Stratigraphic Controls on the Structural Evolution of the Sierra Madre Oriental Fold-thrust Belt, Eastern Mexico

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A Thesis Presented to the Faculty of the Department of Earth and Atmospheric Sciences

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Geology

By

Zachary David Wolfe

May 2012

Stratigraphic Controls on the Structural Evolution of the Sierra Madre Oriental Fold-thrust Belt, Eastern Mexico

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Dedication

To Iris, my beautiful and supportive wife

Acknowledgements

I would like to thank Dr. Michael Murphy of the University of Houston. Throughout my educational career at UH, Dr. Murphy has provided countless words of wisdom and advice in my studies and my own personal education. I am greatly appreciative for his insight and energy spent in teaching me. I would also like to thank Dr. Paul Mann of the University of Houston; through his research group, the Caribbean Basins, Tectonics, and Hydrocarbons (CBTH) consortium, I was able to produce the quality interpretational figures seen in this thesis.

Special acknowledgement goes to Dr. Ricardo José Padilla y Sánchez of the Universidad Nacional Autónoma de México (UNAM), who acted as an outside committee member and whose previous work in Mexico has provided a lasting document which has withstood the test of time.

Throughout this research I found help from many people who gladly provided me with information which made the work ever more enjoyable. Dr. Veronica Sánchez of the University of Houston always provided assistance with the utmost patience, and I thank her for her time. Thanks go to the members of the CBTH group for your hospitality, and inviting me to take a synergistic place within the group. Thanks to Murad Hasan for his knowledge of ArcGIS. Thank you to Dr. John Casey for taking the time to make a difference early on in my bachelor's career. Thank you to the entire faculty at the University of Houston who helped to shape my educational experience and as well prepared me for the demands of completing this thesis work. To Connie VanSchuyver for being a great mentor of geophysics as well as a great friend.

Thank you to Dr. Yong Zhou, for completing the initial works which guided and shaped my role in the project.

I would like to thank my wife Iris for her amazing support throughout this project; it would not have been as gratifying without her. Thank you to my family and brothers who have never given up on my ambitions. I have always been able to count on you for support.

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ABSTRACT

Late Cretaceous–Paleogene Laramide shortening within the Sierra Madre Oriental fold-thrust belt (SMO) along the western margin of the Gulf of Mexico is the product of shallow subduction of the Farallon plate beneath the western margin of Mexico. Changes in detachment strengths during this thin-skinned shortening episode created alternating salient and recesses along the 1500-km strike of the SMO that include the ~200-km-long Potosi recess located southwest of the city of Ciudad Victoria. I propose that the observed orogenic curvature of the SMO is controlled by evaporite remobilization by the Laramide thrust detachment evaporates. Salients of the SMO are underlain by evaporates while areas like the Potosi recess lack underlying evaporites. In addition to these stratigraphic controls of the SMO, the linear frontal thrusts of SMO were influenced by inversion of a linear, pre-existing rift of Jurassic age and by thrusting of weak Upper Cretaceous shales.

In this study I used previously published geologic maps, well data, and new interpretations of satellite and magnetic data to provide insights into the formation of the Potosi recess. Results of this study include the following: 1) Frontal thrusts along the leading edge of SMO dominantly occur along weak Upper Cretaceous shales and are located above a partially inverted and linear Jurassic rift system related to the opening of the Gulf of Mexico; 2) Salients north and south of the Potosi recess are controlled by the presence of two salt bodies known from well data compiled in this thesis; 3) Topographic variation and previous thermochronologic studies along the leading edge of the SMO suggest that a late stage (30-40 Ma), thick-skinned Laramide event inverted the Jurassic rift system at differing amounts along its strike.

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History of this Project

As an undergraduate geology major at the University of Houston I visited the Parras Basin located within the western limb of the Monterrey Salient of the Sierra Madre Oriental, I realized that I had many unanswered questions regarding the origin of these magnificent structures. I found that much of the work performed previously relied heavily on field data and very little from subsurface information (e.g. seismic reflection and well data). This left little option for data generation but did however necessitate the development of thorough research.

