Tectonic Inversions in the Northern Bend of the Chihuahua Trough

Roberto Ortega and Dana Carciumaru

Abstract**—** The Chihuahua trough is a deep sedimentary basin of Mesozoic age that lies along the southwestern margin of the North American Craton in northeastern Chihuahua and adjacent regions of Texas, New Mexico and Sonora. Two regions are studied, the East Potrillo Mountains and the Northern Franklin Mountains both being located at the northern rim of the Chihuahua trough. In the East Potrillo Mountains are exposed Permian and Cretaceous rocks that have been strongly deformed during the Laramide orogeny whereas in the Franklin Mountains the Laramide structures outcrop at the western flank of the range. The regions studied in this work underwent substantial deformation from high and low angle normal faults to thrust and extensive folding. This work presents a tectonic evolution of the northern margin of the Chihuahua trough via dihedral and stress inversion and by different strain geometrical analyses. The overall results suggest that this region have been under different stress and tectonic regimes. The faults were reactivated at different times, breaking preexisting fractures. The compressional and extensional sequences induced tectonic inversion. These tectonic processes suggest an old lithospheric weakness reactivated during different periods.

Keywords**—**Chihuahua Trough, kinematics analysis, stress inversion, tectonic inversion.

I. Introduction

THE Chihuahua trough is a sedimentary basin located in the northern part of Mexico. It is a complex basin characterized by important sequences of deformation. The most evident compressive deformation occurred in the late Cretaceous-Early Tertiary during the Laramide orogeny. However, it is widely recognized that the Chihuahua trough has a long deformation history beginning in the early Mesozoic.

Despite its strategic location, the Chihuahua trough suffers from a lack of high quality structural data. Only a few descriptive models[1] have been presented to explain its evolution. No quantitative study has been reported for the different processes that have affected the area. In order to investigate the dynamic evolution we inverted the stress and strain field. This work is relevant not only for the information that it can provide on fundamental tectonics, but also adds important insights about the mechanical characteristics of the lithosphere. Laramide orogeny and the Rio Grande rift are the two major geological events that have affected this region.

Laramide orogeny has been a highly debated topic. Many authors have tried to explain this complex deformational process. There have been suggested many hypotheses and models concerning Laramide deformation in the southern part of North America. In [2], Wilson stated that the major episode of Laramide folding occurred in the Late Paleocene in the Big Bend area and probably throughout Trans-Pecos Texas. Previous authors[3] postulated several episodes of folding, the primary one being at the end of the Cretaceous. Regional uplift without major folding probably occurred at the end of the Early Cretaceous and several times in the Late Cretaceous so that erosion surfaces developed on some of the older rocks. In the southern New Mexico, Seager et al.[4] suggested that the Laramide shortening began between Campanian and latest Maastrichtian time and created at the beginning symmetrical, northwest trending folds and symmetrical uplifts. The basins created during Laramide deformation are mostly known from seismic and drill data, because they have not been extensively exhumed. The Laramide structures of the southern New Mexico are similar to those located to the north and are comparable in style, trend and size with the classic Laramide foreland of Wyoming, Colorado and Montana with the only difference of a complex burial history and subsequent segmentation of Rio Grande Rift[4].

On the other hand, the Rio Grande rift opened in two stages associated with different stress regimes. The first phase of deformation occurred from 30 to 18 Ma, when shallow basins bounded by low angle normal faults were formed. This period is associated with volcanism and is attributed to a thinning of hot lithosphere with a shallow brittle - ductile transition. A later rifting phase beginning 10 Ma is associated with classic Basin and Range style block faulting, with delineation of the present interconnected rift basins and uplifts. However, there are few studies concerning a comprehensive structural evolution in northwestern Chihuahua -southwestern New Mexico. In this article we analyzed structural data and present results in order to establish consistent relations between the major geological episodes.

Some authors tried to integrate compressional and extensional events by recognizing strike slip movement on some Laramide structures [5]-[6]. This was very much debated

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in north-central New Mexico whereas some authors advocate a north-south strike-slip faulting favoring transpression and others advocate east-west shortening by thrust faulting. Recent studies[7] show that both hypotheses could be valid, although neither is sufficient to exclude each other.

The analyses concerning the Laramide structures were performed in both ductile and brittle domains, the former for the determination of the strain direction and the latter for the paleostress analysis. For the determination of the strain direction, fold limbs and bedding planes were measured in order to obtain the fold axis. For the paleostress analysis we inverted the fault slip considering that the maximum shear occurs parallel to the fault displacement. The set of data in both areas was split in domains based on structural differences.

