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Original paper

On the origin of low angle normal faulting in the Southern Rio Grande Rift

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Resumen

La parte sur del Rift Rio Grande está definida por una serie de fallas normales de alto ángulo que separan bloques elevados de grandes cuencas de depósitos del Cenozoico. Una serie de fallas normales de bajo ángulo se encuentran en los bloques elevados y sus relaciones con la cuenca y con las estructuras montañosas es controversial. Estudios preliminares concluyeron que las fallas de bajo ángulo se formaron en una fase previa de extensión y después fueron inclinadas sobre la orientación actual de fallas más recientes. Otros estudios concluyeron que estas fallas son el resultado de un fallamiento reciente y son un factor clave en el desarrollo de las cuencas actuales y de la topografía montañosa. Por esta razón, en esta parte de la dorsal de Rift Rio Grande el análisis de esfuerzos es una tarea difícil. Fechar la edad geológica de las estructuras y el basculamiento extensivo del área son las principales fuentes de error. En este artículo reconstruimos el régimen de esfuerzos usando técnicas numéricas basadas en estadística para dos montañas del Rift del Rio Grande: East Potrillo Mountains y Franklin Mountains. El campo de esfuerzos y la historia tectónica también se discuten. Las direcciones de las venas extensionales fueron comparadas con el campo general de esfuerzos. Se encontró que la mayoría de las fallas fueron reactivadas en la primera etapa de extensión de Rio Grande, además con la ocurrencia de un basculamiento extensivo con rotaciones. En Potrillo Mountains se requiere un proceso de corrección angular por basculamiento de W25 SE y W45 SE orientado N30W para obtener dos campos de esfuerzos homogéneos. El plano de falla corregido muestra un componente oblicuo en estos dos campos de esfuerzos; el primero corresponde a la reactivación de las fallas con el σ1 y σ3 orientados N78E y N69E respectivamente mientras el segundo campo de esfuerzos es relacionado con las fallas más actuales y es orientado N64W y N61E respectivamente. En Franklin Mountains el basculamiento es menos importante sin embargo dos campos de esfuerzos con orientaciones similares pero valores de phi diferentes fueron detectados (reconocidos). La historia de esfuerzos post – Laramidica de la región es controlada de diferentes eventos exensiónales que influenciaron las estructuras pre – existentes y también generaron un sistema de falla nueva.

Palabras clave: inversión de esfuerzos, falla normal de bajo ángulo, correccion angular por basculamiento, rift del Rio Grande.

Abstract

We reconstruct the stress regime in the East Potrillo and Franklin Mountains. Using modern numerical techniques the stress field and the tectonic history of this region is discussed and extensional veins were compared with the general stress field. The majority of faults were reactivated during the first Rio Grande rift extensional event and occurrence of extensive tilting and rotations occurred. In the East Potrillo Mountains, back tilting by W25°SE and W45°SE oriented along strikes of N30°W are required in order to obtain two homogeneous stress fields. The corrected fault plane shows a significant oblique component in both stress fields. The first stress field corresponds to a fault reactivation with σ1 and σ3 oriented N78°E and N69°E respectively, whereas the second stress field is related to the youngest fault oriented N64°W and N61°E respectively. In the Franklin Mountains, tilting is less significant; however two stress fields with similar orientations but different phi values are recognized. The post – Laramide stress history of the region is controlled by different extensional events that influenced the preexisting structures and generated other young fault systems.

Key words: stress inversion, low angle normal faults, back tilting, Rio Grande rift.

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Introduction

The southern Rio Grande rift is defined by a series of high angle normal faults which separate uplifted blocks of bedrock from large basins with deep Cenozoic fill. Numerous low angle normal faults occur within the uplifted blocks whose relationship to the current basin and range structure has been controversial. Several previous studies have concluded that the low angle faults were formed during an early phase of extension and were tilted into their present orientation by younger faults. Other studies have concluded that the faults are the result of recent faulting and are a key factor in the development of the modern basin and range topography. For this reason in this part of the Rio Grande rift, paleostress analysis is a difficult task. Dating uncertainties of the geological structures and extensive tilting during periods of late Cenozoic extension are the main sources of error.

In the southern Rio Grande rift, a key problem is determining if normal faults formed in response to different stress regimes or to a single progressive deformation. Dating geological structures in this region by means of crosscutting relations, mineral associations or stratigraphy is difficult because many normal faults are young or reactivated older faults. Therefore, low and high angle normal faulting in the Rio Grande rift is controversial (Lewis and Baldridge, 1994). Extensive faulting and tilting may have occurred during two distinct extensional phases in the Rio Grande rift (Aldrich *et al*., 1986; Henry and Price, 1984; Morgan *et al*., 1986; Seager *et al*., 1984). Therefore, back tilting from a single correction factor is unlikely and rotation corrections are needed in order to reconstruct reliable paleostress fields.

Classical stress inversion is based on the idea of infinitesimal strain. A definition of stress for the case of deformation with finite rotations is not unique (Fung, 1965). Therefore it is necessary reconsider the analysis of deformation without a restriction of infinitesimal displacements. The generalization from infinitesimal strain theory to finite deformation involves tremendous complexity of the normal equations. Nonlinear field theory is beyond the scope of this paper, but another possible approach is to consider mechanical or kinematic constraints. A likely kinematic assumption is that tilted blocks are produced from an identical normalized stress tensor that conserves similar relations before tilting, as successfully tested by Yamaji *et al*. (2005) using artificial data. Their technique is based on a multiple inverse method (Yamaji, 2000) that separates reduced stress tensors from the earlier back tilted data. In heterogeneous data, subsets of faults are analysed with the classical stress inversion method of Angelier (1994) so that a large number of optimal stresses is computed and analysed as a point in stress space. Significant stresses are thus represented by clusters of points. Here we analyse multiple inverse method results by the stress difference technique proposed by Orife and Lisle (2003).

Once the data set is corrected, we apply the classical stress inversion technique of Michael (1984) in order to reconstruct the tectonic history of the region. Two regions, the East Potrillo and Franklin Mountains in the southern Rio Grande rift are studied. Results in the East Potrillo Mountains suggest that a substantial tilting correction is needed. In the Franklin Mountains the tilting correction is less significant and two stress fields with similar stress orientation but different stress ratio (phi value) were obtained. This suggests that the region has been under continuous deformation.

Geological setting

The Laramide tectonics of southern New Mexico remains controversial (Seager, 2004). Models include thin - skinned tectonics (Corbitt and Woodward, 1973; Woodward and Du Chene, 1981); coupled with basement - involved foreland uplift (Drewes, 1978, 1981, 1988), with basement block uplifts (Seager, 1983; Seager and Mack, 1985) and inversion tectonics (Bayona, 1998; Lawton, 1996; Lawton, 2000).

Outcrops of Laramide structures are mostly uplifted bed rock blocks. Most of the early Tertiary deformation was restricted to narrow north - west trending fault zones that resulted in a series of northwest trending uplifts and basins (Seager, 2004). The basins are asymmetrical; they deepen to the south toward a thrust or reverse fault and they are generally associated with uplifts along their southwestern margins.

