STRUCTURAL GEOLOGY AND TECTONICS ON THE NORTHERN CHIHUAHUA TROUGH

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I dedicate this thesis to my mother,
who taught me to strive for the best in life.

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I dedicate this work to the memory of my friends, Camelia and Gilda. During their short life I had the privilege to share part of it with them.

To my beloved family for their patience, encouragement and great support during these four years. Without all of them everything could be almost impossible for me.

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ABSTRACT

I present results from a study of the structural geology of the northern part of the Chihuahua trough where the Laramide orogeny and the Rio Grande rift affected the region. Laramide style of deformation changes from motion on moderate to low angle thrust and reverse faults within the interior of the basin to basement involved reverse faulting on the adjacent platform. Shortening directions estimated from the geometry of folds and faults and inversion of fault slip data indicate that both basement involved structures and faults within the basin record a similar Laramide age deformation field. Laramide shortening was focused into the relatively weak sedimentary rocks of the Chihuahua trough that piled up on the rigid basin margin. Along strike variations in shortening direction and kinematics are controlled by the curved northeast margin of the trough and reflect stress reorientation along the weak interface between the strong platform and weak basin interior.

In addition, I reconstructed the stress regime of the Rio Grande rift. Structures in the southern Rio Grande rift are consistent with prior inferences that the Rio Grande rift formed during two phases of extension. Low angle normal faults were active during both phases of extension and are not restricted to the first extensional phase, as has been previously inferred. In the East Potrillo Mountains back tilting of W25°SE and W45°SE about a N30°W axis are required in order to obtain two homogeneous stress fields. The corrected fault planes show significant oblique component in these two stress fields; the first stress field corresponds with $\sigma 1$ and $\sigma 3$ oriented N78E and N69E respectively whereas the second stress is that related to the youngest faults oriented N64W and N61E respectively. In the Franklin Mountains tilting is less significant; however two stress fields with similar orientations but different ϕ values are recognized.

The combined data sets show that the northern Chihuahua trough has been affected by three major deformation events since its formation with the stress fields varying over time. These deformation events led to the production of the complex basin and range structure found throughout northern Chihuahua, southern New Mexico and west Texas. Additionally, these events are similar to those that affected much of the Rocky Mountain region in Colorado and New Mexico. This shows that despite differences in physiography between this region and the Rocky Mountains, it records a similar tectonic history with much of the Rocky Mountain foreland.

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Introduction

Styles of deformation in extensional and compressional regimes are fundamental topics in structural geology. Studies of the relationship of faults to folds in thrust belt regions have advanced considerably from the last century and modern techniques such as kinematics analysis have opened the opportunity to analyze results in a quantitative manner. On the other hand, in extensional regimes, apparently the styles of deformation are simpler than those of compressional regimes, but fault systems play an important role in understanding the rifting process where thinned continental lithosphere basically controls extensional deformation. In nature, it is common to find regions that have been affected by both extensional and compressional regimes at different times. In these regions, isolated study of the different tectonic events is not an easy task. This work focuses on the structural geology of the northern part of the Chihuahua trough where the Rio Grande rift dominates the active tectonics, overprinting the older Laramide orogeny compressional event, that affected the region.

Over the years, there have been many attempts to understand the deformation style of this region. In New Mexico and Colorado, the Laramide foreland is composed of a relatively thin marine sedimentary wedge where the thrust system flattens into a subhorizontal detachment separating the deformed rocks from the basement below, namely thin - skinned deformation. However in southern New Mexico, west Texas and northern Chihuahua, the style of deformation usually involves both the basement and decollement along crustal faults. The nature of this thick - skinned style of deformation has been under debate for many years. This debate has centered on whether the main style of deformation is the thin- or thick - skinned model (Seager and Mack, 1985). Recent geological and geophysical studies show that the reverse faults in the Chihuahua trough may have been reactivated by the Laramide compressional event (Lawton 2000, Bayona and Lawton, 2000) and that the fault dip varies at different angles (Keller et al., 1986; Keller, 2004), thus the deformation style does not necessarily fit either the thin- or thick-skinned model. Later, during time just preceding the initiation of the Rio Grande rift (Eocene-Oligocene), extensive magmatic activity occurred.