II. Geological Setting

A. Location

DeFord[8] first used the term "*Chihuahua trough*" to name the depositional basin that formed the Laramide Chihuahua tectonic belt. The extent of Chihuahua trough as defined by DeFord was uncertain. It was defined as the area of northeastern Chihuahua and adjacent parts of Texas, New Mexico and Sonora that form a Mesozoic basin. An arbitrary southern boundary (Fig. 1) is placed at the edge of the North American Craton and the Alamitos lineament, south to Aldama City. Also, an arbitrary northwestern limit is selected along the 109^{o} W meridian (the pre-Albian basin extends beyond these boundaries to the south into Coahuila and to the west into Arizona and Sonora). In its present configuration, the Chihuahua trough is a NW-SE elongated-ellipse shaped basin surrounded by the Aldama Platform in the south and by the Diablo Platform in the north. It is widely recognized that the Late Paleozoic Pedregosa basin is, in effect, the proto-Chihuahua trough.

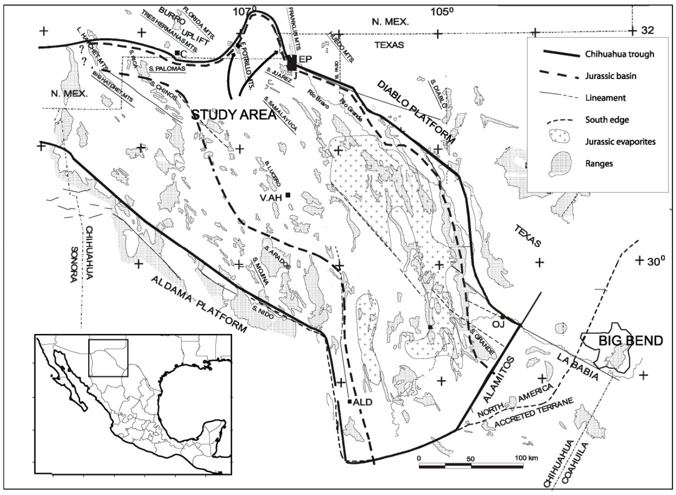

Fig. 1 Geological features of the Chihuahua trough. The current boundaries are the Aldama and Alamitos platform at the south and the Diablo Platform at the north. Villa Ahumada (V.AH), Ojinaga (OJ), Aldama (ALD), Van Horn (VH and El Paso (EP) are indicated.

B. Triassuc and Jurassic

Triassic and Jurassic rocks generally are absent over most of southern New Mexico, although marine Jurassic rocks are known from a deep oil test southwest of Las Cruces[9]. These Jurassic carbonates probably thicken southward into Chihuahua trough where Jurassic evaporates are diapiric and may be responsible for Laramide decollement and thin-skinned folding in the Chihuahua tectonic belt, including the Sierra Juarez [10]-[11]. Upper Marine and non-marine rocks, having a thickness of 980 m (3200 ft), have been preserved in Laramide intermountain basins. Greater thickness of uppermost fanconglomerates, redbeds, and sanstones are present in the same basins[6],[12]-[15].

Important changes in plate tectonic regimes occurred in the southern Cordillera between Triassic and Jurassic time. These changes were caused by major global plate tectonic transitions during the break up of Pangaea[16]. Coney[17] postulated a major subduction related arc system trending northwest-southeast across southwest Arizona and into Sonora and Chihuahua in the early Mesozoic. This subduction related arc along the Cordilleran margin marked the origin of the modern circum-Pacific orogenic system. Beginning in Late Triassic the opening of the Gulf of Mexico occurred.

C. Late Cretaceous to Early Tertiary

The northeastern margin of the trough consists of a series of large-displacement, down-to-the west normal faults. The margin roughly parallels the Rio Grande and encroaches up to 25 km onto the Texas side of the border, from El Paso to the southwestern edge of Big Bend National Park. Muehlberger [18] also postulated a reentrant into the eastern part of the Big Bend area because the Laramide structures are similar to those along the margin of the trough. The normal faults were subsequently buried by a thick Cretaceous sequence, but Uphoff[19] interpreted well data to show the existence of one of these faults beneath the Hueco Bolson. These normal faults are important because they determine the geometry of the sedimentary basin and helped control the location of Laramide deformation.

The tectonic regime of southwestern North America was influenced during Laramide orogeny, from late Cretaceous to early Tertiary[20]. The Laramide orogeny is the most extensively documented compressive event in this region. This compressional event is probably due to an increase in the convergence rate of the Farallon plate as it subducted beneath North America or shallow slab subduction. In eastern and southeastern Chihuahua Laramide structures are well documented [10],[21]-[23].

D. *Early Cenozoic to Recent*

Fom early Ceneozoic (Eocene) to Recent, the tectonic regime of the state of Chihuahua transformed from compression to extension. In western Chihuahua the ignimbrite flare-up initiated during the period from Eocene to Miocene. Damon and Bikerman[24] term this event as post Laramide - pre-Basin and Range. The ignimbrite event is well documented[25]-[27]. Many of the calderas lie along the margin of the Chiuhuahua trough, where rising magmas may have followed established zones of weakness. Price and Henry[28] showed that up to about 30 Ma volcanism including most caldera formation occurred while the area was under east-northeast compression remaining from Laramide deformation. A transition to the tension took place about 30 Ma subsequent volcanism, including formation of the two calderas in Chihuahua and minor basalts in Texas and it is related to Basin-and-Range extension[29]. A similar change in stress orientation occurred in the northern and southern Rio Grande Rift at about this time[30]-[31]. The problem of tracing the Rio Grande Rift into Chihuahua has also been well documented [32]-[36].