Dr. Michael Murphy of the University of Houston specializes in the structure and tectonics of the Tibetan Himalayas as well as research interests in Mexico. Dr. Murphy along with Dr. Yong Zhou and Ali Hamade made advances in the structural regimes of the Peregrina-Huizachal Anticlinorium and Aramberri, respectively (Zhou et al., 2006). After inquiring on opportunities to work on aspects of this field area I was given permission to do so.

This thesis was an extension of these earlier studies. While I did not conduct original field work for this thesis I did compile the work of Zhou et al. (2006) along with adding information on the strike and dips of bedding and contact validation when needed using SPOT, SRTM; and ASTER satellite imagery. Incorporation of subsurface data taken from previously published work by Mexican geologists also added value to this research.

Introduction

Most, if not all, fold-thrust belts in the world display curved geometries in map-view. The Sierra Madre Oriental (SMO) fold-thrust belt is a natural laboratory for understanding how fold-thrust belts become curved because: 1) it displays a variety of distinct curved geometries; 2) it hosts most of the primary factors identified to influence map-view curve development; and 3) it is well-exposed and accessible. The Sierra Madre Oriental fold–thrust belt (SMO) is 1500 km long and extends along the east coast of Mexico (Figure 1). Geologic maps show that variations exist in the structural trend of the SMO and can be used to delineate several regions that display distinctive map-view fold patterns. Among the many intriguing structural relationships, one stands out in east-central Mexico. In this region the SMO fold-thrust belt displays a curved geometry in the hinterland and a linear geometry in the foreland. The curved hinterland consists of a pair of salients flanking a recess, here named the Potosi Recess (Figure 1). The linear thrust belt in the foreland is referred to as the Mante structural belt (Figure 1). Existing models describing the geometric and kinematic development of map-view curves do not readily explain these differences. Various mechanisms for the formation of thrust salients have been proposed by Macedo and Marshak (1999) (Figure 2). These models describe the formation of salients by variations in: 1) the thickness of the thrust sheet; 2) the strength in the basal detachment; and, 3) presence of “rigid” objects in the foreland. This research investigates the structural development of this transition between the Potosi Recess and the Mante Structural belt. In addition, this research assesses the applicability of these previously proposed models to this structural transition.