The post - Laramide stress regime is widely recognized (Aldrich *et al*., 1986; Baldridge *et al*., 1980; Morgan and Golombek, 1984; Morgan *et al*., 1986). 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 (Baldridge *et al*., 1995; Keller *et al*. 1991; Morgan and Golombek, 1984). Such low angle normal faults are only known in isolated areas, and their nature is still a point of debate. A later rifting phase beginning 10 Ma is associated with classic Basin and Range style block faulting (Keller *et al*., 1991) with delineation of the present interconnected rift basins and uplifts.

Aldrich *et al*. (1986) associate many faults and dikes with reactivated structures, but their strike was not defined in most areas due to lack of structural data. From dikes in plutons, and dating, they found the orientation of the least compressive stress was N - NE to S – SW; in the late phase they found west - northwest to east - southeast extension. Aldrich *et al*. (1986) and Chapin and Cather (1994) considered early Miocene dikes in the roofs of plutons as the best indicators of regional stress orientations. Since they are only known at two locations, they may not be representative of the regional stress regime. In this study fault slip inversion is used to determine the state of stress adjacent to major low angle normal faults in the southern Rio Grande rift.

Studied region

The East Potrillo Mountains and the Franklin Mountains were studied in detail (Figure 1). The East Potrillo Mountains are located 20 to 22 miles south of Las Cruces, New Mexico. They are part of a north - northwest trending mountain chain that crosses the Mexican border. Exposed Laramide thrust faults belong to the southwestern margin of the Potrillo basin. The northwest extension of this range subsurface is called "Potrillo uplift" (Lawton 2000).

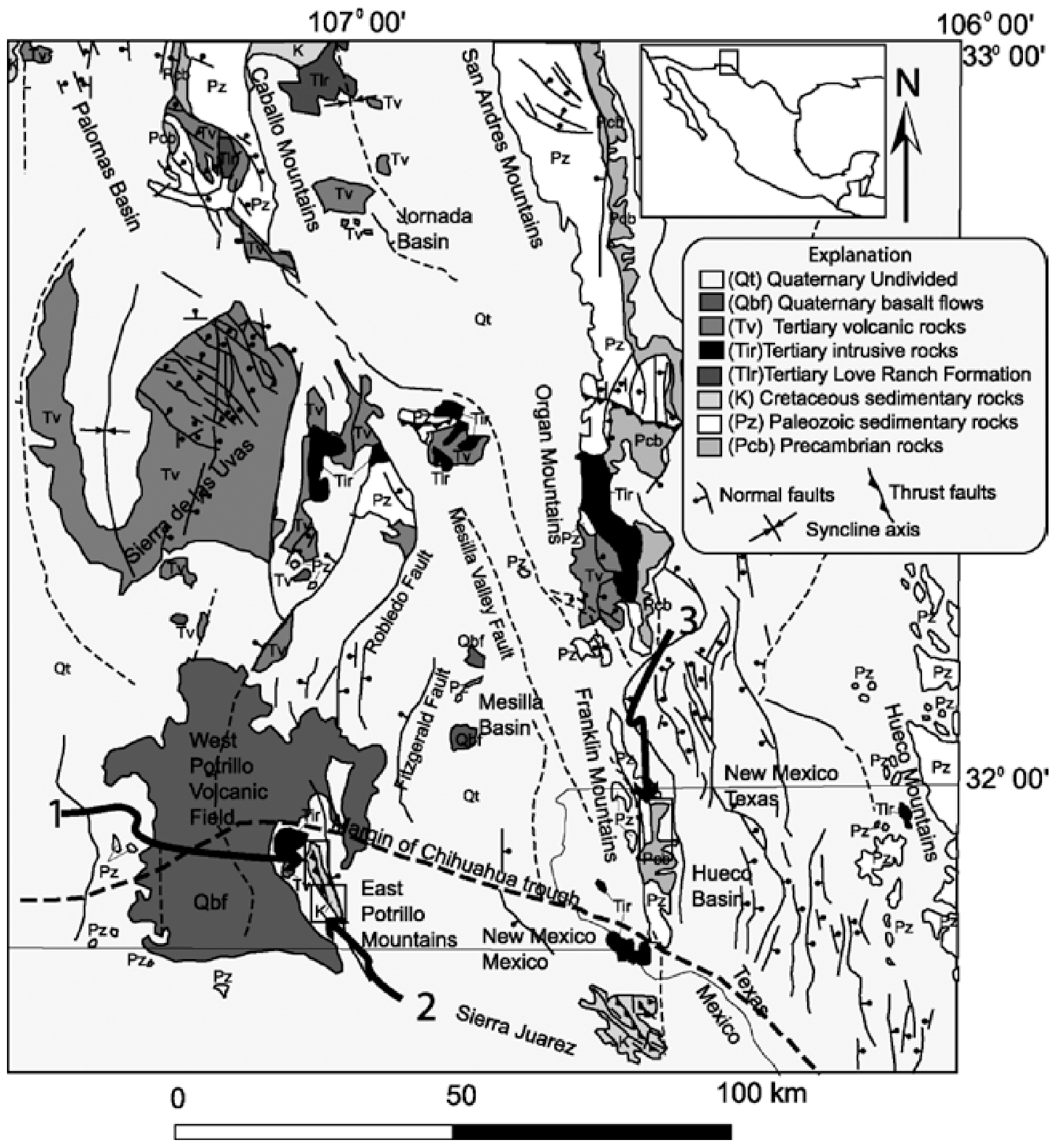

Figure 1. Geological map of the region. The two studied areas are the East Potrillo Mountains (insets 1 and 2) and the Franklin Mountains (inset 3). Both ranges are located at the northern margin of the Chihuahua trough (modified from Ruiz, 2004).

Lower Cretaceous rocks are dominant in the outcrop of the East Potrillo Mountains, with narrow belts of Permian rocks on the east and west sides of the range. Seager and Mack (1994) described marine clastic and carbonate shelf deposits above a basal conglomerate: all of them thin southward. These somewhat arkosic clastic rocks and limestones contain Albian - Aptian fossils and correlate with the Hell-to-Finish and U-Bar formations of southwestern New Mexico. Conglomerate beds contain clasts of lower Cretaceous carbonates (Broderick, 1984) and must be, younger than early Cretaceous. The arkosic rocks may indicate uplift and erosion of the underlying or adjacent Precambrian granite during Laramide time. Laramide deformation in the East Potrillo Mountains is intense. Folds and associated thrust faults involve lower Cretaceous and Permian rocks trending N30°W and converging toward the northeast (Fig. 2 and Fig. 3). A system of low - angle normal faults is also exposed in the East Potrillo Mountains. Seager and Mack (1994) consider these faults to be probably early Miocene in age, thus they must have formed during an early phase of extension in the Rio Grande rift.

In the Franklin Mountains, substantial tilting occurred late during the range uplift. According to Lovejoy and Seager (1978), 35° tilting took about 23 MA to develop. They attributed most of the low angle faults to large scale landsliding and "gravity glide" as the range was uplifted. However, several recent studies have concluded that the Franklin Mountains are the result of tilting within the last 10 ma (Lueth *et al*., 1998; Seager, 1981). The northernmost part features homoclinally west dipping Paleozoic limestones and shales (Fig. 4). Unusual structures in this part of the range include north - northwest - trending low angle normal faults. Kelly and Matheny (1983) concluded that these faults were produced by tilting of steeper faults and fractures as the Franklin Mountains were uplifted and tilted west (see also Seager, 1981).