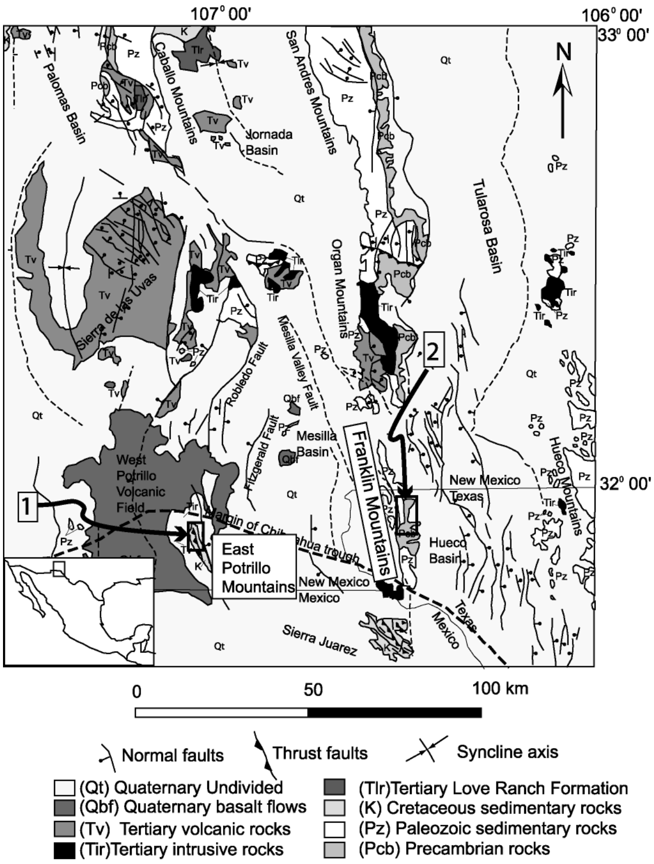

Fig. 2. Geological features of southeast New Mexico and adjacent regions. The major faults and geological units are indicated. The two important ranges in the southern Mesilla basin are the East Potrillo Mountains and Franklin Mountains. Insets of detailed geological maps are indicated

III. Characteristics of the Studied Area

The region studied in this work is depicted in Fig. 2. Around Mesilla basin, the two most important sierras are East Potrillo Mountains and Franklin Mountains. This basin is located at the border of the states of Chihuahua (MX), New Mexico (US) and Texas (US). The Mesilla basin is interconnected with other north-south trending basins such as Jornada and Palomas basins that are parallel to the Rio Grande Rift and flanked by high angle normal faults in series of grabens that characterize the basin structures. This region comprises the northern margin of the Chihuahua trough (Fig. 2).

A. *East Potrillo Mountains*

The East Potrillo Mountains are located 32-35 kms south of Las Cruces, New Mexico and are part of a north-northwest trending mountain chain that crosses the Texas-Mexico border (Fig. 1). They form an isolated outcrop of Permian and Cretaceous rocks along the northwest margin of the Chihuahua trough.

Lower Cretaceous rocks crop out in the East Potrillo Mountains as well as at Eagle Nest (SE, Texas). In the former area Seager and Mack[37] measured 500 m of marine clastic and carbonates shelf deposits above a basal conglomerate, all of which thin southward. These somewhat arkosic clastic rocks and limestone contain an Albian-Aptian fauna and correlate with the Hell- to- Finish and U-Bar Formations of southwestern New Mexico (Fig. 3.). There is evidence of the Laramide deformation in the East Potrillo Mountains and at Eagle Nest and Granite Hill. Folds and associated thrust faults in the East Potrillo Mountains involve Lower Cretaceous and

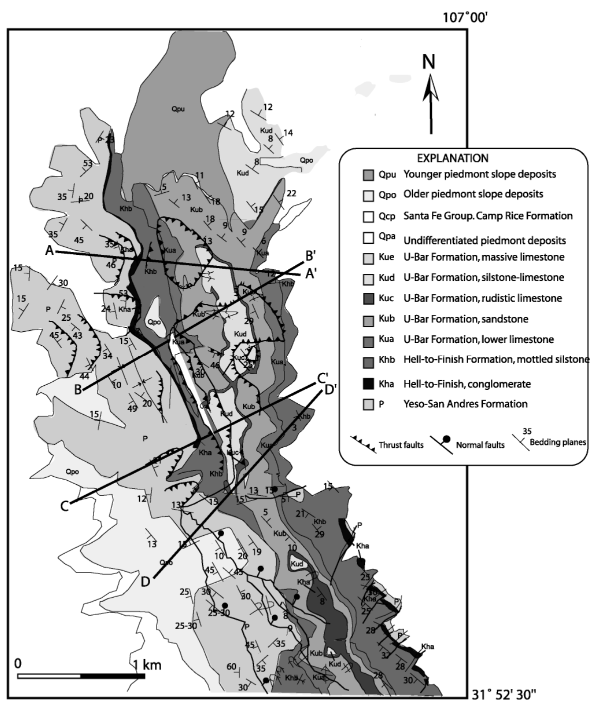

Fig. 3. Geologic map of the northern part of the East Potrillo Mountains .