A

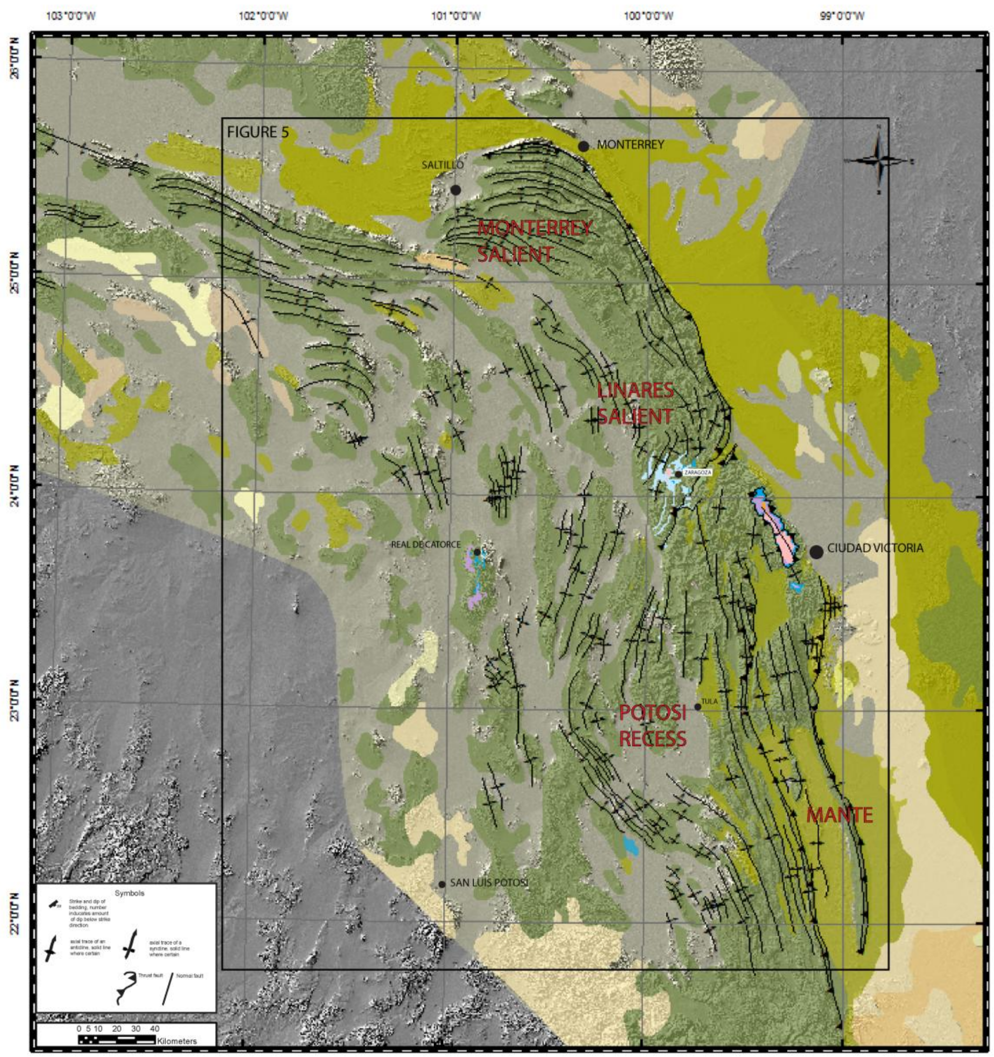
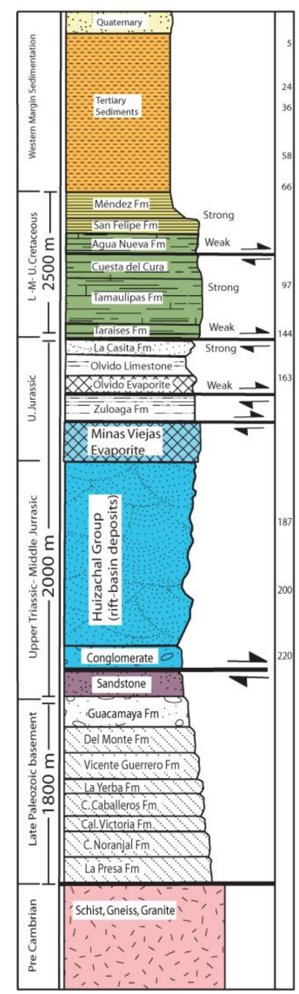


Fig. 1. (A) Regional geologic map on SRTM overlay, showing main structural features, including structural domain locations and names; (B) generalized stratigraphic column for the region.