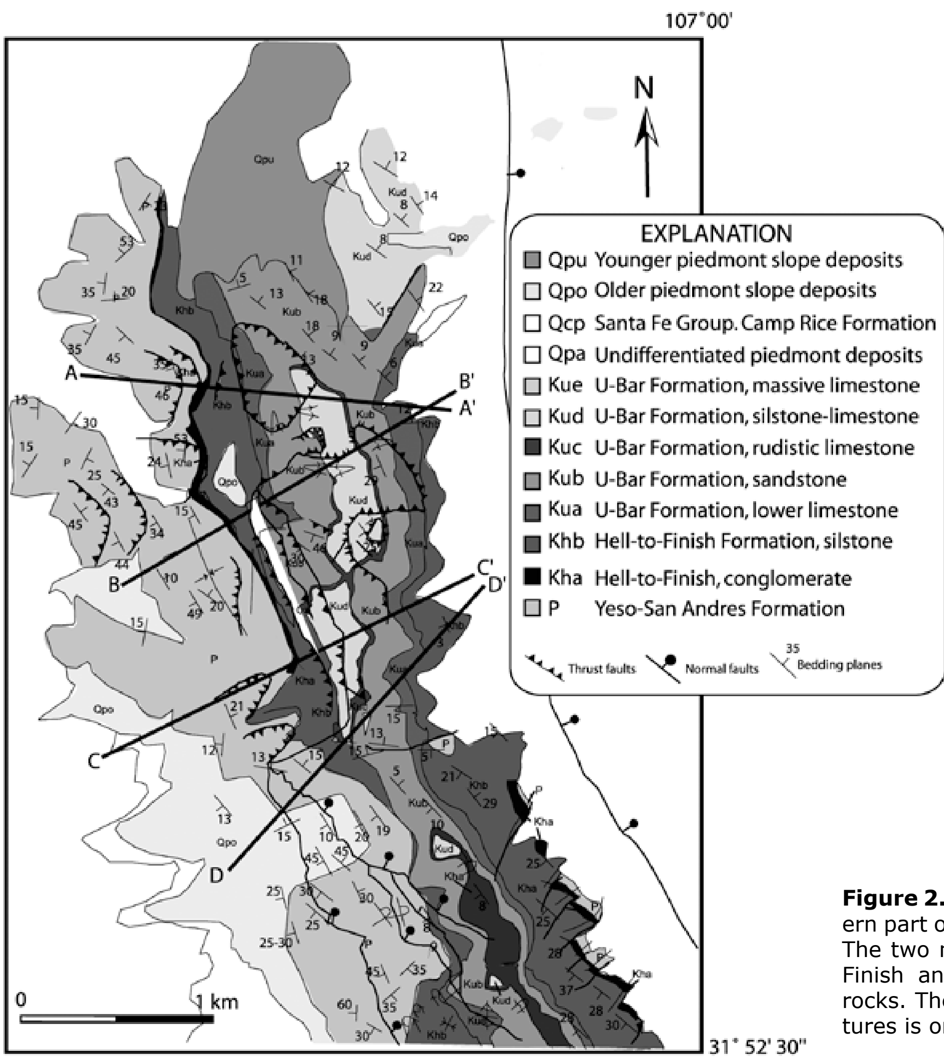

Figure 2. Geological map of the northern part of the East Potrillo Mountains. The two main formations are Hell-to-Finish and U-Bar, overlying Permian rocks. The general trend of the structures is oriented N36°W (after Seager and Mack, 1994).

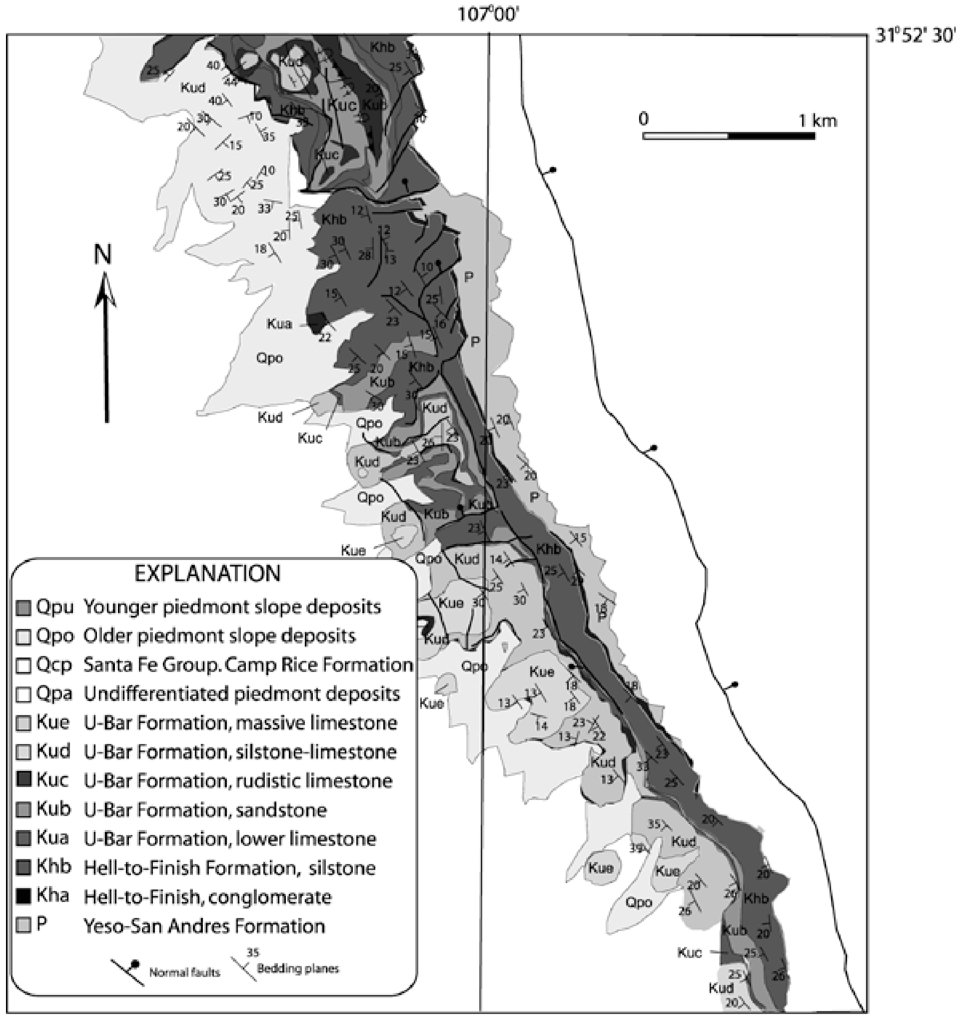

Figure 3. Geological map of the southern part of the East Potrillo Mountains. The two main formations are Hell-to-Finish and U-Bar, overlying Permian rocks (after Seager and Mack, 1994).