Permian rocks, trend N30W, and verge toward the northeast. A system of low-angle normal faults is also exposed in the East Potrillo Mountains. Seager and Mack[37] consider the faults to be probable early Miocene in age, formed during an early phase of extension in the Rio Grande rift.

B. Franklin Mountains

In the northern Franklin Mountains the only structures supposed to form during Laramide event are Early Tertiary folds. In the central part, where the deformation is less severe, the general structural style can be described as an overturned anticline-syncline pair with a west-dipping thrust fault. Laramide structures appear well exposed in the central part, in the hanging wall of a younger low angle normal fault that formed during the extensional event, which followed the compressional deformation. In the northern Franklin Mountains the Laramide structures are represented by south-plunging syncline and anticline west of the main range (Fig. 4), the west-trending monocline north of the Webb Gap and the southwest-trending monocline southeast on North Anthony's Nose[38]. Because these folds are not entirely dated it is very hard to know the exact origin of these structures. Chapin and Seager[39] think that the large, south-plunging syncline and

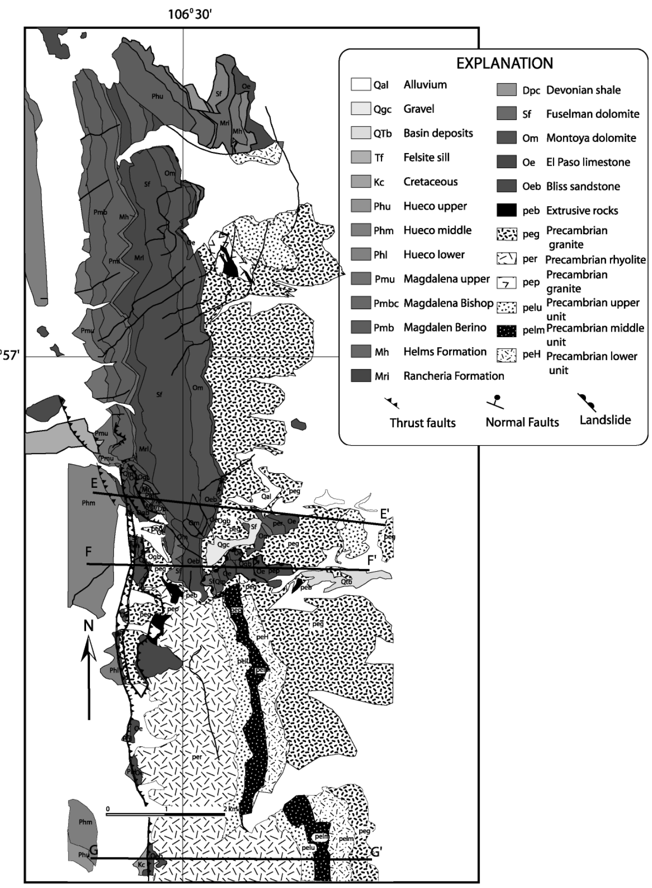

Fig. 4. Geologic map of the northern Franklin Mountains .

anticline of Anthony Gap could be formed during Laramide event, based on their similar structural style that affected much of southern New Mexico. The high angle thrust faults in the western flank are stratigraphically inverted, suggesting that they were reactivated from the early Cretaceous normal faults.

Methods

A. Stress and strain reconstruction

Paleostress reconstruction is based on fault slip inversion. Whereas stress is a clear concept in continuum mechanics it is important to note that stress and strain are highly debated concepts in structural geology, especially in the use and limits in tectonic studies. Strain describes the deformation of a body in terms of its final shape relative to its initial shape whereas stress describes the forces acting on every point of this body. We used two different methods: a)one to solve the principal axis of shortening and elongation based on the assumption that each axis would be situated on a different dihedral of the moment tensor, b)the second method solves the principal stress vectors (σ_1, σ_2, σ_3) of the infinitesimal Cauchy stress tensor via fault-slip inversion. The displacement vector measured on any fault represents the sense of the shear stress. Since only angles are measured, we obtain only the deviatoric part of the full tensors. The moment tensor method used here is the tensor summation technique as coded by Allmendinger[40] and the stress inverse method is that of Michael[41] which allows the use of fold measurements. The results are obtained in terms of a 1) reduced stress tensor, consisting of the components of the principal stresses and 2) the ratio of principal stress differences. In the case of multiple tectonics (polyphase), data are analyzed separately based on crosscutting relationships of different structures. Each subset represents one specific stress regime. The final tectonic reconstruction consists of integrating these results within the regional setting, including geophysical studies into the geodynamic framework