B



FIGURES 1, A & B

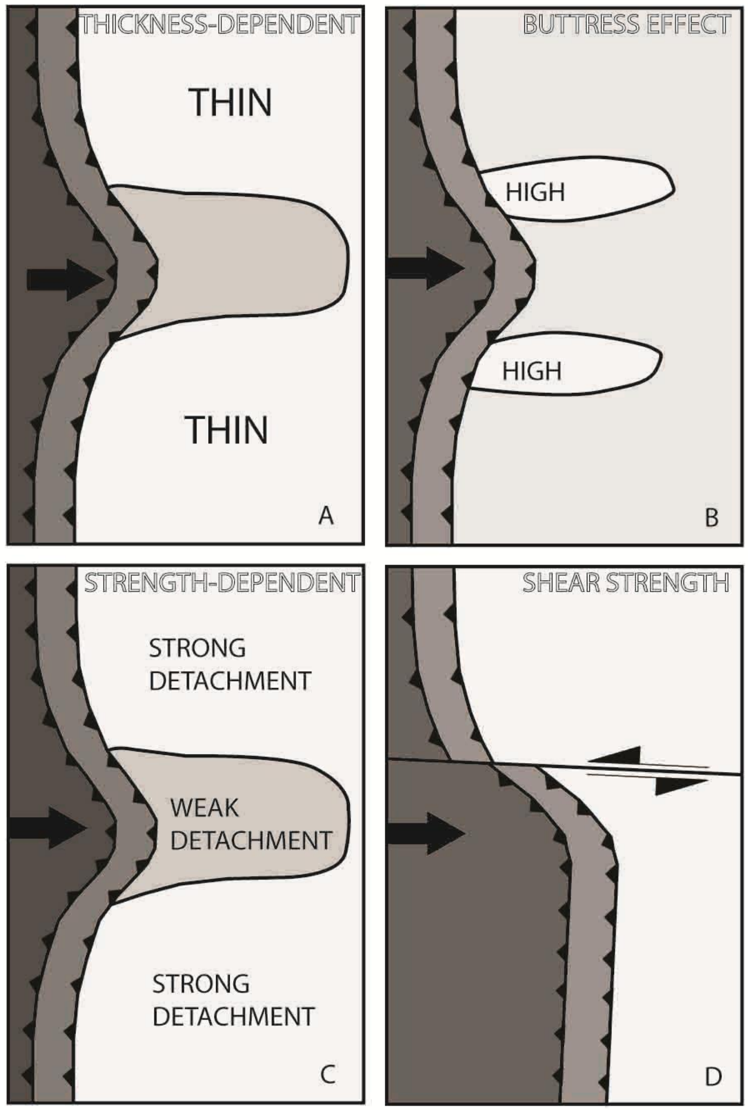


Fig. 2A-D. Models for salient and recess formation in fold-thrust belts modified from Macedo and Marshak, 1999. (A) sediment thickness dependent indenter; (B) buttress indenter; (C) strength dependent indenter; (D) reactivation of pre-existing basement fault.

Regional Geology

Our current understanding of the geologic framework of Mexico suggests that the Mesozoic paleogeography may have had a significant impact on the subsequent development of the SMO passive margin. Field investigations in eastern Mexico suggest that both Late Triassic-Middle Jurassic rift basins and Early Cretaceous carbonate platform build-ups and associated evaporite deposits need to be considered as factors influencing the spatial distribution of contractional deformation (Eguiluz de Antuñano et al., 2000).

Structural evolution and environments of deposition

The Sierra Madre Oriental lies between the late Cretaceous-Paleogene Laramide compressional-related tectonics being experienced on the western coast of Mexico (Goldhammer, 1999; Dickinson and Lawton, 2001) and Jurassic-Cretaceous extensional tectonics related to the opening of the Gulf of Mexico on the eastern coast of Mexico (Salvador, 1987) (Figure 1A). This created a paleogeography of many positive and negative relief areas throughout the region.

Late Triassic – Middle Jurassic extension

During the Late Triassic through Middle Jurassic, deposition of continental fluvial, alluvial and at times volcanic epiclastic hematitic sediments occurred within the developing rift graben (Figure 1B). These red beds known as the Huizachal Group were deposited directly atop the Precambrian and Paleozoic basement rocks (Salvador, 1987), similar to those of the Marathon Uplift (Mixon et al., 1959). Rifts are thought to trend north-northwest and is interpreted to result from back-arc extension associated with the convergence along the western coast (Goldhammer, 1999; Dickinson and Lawton, 2001), as well as extension associated with opening of the Gulf of Mexico (Salvador, 1987). Rift structures are present in various locations throughout Mexico. Areas near Ciudad Victoria, Zaragoza, Miquihuana, and Villa de Bustamante are just a few example locales which offer a structural window into the basement architecture of Mexico (Mixon et al., 1959; and Zhou et al., 2006). The locations also highlight the local involvement of the basement with respect the deformation history of the region, since great thicknesses of deformed sedimentary rock surround these basement outcrops (Figure 3).