Methods

Finding the stress tensor from fault orientation involves an assumption that the direction of tangential traction in the plane tends to be parallel to the slip direction; this tangential traction is also assumed to be parallel to the shear stress (Ramsay and Lisle, 1997). We assume that the incremental principal strain axes coincide with the principal stress axes. Therefore if the tangential traction can be determined on a variety of planes in a region, it may be possible to make inferences about the regional stress field by inversion.

Low angle normal faults are difficult to reconstruct in terms of stress inversion since they cannot be easily explained from Mohr-Coulomb failure criteria (Davis *et al*., 1983). The direction of maximum resolved shear stress is constrained by experiment and observations to lie in the plane of the fault and in the σ_1 - σ_3 plane. Mohr-Coulomb criteria lead to some assumptions on the orientations of the principal stresses, including that fractures form at ~30° to σ_1 and that σ_3, generally angles at ~60° to the fractures, which would correspond to normal faulting by Anderson´s criteria. Caution is required when dealing with other types of faults (e.g, listric or low-angle normal faults).

Multiple inverse method is a numerical technique for separating stress from heterogeneous fault-slip data (Yamaji, 2000). It is based on classic stress inversion by grouping data in multiple sets in order to analyze their statistical behavior. We minimize the observed and theoretical fault-slip data obtained from outcrops. The inversion data include the attitude of fault planes, the orientation of striations and the slip directions. These quantities are non – dimensional: only the deviatoric part of the stress tensor can be obtained. However, the stress ratio phi is also determined in order to characterize the relationship between the principal stress components.

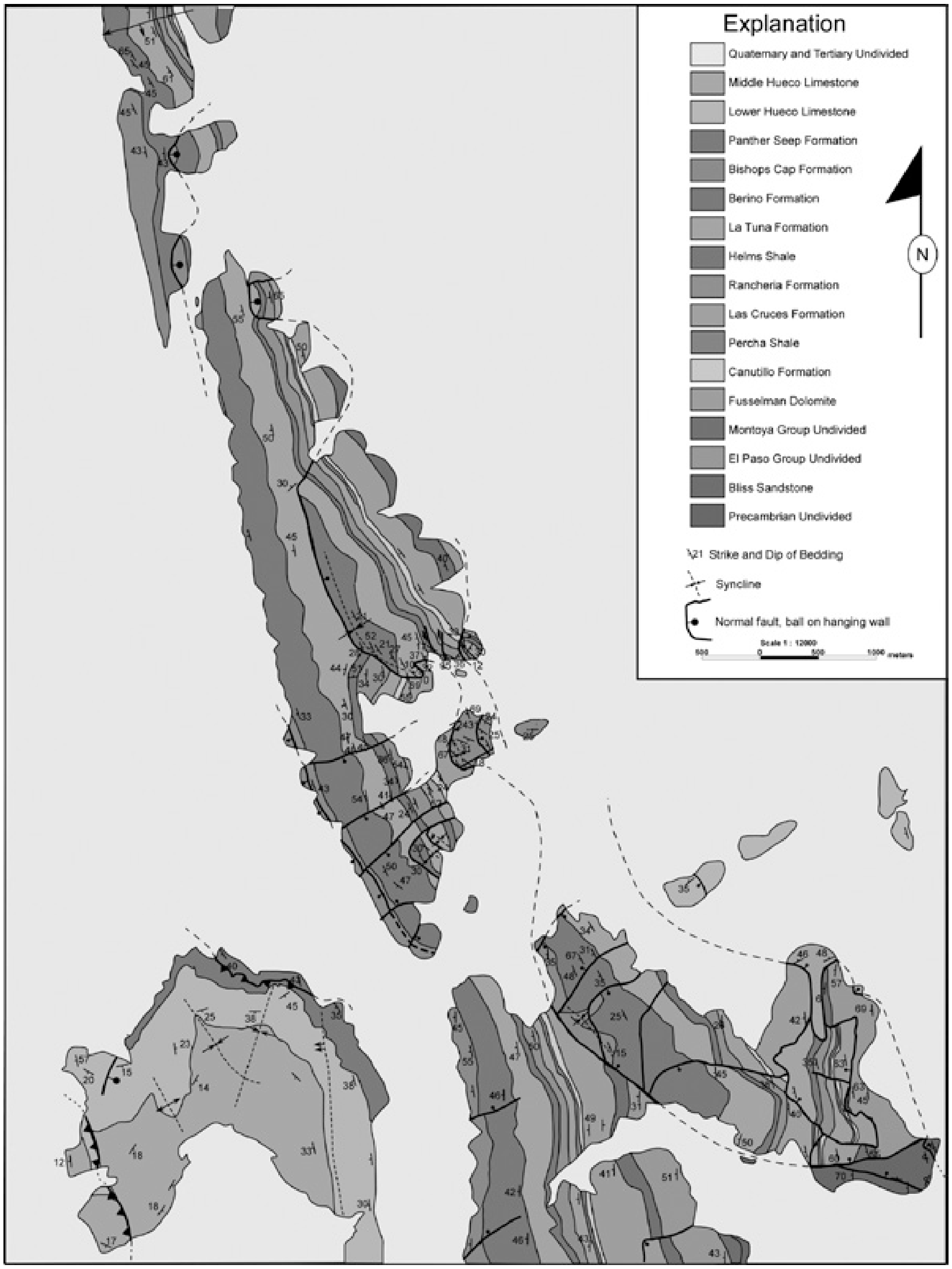

Figure 4. Geological map of the Anthony Gap area, northern Franklin Mountains (after Kelley and Matheny, 1983; Figuers, 1987, and Harbour, 1972).

In the East Potrillo Mountains, faults with good slickenside lineations were found in silica-cemented calcareous siltstones, which are common in the Hell-to-Finish formation. Slickenlines within major fault zones are rarely observed due to poor exposures and pervasive cataclasis. Fault strike and dip as well as slickenline trend, plunge, and shear sense were measured at outcrops. All data were inverted using the tilt correction for paleostress analysis (Yamaji *et al*., 2005). After the fault population was back tilted, we used the inverse method of Michael (1984) to estimate the regional stress tensor: it revealed a tensional regime with an important oblique component. The phi value was about 0.5, it measures the relative size of the principal stresses. It suggests a possibility to exchange the principal and intermediate axes. The principal axes may be difficult to be exchanged, but this strongly depends on the frictional coefficient factor (Hu and Angelier, 2004).

Data

We collected fault data from available 1:24000 geological maps (Harbour, 1972; Kelly and Matheny, 1983; Seager and Mack, 1994) and from field data. Topographic maps were used as field guides. Stress and strain inversions require accurate slickenline data: fault striations are sparse in published maps. Useful structural data included extensional veins, fold limb orientations, cleavage planes and bedding directions. Seager and Mack (1994) suggested that a tilt correction of 25°SW is required in the East Potrillo Mountains; this was obtained from few field observations of bedding. It is important to note that this angle merely corrects the range position, but does not restore individual displacements on each fault due to incremental strain during the youngest extensional period. It is the minimum correction to obtain the original position of the faults.