B. Kinematics indicators

For the determination of transport direction, fold limbs and bedding plane orientations were measured in order to obtain the fold axis direction. Assuming a nearly cylindrical geometry of the folds, a best fit circle can be fit to the poles to bedding planes, and the pole to this great circle represents the fold axis[42]. Slaty and pencil cleavage were used in order to constrain better the shortening direction. Field data are measured at the site and only reliable and useful information was analyzed. If the fold is exposed on a smooth two-dimensional plane then the orientation of the fold hinge cannot be measured.

It is important to note that the inversion of the principal axis is commonly misinterpreted in the literature, whereas the dihedral method solves the moment tensor solution it attains the principal displacement on a fault without assuming forces, therefore it is adequate to refer the dihedral method as a kinematics inversion. On the other hand, the stress inversion is considered as a dynamic inversion since it solves the principal forces acting on a plane, assuming that the shear direction coincides with the displacement of the fault. These two methods are not necessary equivalent but in an isotropic and homogeneous media we can consider that they may have similar results. A detailed description of both methods is out of the scope of this article. It is also worthy to note that tensor inversion is a mathematical analysis based on *inverse theory* whereas tectonic and basin inversions refer to the changes of the stress field from compression to extension or vice versa.

IV. Results

A. Stress and Strain Analysis

The East Potrillo Mountains Laramide paleostress pattern was reconstructed from the exposed faults in the northern part

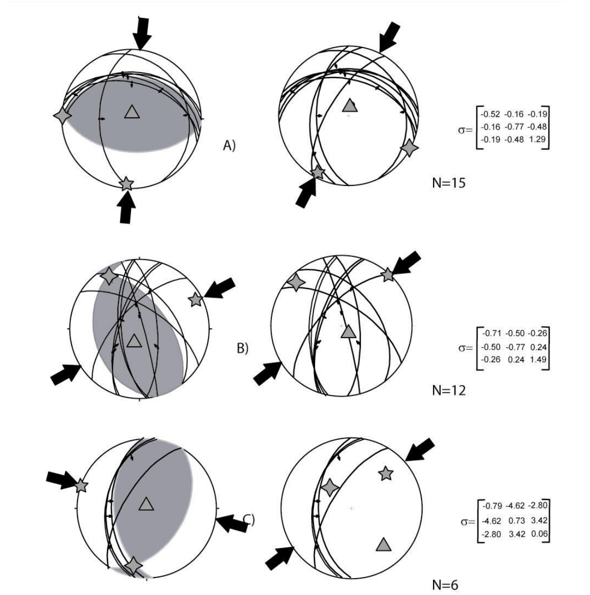

Fig. 5. Example of dihedral and stress tensor analysis in the East Potrillo Mountains. A, B and C are northern, central and southern regions respectively. σ1, σ2 and σ3 are the invariants of the stress tensor (σ1>σ2>σ3) represented with five, four and three star points respectively. The first column is the summation moment tensor and the average plane solution is represented as a dihedral equal area projection. The elongation region plotted as dark area.

of the range. The window and klippe structures are not considered in the data inversion. The thrust faults are oriented NW to NNW and heterogeneously distributed. In Fig. 5, the dihedral and stress methods are depicted. In both methods we observe similar results. At the southern region we observe a more heterogeneous fault population in terms of fault orientation compared to those in the northern part, suggesting that this region has suffered intense deformation or it has been under different stress changes. In addition, the presence of intense folding, thrust and normal faults in a relatively small area reveals that this region has been reactivated from previous structures. At the site PT15 (Fig. 6) we observe structural characteristics related to intense shear, strike-slip, thrust and normal faults. This place gradually divides the range from thrust to normal faults indicating that it has been under differential changes of the local stress trajectory. The structural characteristics of the northern part of the East Potrillo Mountains are represented in Fig. 6. Thrust and normal faults are clearly divided by a transfer zone. In the northern part, the conjugate faults follow the same trend of the normal faults but dipping at lower angles.