Middle-Late Jurassic evaporite deposition and Cretaceous carbonate platform development

The continued development of a passive margin along eastern Mexico took place during the Middle to Late Jurassic as a result of the formation of the Gulf of Mexico (Pindell, 1985; Bird, 2005). Due the rapid and wide spread subsidence of the continental platform, a transgression ensued, exploiting many of the depositional environments available with the negative structures associated with this passive margin. A regionally extensive evaporite was initially deposited throughout central Mexico (Lopez-Ramos, 1985). Named the Minas Viejas (formerly the Metate Formation) and Guaxcama Formations, it forms a semi-continuous patchwork of deposits varying in thickness from 20 meters to greater than 2600 meters in thickness (Basanez-Loyola et al., 1993). As part of the Wilson facies belt, the Guaxcama formation formed at times, contemporaneously with the evaporitic lagoons of the VSLP (Wilson, 1975). Surrounding these extensive deposits were the carbonate lagoon and reefal facies of the El Abra limestone (Minero, 1991; Basanez-Loyola et al., 1993) (Figure 3). Well data show these platform deposits to be highly variable in thickness throughout the region, with the thickest occurrences lying above basement highs. When datumed to the top of the Aptian-Albian transition of the Guaxcama evaporite, wellbore stratigraphy suggests dominance of the thickest deposits of evaporites to be greatest towards the hinterland of the SMO and thin completely to open-shelf and basinal facies within the easterly portion of the focus area. Original thickness based on facies correlation shows the rate of subsidence was greatest towards the east (Basanez-Loyola et al., 1993), representing a slow subsidence along the eastern margin of Mexico.

Late – Cretaceous – Eocene shortening

The Late Cretaceous – Eocene shortening marks the culmination of the Laramide thrusting in this region, driven by shallow subduction of the Farallon plate beneath the North American plate (Goldhammer, 1999; Dickinson and Lawton, 2001). In the southeast region of the SMO, the contact between deformed Late Cretaceous Mendez shale and the undeformed Eocene continental red beds of the (Ahichila and El Morrow Formations) marks the cessation of Laramide shortening in the SMO (Mossman and Viniegra, 1977; Padilla y Sanchez, personal communication). De Cserna (1956) also notes that Upper Eocene strata contains thrust sheet lithologies as well as reworked Lower Eocene conglomerates. This is inferred to mark the timing of uplift and shortening of foreland basin deposits. The foreland basin deposits of the La Popa and Parras basins mark the northern cessation of shortening in the Eocene, inferred by age of sediments within the basin (Soegaard et al., 2003).