The Rio Grande rift is an important lithospheric scale feature associated with significant thinning of the crust and mantle lithosphere, high heat flow and low upper mantle seismic velocities

(Keller et al. 1990). One striking feature is the presence of low angle normal faults. The fault systems in the Rio Grande rift have been affected by considerable rotations, tilting and change in the stress field (Seager, 2004). Thus, understanding the nature of the low angle normal faults is not an easy task.

This dissertation attempts to resolve these two controversial but challenging enigmas of the Chihuahua trough: the deformation style during Laramide and the nature of the low angle normal faults related to Rio Grande rift extension. In order to achieve these goals, I used a quantitative approach based on fault slip inversions and fold geometries correlating the results with map scale structures, published maps, previous studies and field observations.

1.1 Tectonic overview

During Paleozoic time, marine rocks, mostly carbonates, were deposited in the region. The Paleozoic rocks are more than 4000 m thick in the southwest corner of New Mexico and about 2500 m thick near El Paso (Seager and Mack, 1985). Thickness variations are the result of Paleozoic subsidence of the Pedregosa Basin in the southwest corner of New Mexico and adjacent parts of Arizona, as well as subsidence of the Rio Grande basin in the south - central part of New Mexico. Approximately 3000 m of Pennsylvanian and Permian marine strata accumulated in the Pedregosa basin and half that amount in the Orogrande basin, Laramide in age (Seager and Mack, 1985).

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 (Seager and Mack, 1985). These Jurassic carbonates probably thicken southward into Chihuahua trough where Jurassic evaporates are diapiric and may be responsible for Laramide decollements and thin-skinned folding in the Chihuahua tectonic belt, including the Sierra de Juarez (Gries and Haenggi, 1970; Gries, 1979). Upper Cretaceous marine and non - marine rocks, having a thickness of 980m (Seager and Mack, 1994) have been preserved in Laramide intermontane basins. Greater thickness of uppermost Cretaceous and lower Tertiary conglomerates, redbeds, and sandstones are present in the same basins (Doyle, 1951; Kelley and Silver, 1952; Bushnell, 1953; Zeller, 1965, Seager, 1981).

Important changes in plate tectonic regimes occurred in the southern Cordillera between Triassic to Jurassic time (Figure 1.1). These changes were caused by major global plate tectonic transitions during the break up of Pangaea (Dickinson, 1981). Coney (1978) postulated a major subduction related arc system trending northwest southeast across southwest Arizona and into Sonora and Chihuahua in the early Mesozoic. This, a 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 (Silver and Anderson, 1974).

The Chihuahua trough was the major structure during mid - Mesozoic time. This basin followed essentially the same trend as the Pedregosa Basin, but it was more extensive, especially to the south where it extends into the state of Durango. During mid - Mesozoic rifting (Figure 1.2), the Gulf of Mexico subsided, allowing marine waters to advance northward around the Coahuila Platform and into the growing Chihuahua trough (Dickinson, 1981). The maximum transgression of these deposits marked by the clastics of the Bisbee Group in southeast Arizona.