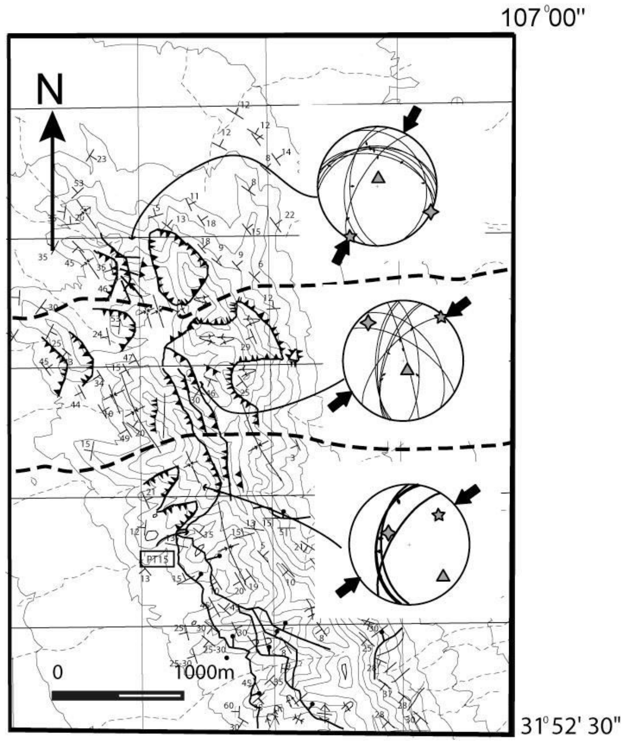

Fig. 6. Structural features of the East Potrillo Mountains. The area was divided in three regions, north, central and south respectively. Stress inversion was added for each region

Despite the fact that the kinematics analysis of the southern part is less robust compared to that of the northern region, it is evident that a gradual increase in the oblique component of the stress field occurs. The stress regime gradually accommodates into a transpressive regime. Difference in the stress trajectory plays an important role in the brittle deformation and it is related to the geometry of the major structures and the regional stress field.

The principal invariants of the kinematic and dynamic tensors are consistent to each other. However, due to the limitation of the methods, we believe that in the subdomain C it is likely that the moment tensor summation should include the isotropic information and not only the deviatoric component since it is possible that these faults were influenced by the extensional effects of the normal faults.

The low angle normal faults were not used in this analysis since they do not have a theoretical background in fault mechanics. A detailed study of the low angle normal faults is out of the scope of this study and it is described at length in Carciumaru and Ortega[43]. These faults are exposed in the central and southern part of the range. They are characterized by substantial tilting and rotations caused by the Rio Grande Rift. There is sufficient evidence that these faults are influenced by the recent active high-angle normal faults in addition to the regional stress field. In Fig.7 we depict the cross sections of the East Potrillo Mountains[37] and the kinematics analysis. At the northern region the strain geometry shows tight clusters in the plane of the fold limbs suggesting a more homogeneous fold system compared to that of the southern and central region. In addition, the absence of normal faults and the agreement with the fault-slip analysis suggest that the thrust and folds are based on a monophase tectonic regime. At the southern part the fold analysis and the fault-slip results indicate that this region underwent to different changes. From the fold analysis and field observations, we think that departure from a perfect cylindrical folding is the cause of a scattered distribution of the poles of the fold limbs

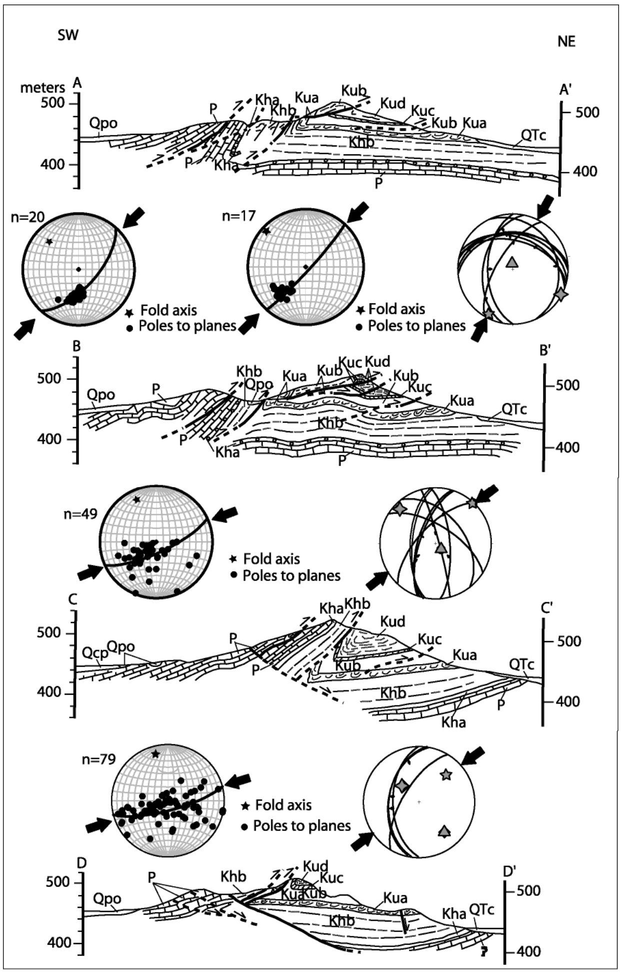

Fig. 7. Cross section in the East Potrillo Mountains. The stereographic projections of poles to bedding and the fold axis were added for all the regions; the shortening direction is indicated. The stress inversion results were added for a better comparison.