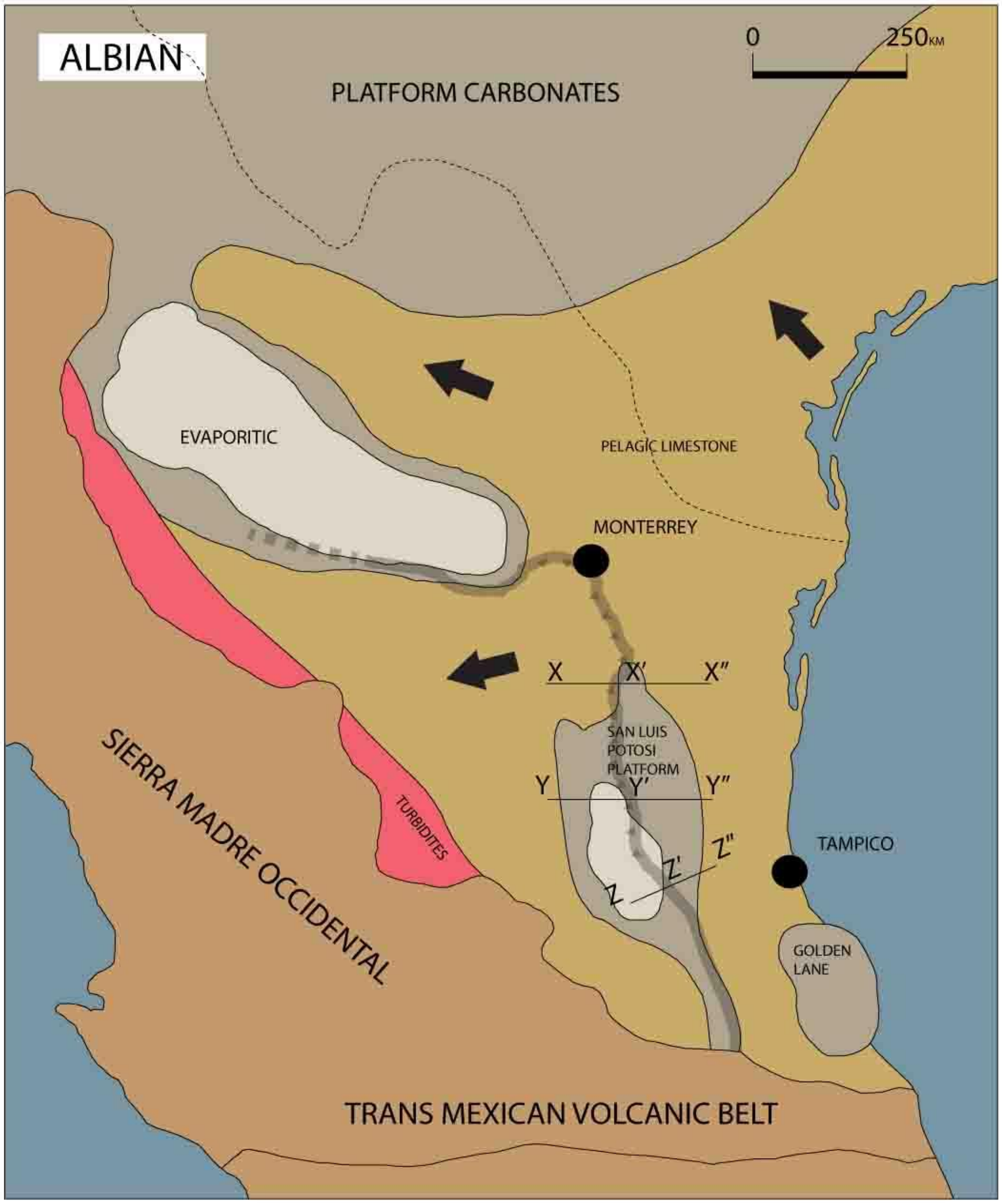


Fig. 3. Regional depositional environment during Albian time showing areas of carbonate platforms and marine incursions from the Gulf of Mexico to form isolated evaporate basins modified from Eguiluz de Antuñano et al. (2000). Lines of section for the focus area shown in figures 7, 8, and 9 are indicated.

Structural Domains – Evidence for thin and thick-skinned deformation

The SMO can be described as consisting of structurally distinct domains as shown in figure 1. These domains are the Monterrey salient, Linares Salient, Potosi Recess, and Mante (a zone of linear thrusts). The development of the SMO is interpreted to be controlled by the presence of basement highs located at the SMO deformation front. These basement highs include; the Coahuila block, remnants of the Tamaulipas Peninsula, as well as the Tamaulipas Archipelago relict blocks (Kellum, 1936; Humphrey, 1956; Padilla y Sanchez, 1982).

The Monterrey salient is composed of dominantly of arcuate northeast-vergent folds. The salient forms a well-known promontory into the foreland basin.

The Linares Salient lies south of the Monterrey Salient and contains similar folds and is also bound by frontal thrusts. This salient however projects to the east and represents both the smooth transition and an abrupt change to the last of the two structural domains of interest, the fold trend of the Potosi recess, and the linear structural-belt stretching from Peregrina some ~200 km south-southeast.

The Potosi Recess is separated from the Linares Salient by curvilinear, parallel folds, exhibiting a northeast structural grain. The recess is positioned directly west of Tampico, Mexico, approximately 200km and overlies much of the Valles San Luis Potosi Platform (~70%), (Basanez-Loyola et al., 1993).

Moving east from the interior of the Potosi Recess, a transition occurs, in that the concave to foreland curvature becomes linear as seen in figure 1A, and 6. The structural domain of the linear trend towards the foreland contains the highest concentration of thrust faults within the entire SMO fold-thrust belt.

Stratigraphic Description

The recess involves predominantly (Figure 4) carbonate strata are deposited unconformably on Precambrian crystalline basement and Triassic-Jurassic siliciclastic rocks.

