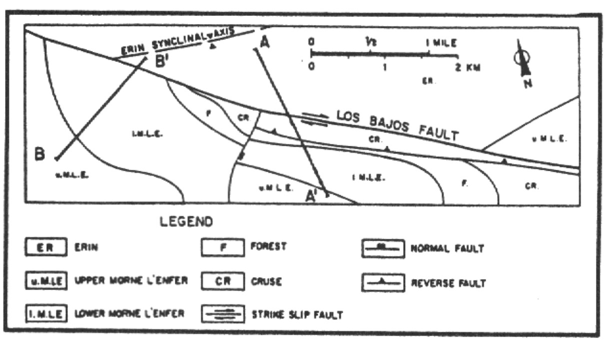

Fig. 15. Los Bajos half-anticline illustrated from surface geology (after Kugler)

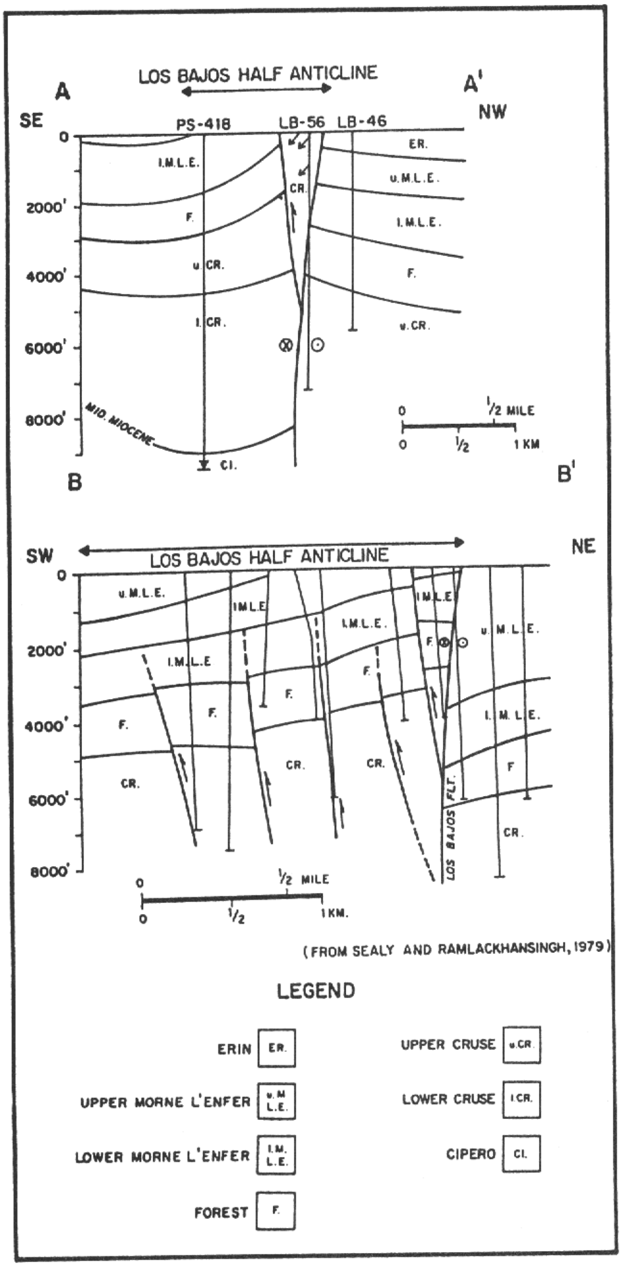

Fig. 16. Structural cross-sections across the Los Bajos half-anticline

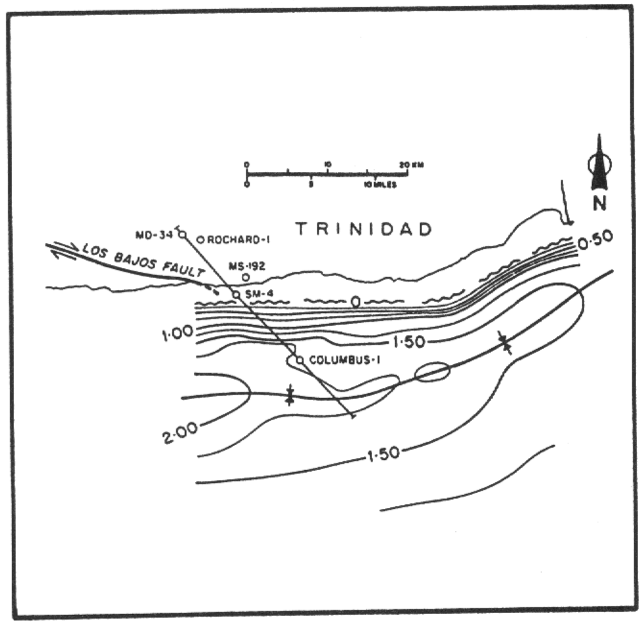

Fig. 17. Structure contour map on Late Pliocene datum of eastern portion of the Columbus Channel Syncline