In the Franklin Mountains most of the data were from the Anthony Gap in the northern part of the range. Here high angle normal faults are exposed as they grade into large displacement, low angle normal faults.

Back tilting

Because of the large differences between the Franklin Mountains and the East Potrillo Mountains, we examined the possibility that the faults were rotated. The back tilting algorithm of Yamaji *et al*. (2005) was found to be useful. This approach assumes that tilted blocks are produced by an identical normalized stress tensor that preserves its orientation before and after tilting. They suggest that the method can be applied when fault orientation was changed by later deformation, as in the low angle normal faults of the southern Rio Grande rift (Seager, 1981). It may be used in blocks tilted by extensional tectonics if they have a similar strike of bedding in the hanging and footwall blocks. This constraint may not be entirely justified in the East Potrillo Mountains, given the complex geology of the range. However, Laramide structures in the Potrillo Mountains have similar orientations in the hanging and footwalls of the normal faults, so that the correction may be valid. The multiple inverse method (Yamaji, 2000) separates reduced stress tensors from the previously back tilted data. It analyses stress from heterogeneous data by preparing subsets of faults and applying the classical stress inversion method of Angelier (1984) so that a great number of optimal stresses is computed and analysed as a point in stress space. Significant stresses are represented as clusters of points. Strong clustering is an indication that the multiple inverse results are valid.

In the East Potrillo Mountains, progressive back tilting of the data from 0 to 100% about a trend of N30°W trending rotation axis with a plunge 45°S is depicted in Figures 5 to 9. In addition, the restored stereographic projections are plotted. Beyond 50% (Fig. 7), the tilt correction rotated the attitude of the faults by a negligible amount but the rake of the slip vectors was rotated by few degrees.

Seager and Mack (1994) restored the low angle normal faults by correcting for westward dip of the range by a rotation of 25°. This correction is virtually the same as the 50% tilt correction shown in Figure 7. Note that a 50% correction is adequate only for the NE trending faults. For the other faults, a 100% correction is more appropriate (Figure 9). The fault-slip data at 50 and 100% tilt correction were still heterogeneous, suggesting that a simple progressive back tilting about the N30°W axis was not entirely true. Slight rotations may have ocurred over time. However, these corrections are not important as compared to those from the back tilting correction.

For the Franklin Mountains, back tilting was much less significant (Fig.11). The back tilting corrections yielded no important difference in the results; thus these faults may have occurred after the main tilting of the block. The original faults that were rotated to produce low angle normal faults became inefficient, and high angle faults developed later. The multiple inverse method yields two clusters with similar stress directions but different stress ratios reflecting continuity of stress over time.

Structures in the East Potrillo Mountains after backtilting contain a substantial oblique component. Oblique components are commonly referred to as structures that were formed under a transpressional or transtensional stress regime. In the case of oblique components produced by subsequent rotations, it is inappropiate to use the current structural relations as the present state. Thus, a normal fault generated by an extensional tectonic regime and rotated during subsequent strike-slip should not be called an oblique extension structure. The terms *transtension*, and *oblique extension structure* imply syn-tectonic characteristics. As with any description of strain, it is essential to find out why the oblique deformation occurred, and for which period this geometrical relation is valid.

Extensional veins

Calcite veins are common extensional structures in the East Potrillo Mountains. In Figure 12 the distribution of calcite veins of the central part of the range is shown. In the northern part of the range most extensional structures are distributed more heterogeneously than in the central part of the range. However, there is no evidence that they belong to different episodes, since there is no correlation to other extensional structures. They are located in a much more deformed region where the population of folds, overturned structures and thrust faults is higher. On the other hand, the poles of calcite veins in the central part of the range (Fig.12) are consistent with maximum extension of the Rio Grande rift.

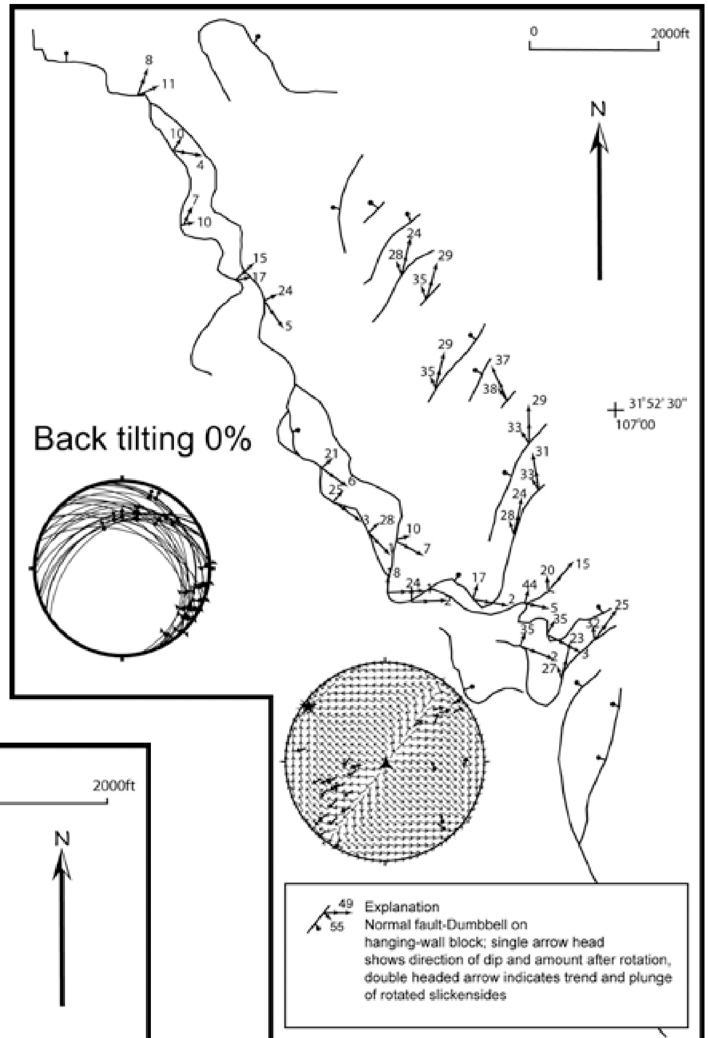

Figure 5. Normal faults of the East Potrillo Mountains back tilted 0%. In addition the stereographic projection and the theoretical and observed tangential lineations of the stress field from the multiple inverse method is shown.