In the Franklin Mountains the faults are only exposed on the western flank of the range[44]. We observe consistent compressive orientations (Fig. 8), however the faults are more homogeneous than those of East Potrillo Mountains. The average plane orientation reveals high oblique component,

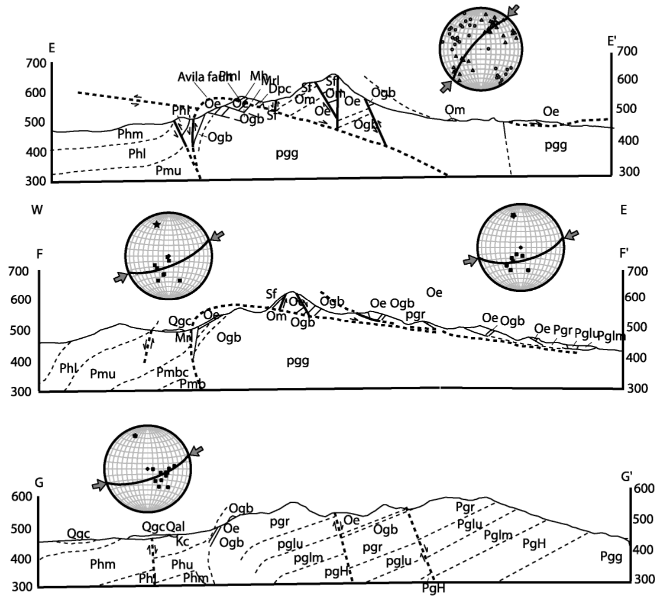

Fig. 8. Cross sections from Northern Franklin Mountains. Stereographic projections of fold axes and poles to bedding are lower hemisphere, equal area projections. The shortening direction is indicated.

indicating that Franklin Mountains could evolve as transpressional and strike slip fault during the late Laramide and Pre-Rio Grande Rift. Most of our results are derived from the analysis of Cretaceous and Permian rocks but we were also able to distinguish compression structures from older rocks. However there is no clear evidence of brittle deformation in the older rocks around Franklin Mountains. The absence of thrust faulting in older compressive structure suggests that compression increased gradually, another possible explanation of this absence of thrust faulting might be the presence of thinner layers than those exposed in the East Potrillo Mountains bending E-W. The analysis of out crop scale structures measured at the field as folds and striations allow the correlation of structural events in East Potrillo and Franklin mountains.

The inferred evolution of the Chihuahua trough shows that tectonic inversion occurred by means of subsequent changes of extension and compression. Most of the inverted structures are related to transpressional uplifting of major basement blocks along old fracture lines. This inversion is the best evidence of lithospheric dynamics dependence in which the preference of the continental lithosphere repeatedly deformed preexisting zones of structural weakness[45].

Basin sedimentary inversions occur all over the world. In central Europe, Ziegler[46] found evidence for most inversion tectonics of the sedimentary basins, in the Rocky Mountains of Colorado and Wyoming the sedimentary inversion of the foreland was described by Bally[47] and the Sahara platform in Africa was studied by Guiraud and Bosworth[48]. Apparently the most common scenario is that sedimentary basins invert during the period of compression [46],[49]-[52]. In the northern Chihuahua trough different deformation phases are found in relatively small areas, for example transtensional, shear fracture zones and transpressional folds are present, indicating that the zones of relative weaknesses are continuous at different phases of the deformation. During the inversion process is common to form marginal sedimentary basins parallel to the grabens or troughs[52]. These structures exhibit symmetry around the inversion axis and they are deeper to the inversion and shallower away from it, the Big Bend structure at the western flank of the Chihuahua trough is a clear example of a secondary structure parallel to the main one. All these tectonic processes open interesting and challenging questions about the different mechanisms about the formation of these structures.

We show that in southeastern New Mexico there is sufficient evidence of tectonic inversion from the Chihuahua trough extensional sequence to the compressional Laramide orogeny. Furthermore, the Rio Grande rifting process changed the stress field from compressional to extensional. In this region there are interconnected basins aligned at the north south. The Mesilla basin in the southernmost part of New Mexico is connected to Jornada Basin and flanked by Franklin and Organ mountains at the eastern side and by the west Potrillo and Sierra de las Uvas at the eastern flank. The gravity alignment[53] shows that the anomaly aligns northeast and northwest and cut across the predominant north trending structures associated with Basin and Range and Rio Grande Rift, suggesting that these faults formed oblique to the trend of the Rift structures. These faults are the main structures of horst and grabens associated with the Rio Grande Rift. Rheological studies of uplifted areas show NNE and oblique orientation to the major axis. There is a strong correlation between the maximum gradients and the major step faults. Lateral structure units are consistent into smaller faults following NNW and NNE trending, suggesting that some lineaments in NM, Texas and Chihuahua have been reactivated at different times [53]-[54].