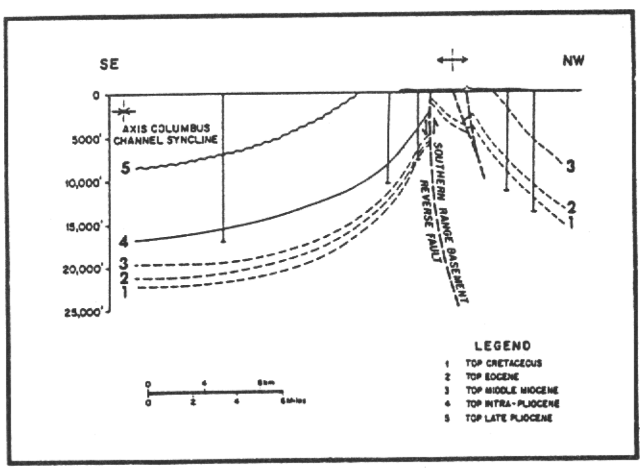

Fig. 18. NW-SE cross section showing the Southern Range basement reverse fault

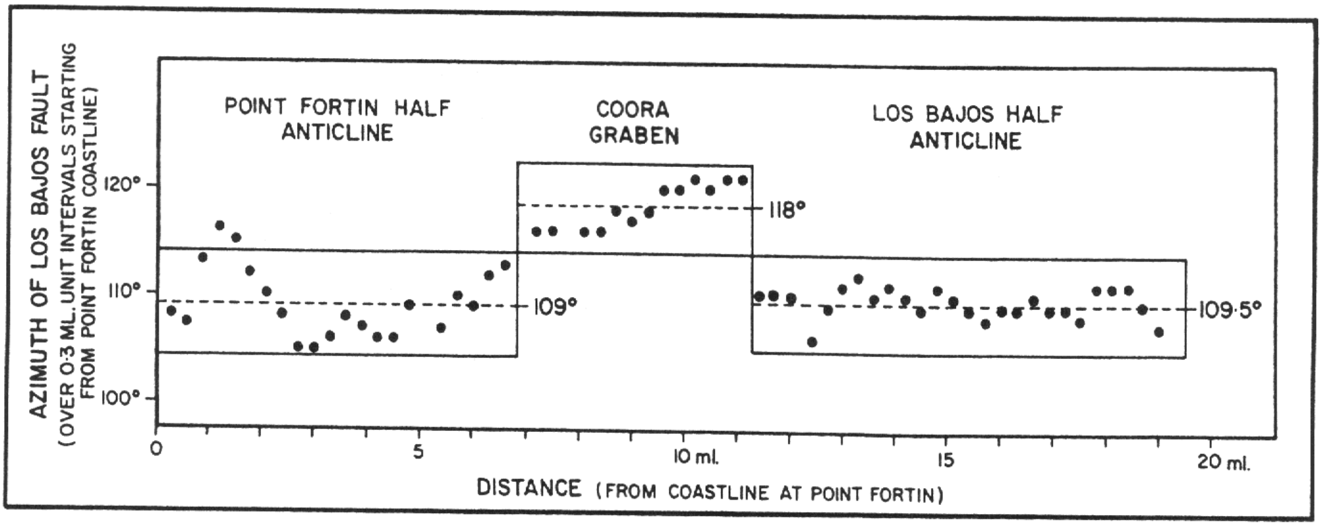

Fig. 19. Relationship of Los Bajos Fault direction and type of structural features developed.