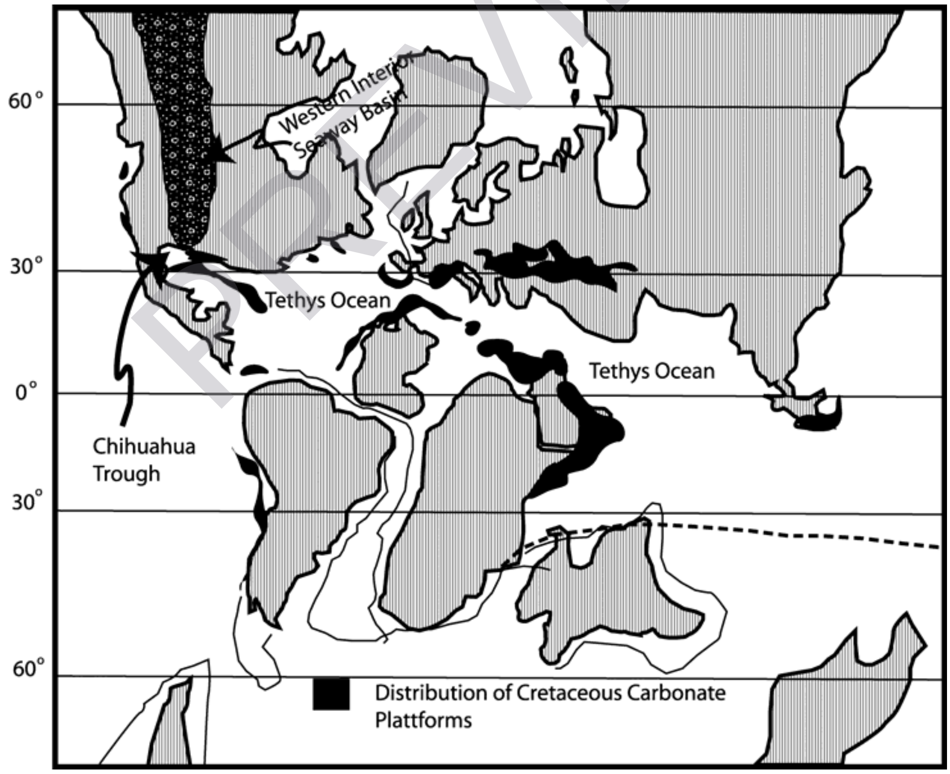

Figure 1.1.Distribution of major basins in North America during the Cretaceous. The Chihuahua trough was influenced by the tropical water of the Tethys Ocean (modified from Barron and Washington, 1981).

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 rift 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 (Figure 1.2). Muehlberger (1980) also postulated a reentrant into the eastern part of the Big Bend area because Laramide structures there are similar to those along the margin of the trough. The normal faults were subsequently buried by a thick Cretaceous sequence, but Uphoff (1978) interpreted drill hole data documenting the existence of one of these faults beneath the Hueco Bolson alignments just southeast of El Paso, TX. These normal faults are important because they determine the geometry of the sedimentary basin and helped control the location of Laramide deformation.