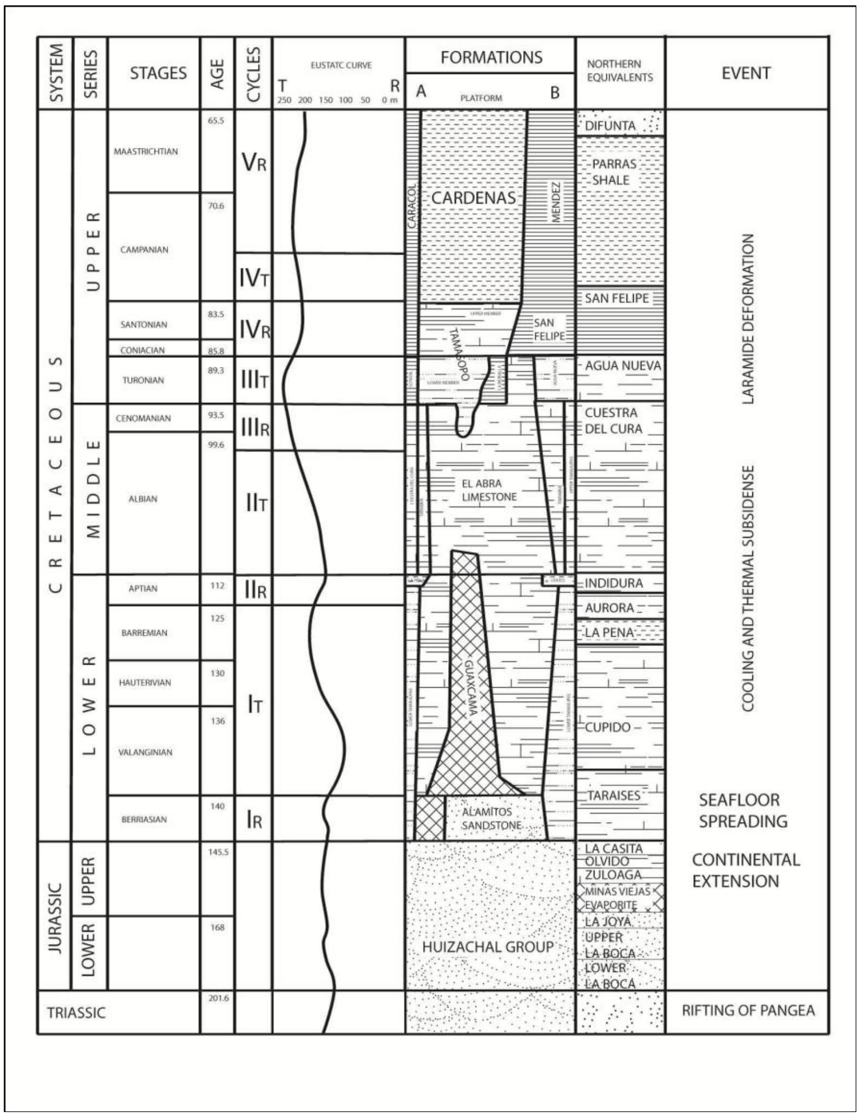


Fig. 4. Stratigraphic column of lithologies found within the Potosi Recess focus area along with main tectonic events. Modified after Basanez-Loyola et al., 1993; Goldhammer, 1999; and Bird, 2005.

Basement rocks

The basement is composed of Precambrian schist and gneiss (de Cserna, 1956; Lopez-Ramos, 1982; Padilla y Sanchez, 1982; Zhou et al., 2006). Crystalline basement rocks in the study area crop out at four localities, Peregrina-Huizachal anticlinorium, Aramberri, Miquihuana, and Villa de Bustamante, but a others have been studied to the north of the field area (de Cserna, 1956). By far, the largest basement outcrop is located in the Peregrina-Huizachal anticlinorium and represents a structural window to the basement (Figure 5). No basement outcrops are known to exist in the study area south of Villa de Bustamante, but there basement present in well data.

Huizachal Group

The continentally derived Huizachal Group stratigraphically overlies the Precambrian crystalline rock of the basement. Inter-mixed with volcanic materials of the Nazas volcanic arc, these non-marine sediments record a period in the development of the region which highlights rapid basement extension and syn-tectonic deposition of horsts and volcanic arc material. These rocks have been determined to be of Late-Triassic to Jurassic age by thermochronologic (Barboza-Gudiño et al., 2010), and by paleontologic methods (Humphrey, 1956; Mixon et al., 1959).