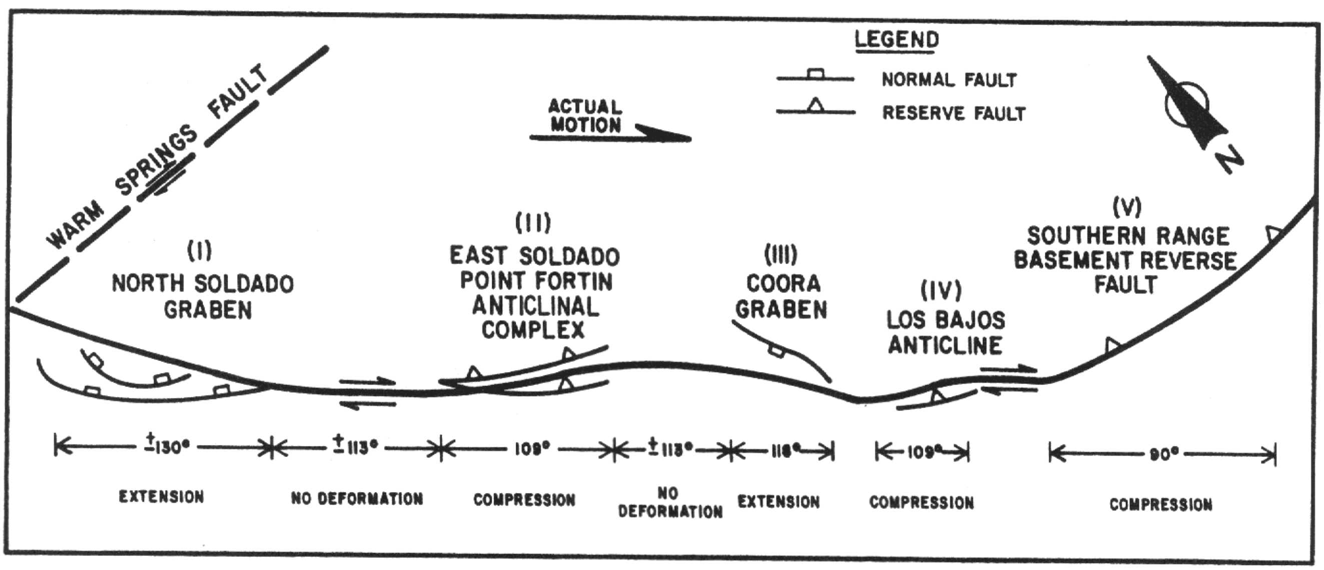

Fig. 20. Schematic illustration of structural features associated with the Los Bajos Fault, and their relationship to change in fault direction

the fault direction can be divided into three parts. The first part, with the exception of two spurious points, corresponds to an ESE direction averaging 109°. The second part averages 118° , whereas the third averages 109.5°. In addition, on the distance axis the positions of each of the three structural features on land have been plotted, and an interesting picture emerges. Average Los Bajos Fault directions from north, corresponding to the Point Fortin and Los Bajos half-anticlines are 109° and 109.5° respectively. These two portions of the fault represent areas of transpression and therefore positive flower development. The change in fault direction to an average of 118° corresponds to the Coora Graben, and represents an area of transtension, and therefore negative flower development. From the correspondence of a fault direction of about 109° to transpression and a direction of 118° to transtension, it is not unreasonable to suppose that parallel wrenching should correspond to an angle of about 113°. The direction of 109° from north for the Los Bajos Fault is maintained as the fault continues offshore into the Gulf of Paria (refer to Fig. 9) just beyond the East Soldado half anticline. The fact that a positive structural feature is still present in the form of the East Soldado half-anticline, fits well the concept that angles like 109° correspond to transpression. In the region of the North Soldado Graben (refer to Fig. 7), the Los Bajos Fault undergoes a change from about 109° to 130° from north, and interestingly enough, this point is associated with transtension. However, as mentioned before, other factors may account for the extensional style of faulting there, i.e. in the North Soldado Graben. Fig. 20 illustrates schematically the role of change of fault direction in influencing the type of structural features present along the Los Bajos Fault.

CONCLUSIONS

(1) There are two types of structural features associated with the Los Bajos Fault - those associated with the fault's terminii and those associated with subtle changes in the fault's direction (Fig.20). The former are of greater magnitude than the latter.

(2) At the WNW terminus of the Los Bajos Fault is the Central Gulf of Paria extensional regime, of which the North Soldado Graben is a part. At the ESE terminus is the basement-involved reverse fault of the Southern Range.

(3) Structural features along the fault are dependent on the changes in direction of the fault (Fig. 20). Where the fault direction exceeds about 113° from north, transtensional features develop, e.g. the Coora and in part North Soldado Grabens. Where the fault direction is less than 113° from north, transpressional features are present, such as the East Soldado, Point Fortin and Los Bajos half anticlines.

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