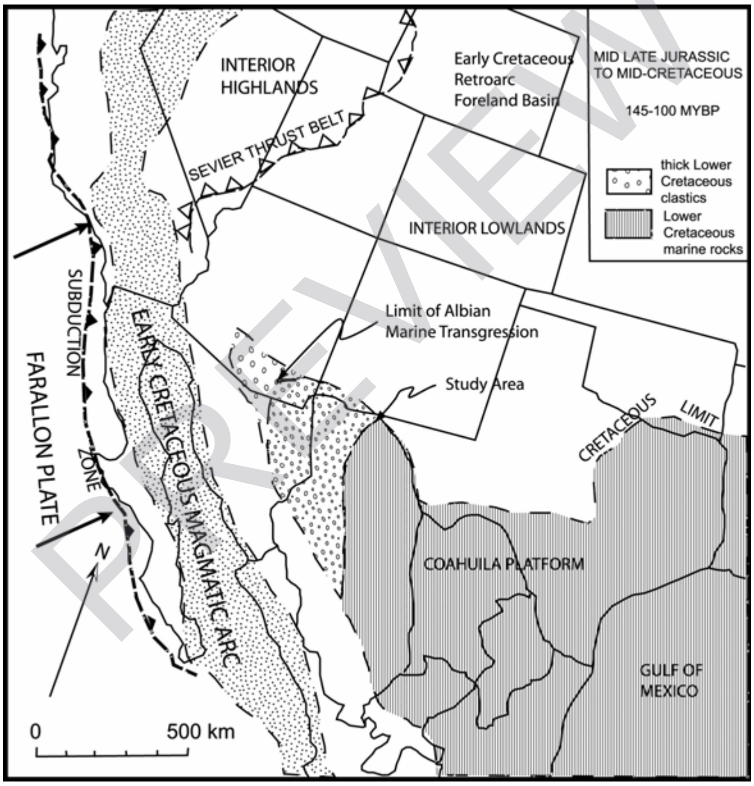

Figure 1.2. Paleotectonic features of the Chihuahua trough during the late Jurassic to middle Cretaceous time. The area of study is marked in the map (modified from Dickson 1981).

Jurassic evaporates are the oldest known deposits in the Chihuahua trough; a thick sequence of mostly Cretaceous marine sedimentary rocks subsequently filled it. Deposits thicken from the Diablo Platform (300 to 600 m thick), into the trough (up to 4,000 m thick) in Chihuahua (DeFord, 1964) (Figure 1.3). Minor Paleocene and Eocene rocks appear in the Big Bend National Park and in

southern New Mexico belonging to the Love Ranch Formation. These rocks are syntectonic with Laramide deformation.

From the late Cretaceous to early Tertiary, during the Laramide orogeny, volcanism and intense deformation dominated the tectonic regime of southwestern North America and plutonism also occurred (Coney, 1978). The Laramide compressive event is the most extensively documented compressive event in Chihuahua. This compressional event is probably due to an increase in the convergence rate of the Farallon plate as it subducted beneath North America (Seager and Mack, 1985).