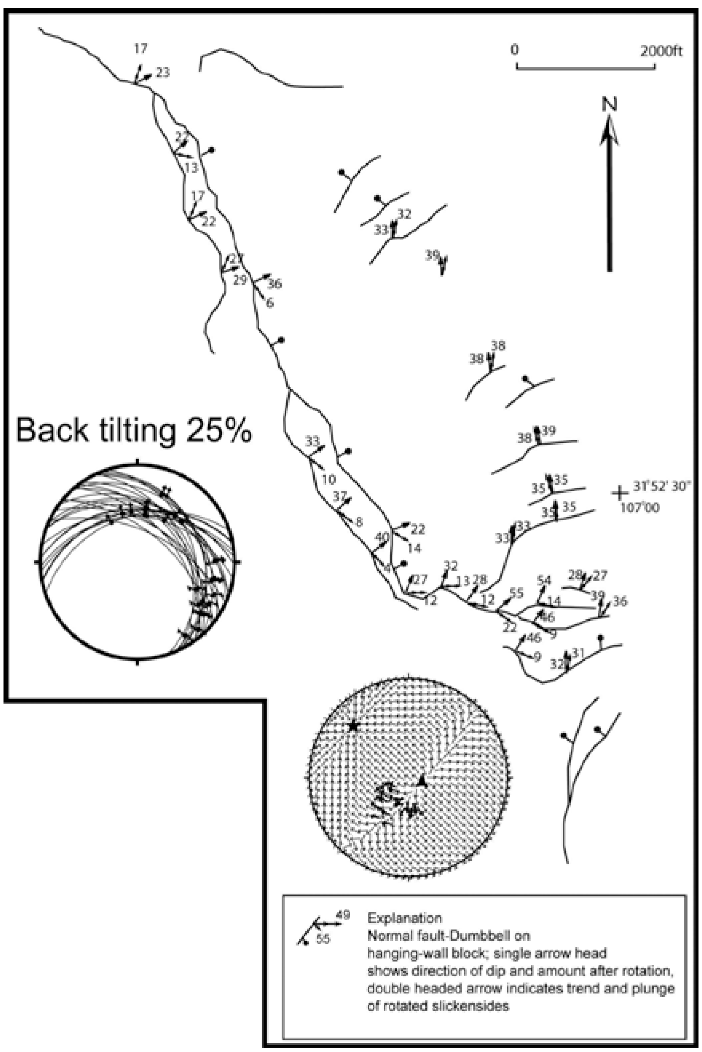

Figure 6. Normal faults of the East Potrillo Mountains back tilted 25%. In addition the stereographic projection and the theoretical and observed tangential lineations of the stress field from the multiple inverse method is shown.

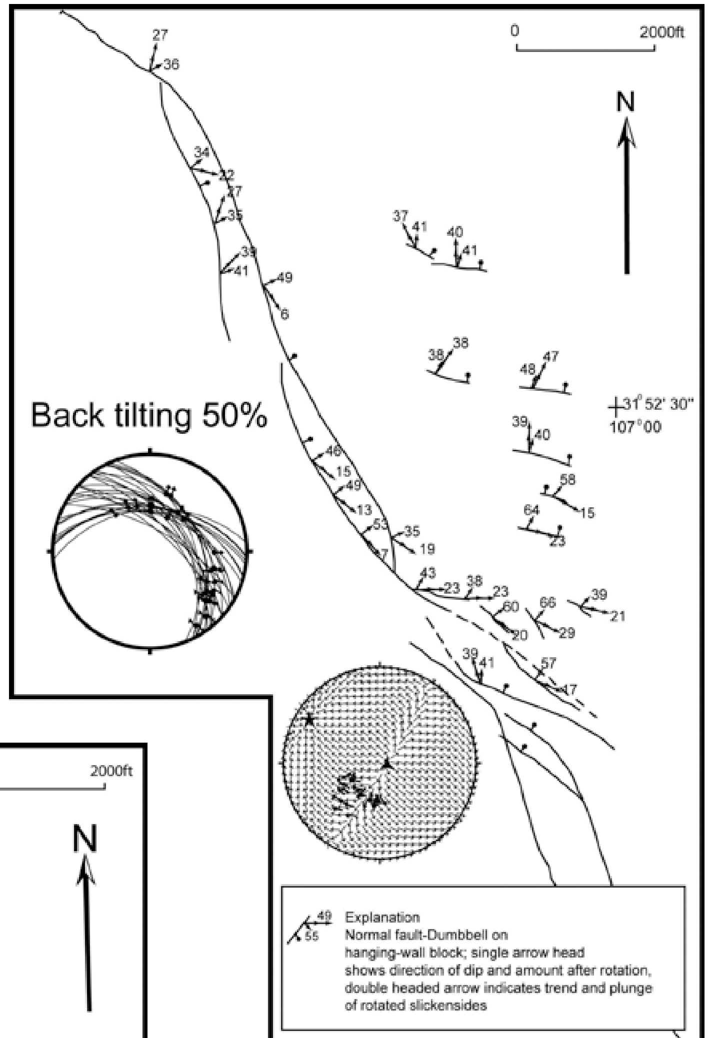

Figure 7. Normal faults of the East Potrillo Mountains back tilted 50%. In addition the stereographic projection and the theoretical and observed tangential lineations of the stress field from the multiple inverse method is shown.

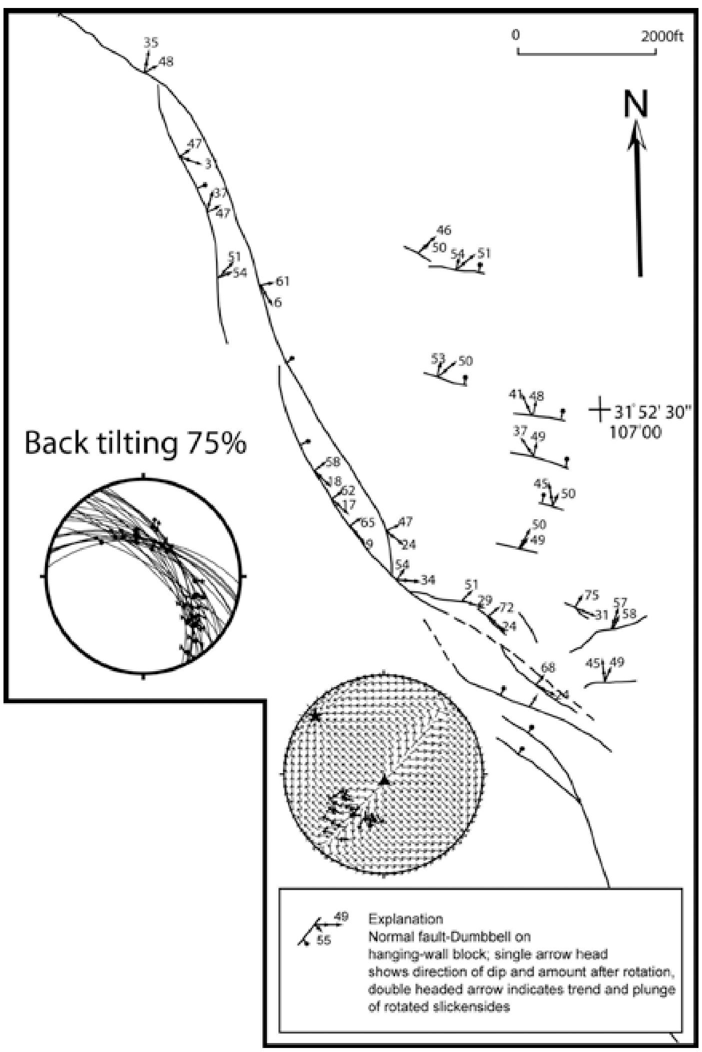

Figure 8. Normal faults of the East Potrillo Mountains back tilted 75%. In addition the stereographic projection and the theoretical and observed tangential lineations of the stress field from the multiple inverse method is shown.