The gravity and magnetic studies[55] in this region suggest that the major structural features broke up along preexisting fractures to form a characteristically pattern in the late Cenozoic (Fig. 9). This system probably existed before the end of the Miocene. Perhaps preexisting fractures determined the near surface structural details, therefore this reactivation may not occurred only in the major structures but also in regions where previous structural sequences determine the structural relations such as the case of the East Potrillo Mountains Cretaceous rocks. In addition to gravity studies, kinematic and dynamic analyses provide important relations about the structures and possible relationships of structure inversions.

In East Potrillo Mountains and Franklin Mountains the two major tectonic processes that occurred during the last 45 Ma are the Laramide orogeny and the Rio Grande Rift. Both processes influence the structural geology of this region. The Laramide orogeny formed the major thrust and belt system. Furthermore, initiation of the Rio Grande Rift, changed substantially the mechanical and lithological character of the lithosphere; normal faulting and large amount of crustal extension involved upper crust and significant heat flow into the crust. The formation of the Rio Grande Rift resulted in the combination of thermally weakened lithosphere with a superimposed stressed regime. Middle Tertiary convecting regime may have been critical in weakening the crust and allowing it to yield.

The overall tectonic history of the region is depicted in Fig. 10. The horizontal stress field and the different events indicate that this region have been under different stress and tectonic regimes. The faults were reactivated at different times, breaking preexisting fractures. The compressional and extensional sequences induced tectonic inversion. These tectonic processes suggest an old lithospheric weakness reactivated during different periods

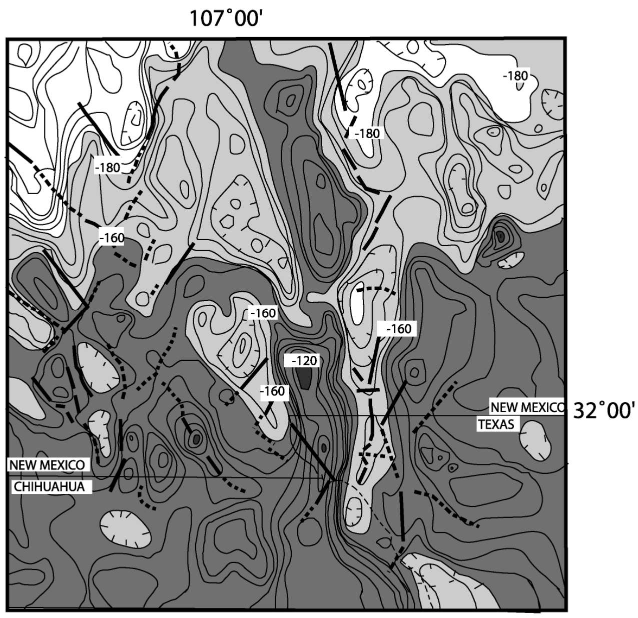

Fig. 9. Bouguer anomaly map of southwestern New Mexico. Gravity lineations of the main anomalies are also shown.

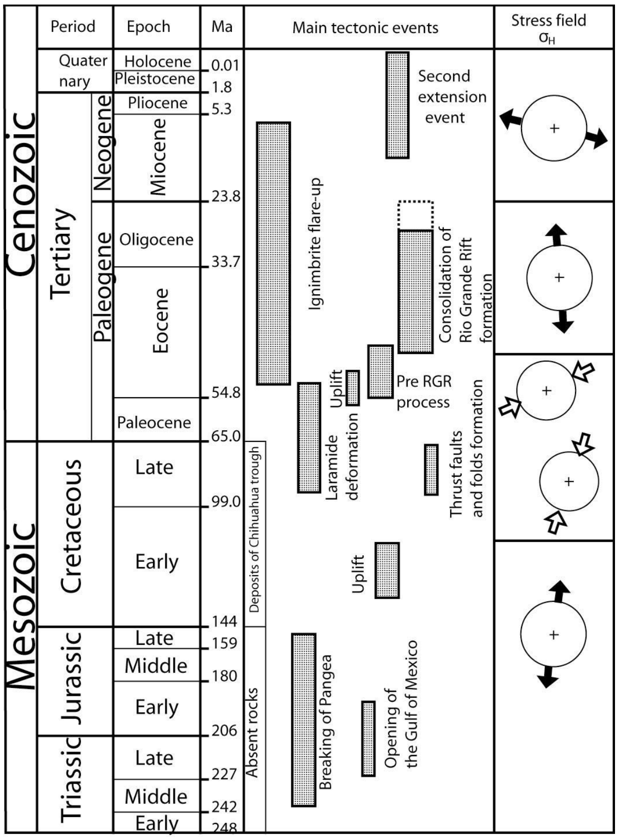

Fig. 10 Schematic tectonic evolution of the northern Chihuahua trough. The main events that affected the area and the horizontal stress field are indicated

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