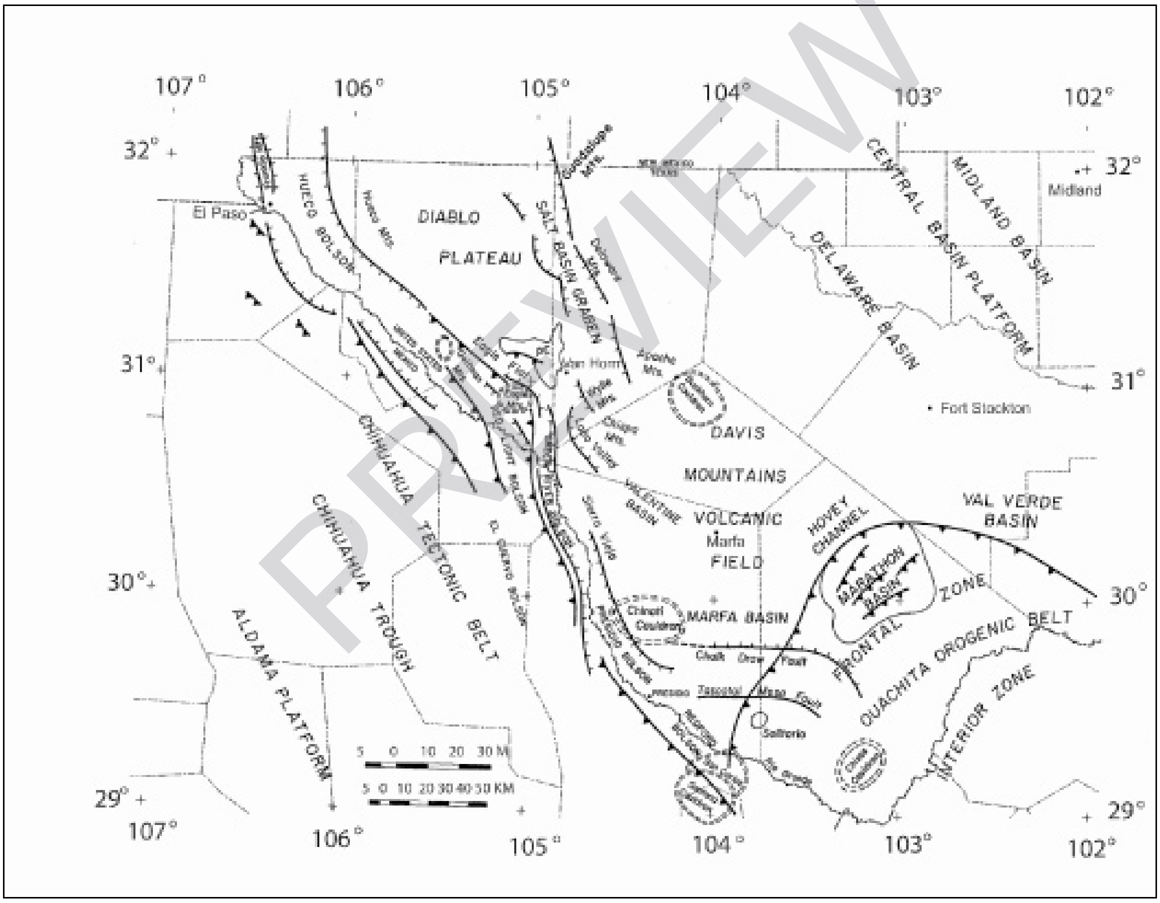

Figure 1.3. Index map of tectonic features in west Texas. Circular features indicated by double-dashed lines are calderas (modified from Keller et al., 1985).

In eastern and southeastern Chihuahua, Laramide structures are well documented from the Sierra de Juarez south along the Rio Grande to the state of Coahuila (Fries, 1960; Bridges, 1962; Gries and Haenggi, 1970; Lovejoy, 1980). It is very likely that basement is involved in deformation

along much of the Chihuahua trough and southern New Mexico. It is recognized both locally and regionally that the thick – skinned deformation is restricted in places where the Cretaceous rocks are absent or very thin (less than 300 m). The thick sequences of marine lower Cretaceous strata that were deposited in the Chihuahua trough are thrust northeast producing folds.

Laramide deformation, produced north and northwest trending thrust faults, folds, and monoclines along the previously established margin of the Chihuahua trough (Gries and Haenggi, 1970) and along the reentrant into the Big Bend area (Muehlberger, 1980). The Laramide fold belt in Texas and Chihuahua is commonly called the Chihuahua tectonic belt. The sedimentary rocks piled up against the stable Diablo Platform so that the most intense structures, such as low angle thrusts and overturned folds are along the boundary between the platform and the trough. In addition, high angle reverse faults, some strike slip faults, monoclines, and broad anticlines and synclines extend out into more cratonic parts of Trans-Pecos Texas. For example, high angle reverse faults bound parts of the Franklin Mountains near El Paso (Harbour, 1972; Lovejoy and Seager, 1978) and the Santiago Mountains north of Big Bend National Park (Muehlberger, 1980).

There are different hypothesis concerning the Laramide folding. Wilson (1971) stated that the major episode of Laramide folding occurred in the Late Paleocene in the Big Bend area and probably throughout Trans-Pecos Texas. He showed that sedimentologic evidence of significant deformation first appeared in lower Eocene deposits. Maxwell et al. (1967) postulated several episodes of folding, with the primary one 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.

Today Laramide structures and sedimentary rocks are exposed only in Basin and Range fault blocks and then only where the volcanic or sedimentary cover has been removed by erosion (Seager and Mack, 1985). Strike slip movement on some Laramide faults has been recognized (Seager, 1981).

1.2 Purpose of this work

This dissertation is organized in two parts: Laramide and Rio Grande rift structures, each part is presented as separated articles. In Chapter 2, I present the results of a study of the Laramide structures in southern New Mexico, the style of deformation and tectonic relations between the geometry of the basin and the stress field is the principal focus of my work. In Chapter 3, I present an analysis of the extensional structures in order to obtain insights about the nature of the low angle normal faults and the tectonic relations of the Rio Grande rift structures. Both studies are based on geometric analysis and paleostress analysis from fault slip data.