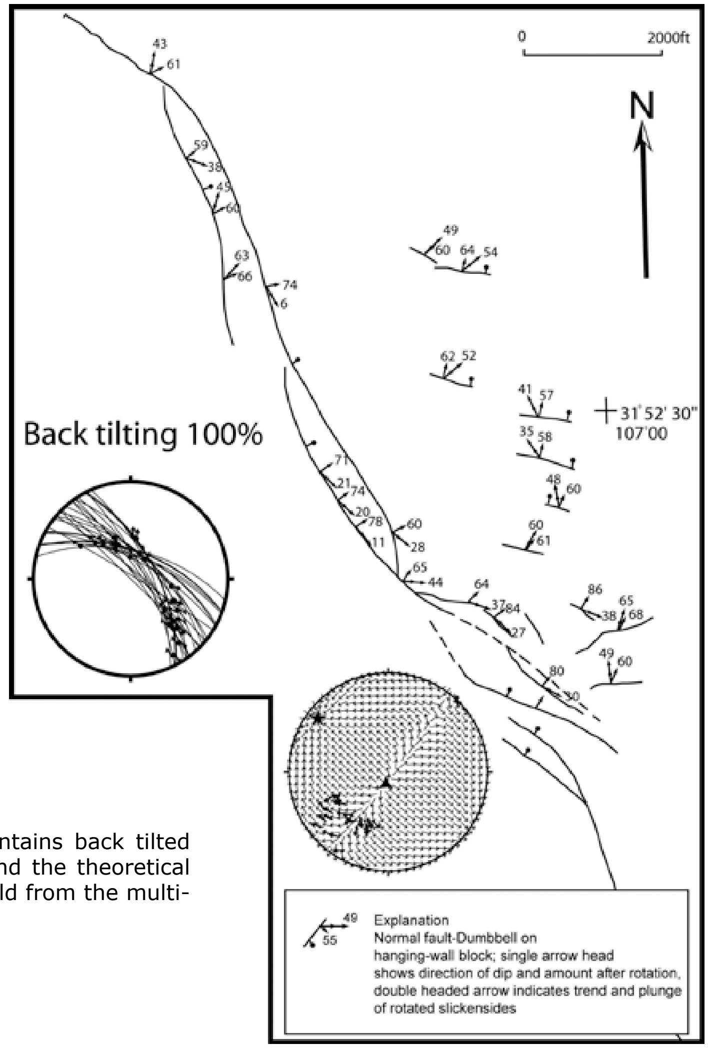

Figure 9. Normal faults of the East Potrillo Mountains back tilted 100%. In addition the stereographic projection and the theoretical and observed tangential lineations of the stress field from the multiple inverse method is shown.

Discussion

The main assumption of stress analysis is that the principal strain axes match the principal stress axes. Some authors prefer a method based on shear and principal stress axis, others tangential traction and principal strain axes. Marret and Peacock (1999) discuss some problems related to terminology that may lead to confusing descriptions. Each method should be described in terms of variables and objectives. Instead of *stress inversion,* a mere correct term would be *principal axis estimation by fault-slip inversion.* Our general results are robust enough to determine the direction of the principal axis of the stress field. The stress and strain inversion shows that the maximum extension is roughly N-S.

During early Miocene, the first extensional episode of the Rio Grande rift caused substantial changes in the stress field of the deformed lower Cretaceous rocks in the region. The first N-S extensional period of the Rio Grande rift generated major extensional structures in the studied area. This period has been considered to have reached the highest extensional rate. It correlates with cinder cone alignments and extensional veins. Therefore, at this time the main normal fault system in the range originated.

The high extensional rate and the increase in extensional structures indicate an important contribution of normal faults over the general fault system. However, these structures were tilted during the last extensional period.

These faults were corrected for N30°W trending in order to restore the tilting. They show evidence of important oblique displacements that can not be restored by tilting correction, suggesting rather an incremental displacement from the last extensional period. This displacement caused such small angles in fault striations since they coincide with the last reported direction of extension in the Rio Grande rift. Figure 13 shows the tectonic history of the region. It is evident that a simple reconstruction is but a crude representation of the episodes from the early Miocene to present, as these events occurred when the evolution of this range was already highly deformed by the Laramide orogeny.

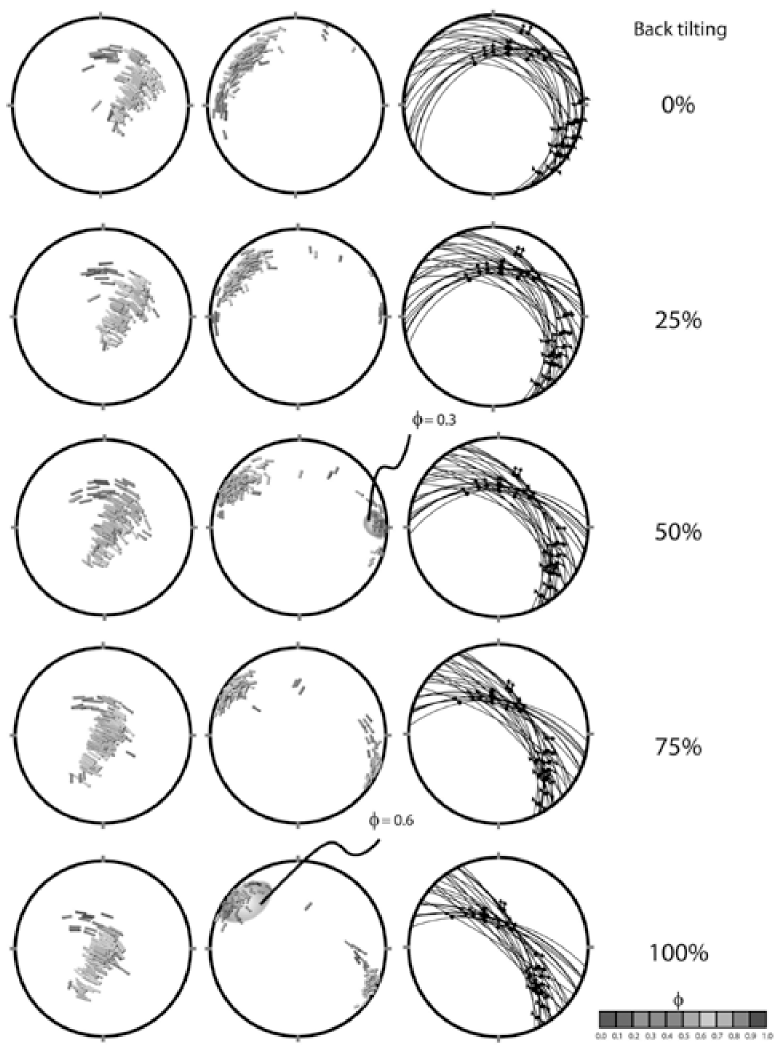

Figure 10. Multiple inverse method results from back tilting in East Potrillo Mountains. Two different clusters at 50 and 100% are recognized. The 50% region corresponds to the NE trending faults and the 100% are the NW older and reactivated faults.