As a final remark, I should note that this region is very complex, mainly because most of the structures are deeply buried beneath volcanic and associated deposits during the Neogene and later uplifts and basin extensional formations. Thus, new quantitative techniques, such as those presented in this work, will give new insights about the tectonic history of this region.

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Chapter 2

Tectonic Evolution of the Northern Chihuahua Trough: Evidence for Anisotropy Controlled Deformation during Basin Inversion

Abstract

The Chihuahua trough is a deep sedimentary basin of Mesozoic age that lies along the U.S.A - Mexico border. Laramide crustal shortening strongly deformed the basin resulting in basin inversion as Cretaceous and Permian rocks of the basin interior were thrust onto Precambrian and Lower Paleozoic rocks of the adjacent Diablo Platform. Style of deformation changes from motion on moderate to low angle thrust and reverse faults within the interior of the basin to basement involved reverse faulting on the adjacent platform. Shortening directions estimated from the geometry of folds and faults and inversion of fault slip data indicate that both basement involved structures and faults within the basin record a similar Laramide age deformation field. Map scale relationships indicate that motion on high angle basement involved thrusts post dates low angle thrusting. This is consistent with the two sets of faults forming during a single progressive deformation with in - sequence - thrusting migrating out of the basin onto the platform.

As the style of deformation changes from the basin interior to the platform, the intensity of crustal shortening decreases from >50% within the basin interior to <20% in reverse faulted regions. Low angle thrusts sole into detachments located in shale and evaporate horizons within Pennsylvanian, Permian, and Jurassic rocks which are absent on the platform. These observations show that Laramide shortening was focused in the relatively weak sedimentary rocks of the Chihuahua trough which piled up on the rigid basin margin. Along strike variations in shortening direction and kinematics are controlled by the curved northeast margin of the trough and reflect stress reorientation along the weak interface between the strong platform and weak basin interior. These processes were wide spread affecting the 300 km long eastern margin of the Chihuahua trough between El Paso and the Big Bend region of west Texas.

2.1 Introduction

The Chihuahua trough is a major sedimentary basin located in the southern part of the North American craton (Figure 2.1). This basin was intensely deformed by contractional structures associated with the Laramide orogeny and extensional structures related to the Rio Grande rift. This paper focuses on Laramide structures which inverted the Chihuahua trough during the late Cretaceous and early Tertiary. Only a few descriptive models (Haenggi, 2001) have been presented to explain the tectonic evolution of the trough. In order to investigate the processes of basin inversion I reconstructed the tectonic history by means of dynamic, kinematic and geometric analysis. This study is based on structural geology of the faults and folds, detailed mapping of East Potrillo, Franklin Mountains and Cerro de Cristo Rey and compilation of the large amount of geological data now available for this region (Zeller, 1970; Harbour, 1972; Corbitt and Woodward, 1973; Seager, 1975; Lovejoy, 1976 and 1980; Brown and Clemons, 1983; Kelly and Matheny, 1983; Seager and Mack, 1985; Drewes and Dyer, 1993; Seager and Mack, 1994; Cather, 2001; Rohrbaugh, 2001; Wu, 2002).

One of the striking features of the Chihuahua trough and much of the Laramide foreland in New Mexico and Colorado is that deposition of marine clastic successions continued until Maastrichtian time (Jones et al., 1998; Seager and Mack, 1985) just prior to the onset of Laramide shortening. Thus, much of the Laramide foreland is composed of a relatively thin marine sedimentary wedge (Coney, 1978; Jones et al., 1998). The Chihuahua trough is one of the thickest sections of Lower Cretaceous rocks within the Laramide foreland and greatly influenced the style of deformation in southern New Mexico, west Texas and northwestern Chihuahua (Seager and Mack, 1985). I show that the variation in structural style between basement involved faulting in southern and southwestern New Mexico and thin skinned thrusting within the Chihuahua trough is caused by changes in thickness of the Mesozoic cover thus helping to explain contrasting views of this part of the Laramide orogen (Seager and Mack, 1985; Drewes, 1982; Corbitt and Woodward, 1973).

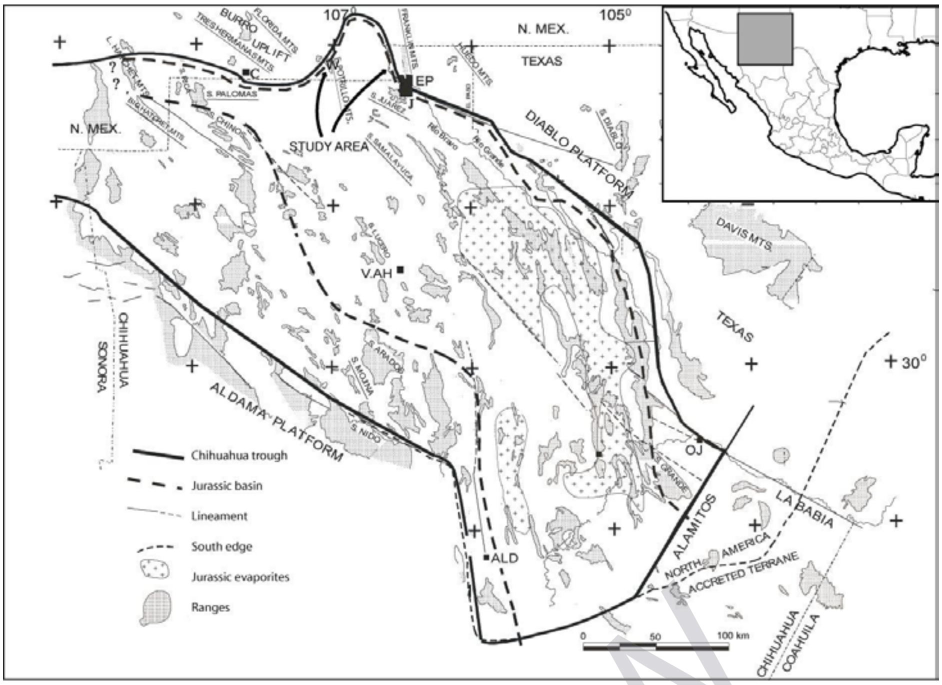

Figure 2.1. Geological features of the Chihuahua trough. The current boundaries are the Aldama and Alamitos platform at the south and the Diablo Platform at the north. Villa Ahumada (V.AH), Ojinaga (OJ), Aldama (ALD), Van Horn (VH and El Paso (EP) are indicated (after Haenggi, 2001).

2.2 Geological Setting

The Laramide orogen of western North America is a chain of generally north trending block uplifts stretching from Montana to Mexico (Coney, 1972). These uplifts are generally cored by Precambrian rocks and commonly have high angle reverse faults on one or both margins of the uplifts which root into subhorizontal detachments at depth (Erslev and Rogers, 1993). Laramide deformation is generally bracketed to have occurred between the late Cretaceous (~85 Ma) and the Eocene (~36 Ma) (Bird, 1998). The earliest Laramide deformation overlaps in time with the end of thrusting within the Cordilleran orogenic belt (Bird, 1988). Several models have been proposed to drive Laramide orogenesis including, low angle subduction (Dickinson and Snyder, 1978; Bird, 1988), detachment and delamination within the crust (Oldow et al., 1990; Erslev, 1993), collisional orogenesis (Maxson and Tikoff, 1996), extension within the Sevier hinterland (Livaccari, 1991), rotation of the Colorado Plateau (Cather, 1999) and lithospheric buckling (Tikoff and Maxson, 2001). All of these mechanisms attempt to explain the transmission of stress well into the plate interior causing deformation of the foreland.