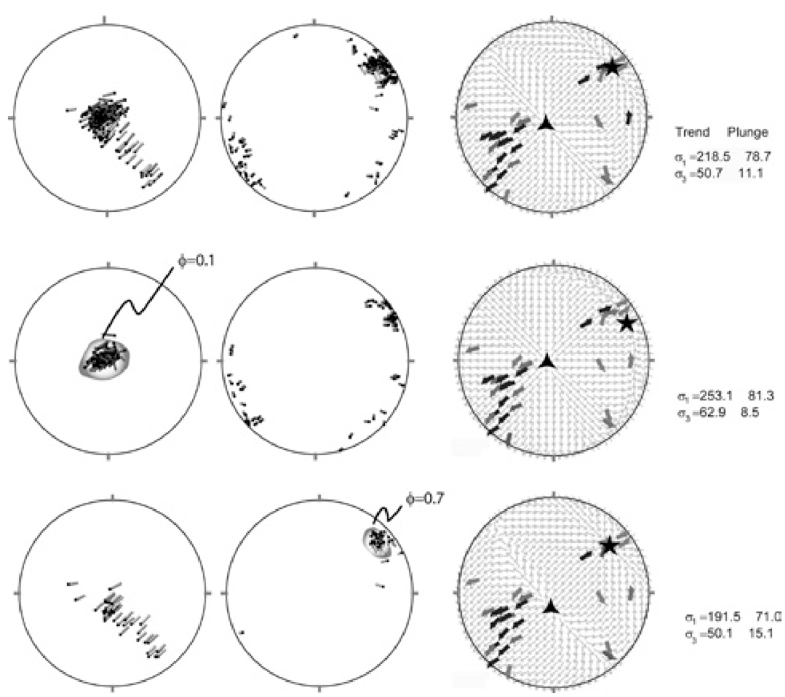

Figure 11. Multiple inverse method analysis in the Franklin Mountains. No back tilting correction was needed in order to obtain robust results. However two clusters of f=0.1 and f=0.7 were observed.

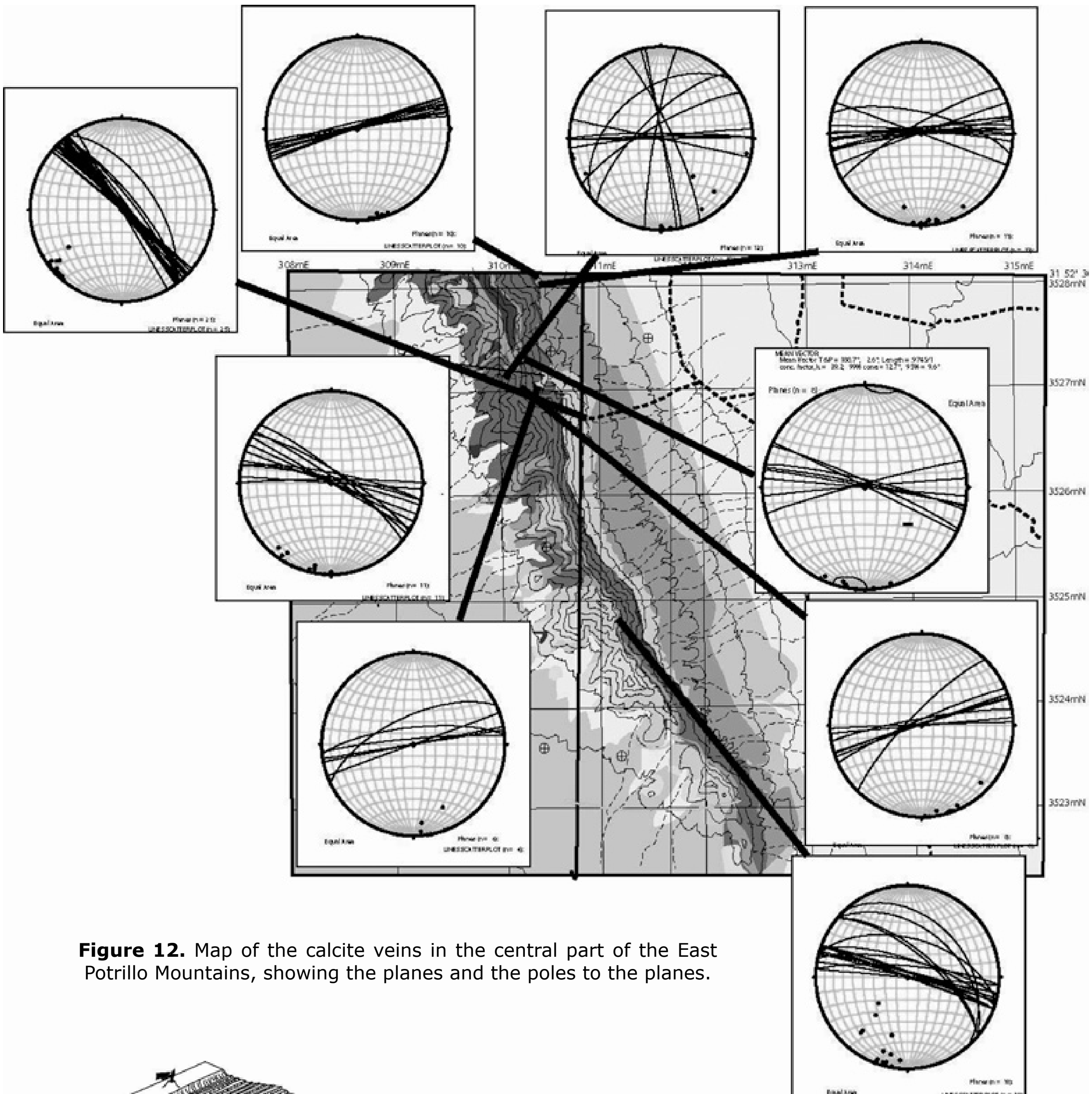

Figure 12. Map of the calcite veins in the central part of the East Potrillo Mountains, showing the planes and the poles to the planes.

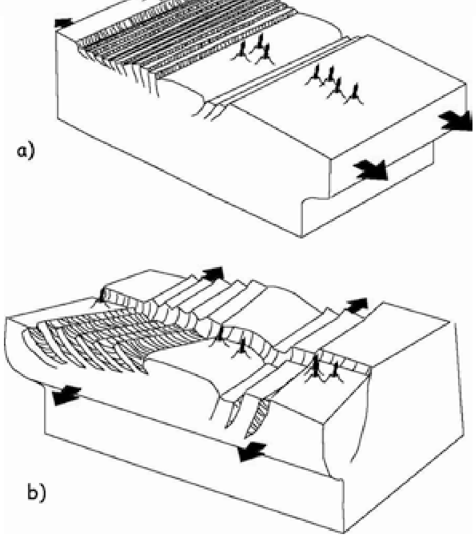

Figure 13. Schematic representation of the two main episodes in the southern Rio Grande rift. a) In the early Miocene, the first N - S extensional period of the Río Grande rift generated the main extensional structures including normal faults, extensional veins and volcanic edifices. b) During the second E - W extensional stage of the Rio Grande rift a substantial oblique displacement generated important rotations over the normal faults. In addition, a second system of N - S normal faults were generated.

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