This red bed sequence, the Huizachal Group consisting of the upper and lower La Boca Formations, capped by the La Joya Formation. The Huizachal outcrops are located in the far northern region of the VSLP platform, while subsurface showings have been reported in well data within the Mante structural-belt. (Imlay, 1948; Salvador, 1987; Basanez-Loyola et al., 1993).

Measurements within the red beds show a highly variable thickness. Thickness variations are interpreted to reflect deposition within half-graben (Salvador, 1987; Zhou et al., 2006). The base of the Huizachal Group is comprised of a conglomeratic material grading into angular clastic fluvial and alluvial deposits of braided streams and continental fan deposits, the red beds in the Huizachal Group are separated into two formations, the La Boca and overlying La Joya. They are separated by an angular unconformity (Imlay et al., 1948; Padilla y Sanchez, 1982; Barboza-Gudiño, 2010; Rubio-Cisneros, 2011). The La Boca Formation is overlain by the La Joya Formation with an angular discordance of ~5 degrees (Kroeger, et al., 2003) the La Joya consists of multi-colored clasts, although more subangular than found in deeper units.

Minas Viejas Evaporites and Guaxcama

The Gulf of Mexico basin is well known for its large deposits of gypsum and anhydrite. The study area of the Potosi Recess lies within the passive margin at the western margin of the Gulf of Mexico basin, and experienced a great magnitude of evaporite deposition as well. Two evaporitic formations are importance to Potosi Recess study area, they are the Oxfordian Minas Viejas Formation, and the Aptian-Albian Gauxcama Formation.

Minas Viejas Evaporite

A thick sequence, known as the Minas Viejas Formation (formerly the Metate) was deposited in Mexico during the Oxfordian as a result of the developing Gulf of Mexico basin; tongues of this formation reached into the passive margin environments of the study area. The Minas Viejas Formation is the age equivalent to the Louann evaporite in the northern Gulf of Mexico margin of the United States and the Louann counterpart of the Campeche formation located in the southern Gulf of Mexico within the sediments of the Yucatan peninsula (Salvador, 1987). Thicknesses range from meters to ~1500 meters throughout the region (Goldhammer, 1999). In the town of Zaragoza at the northern portion of the field area, the thicknesses are ~300 (Hamade, 2006).

Guaxcama Formation

The Aptian-Albian Guaxcama Formation is a laterally variable deposit of gypsum and anhydrite which is found throughout the southern half of the Potosi Recess. Found only in well data, the unit has not been observed to outcrop at any location in the study area.

The formation is interpreted to have been deposited in an evaporitic restricted lagoonal environment and laterally transitions to the El Abra Formation (Basanez-Loyola et al., 1993).

Carbonate platform rocks

The El Abra Formation represents the majority of the Carbonate platform rocks within the Potosi Recess, these deposits are a dominant part of the Valles San Luis Potosi platform. In the Aptian, the El Abra unit was deposited contemporaneously with the Guaxcama evaporites, but persisted throughout the Middle Cretaceous, effectively burying much of the evaporitic units (Minero, 1991). This unit comprises the most lithologically irregular units, containing subtle to strong lateral and vertical variability (Minero, 1991). Dolomitization which occurred throughout the formation of the platform, occurred preferentially within the western portion of the VSLP platform (Minero, 1991). Differences in diagenesis within the western and eastern zones of the El Abra Formation led to much more compaction in the east than in the west (Minero, 1991).

Hemi-pelagic lithologies

Undifferentiated Upper Cretaceous strata

Corresponding to the Cretaceous (light green unit) of figures, 1A, B, 6, 14A, B, the thick sequence of Cretaceous strata consists dominantly of hemi-pelagic limestones with laminated mudstone sequences, but can include open platform marls. The thickness of the unit is approximated to be as great as 500 - 1200 meters in thickness in the region.

Mendez Shale

The Late Cretaceous foredeep deposits of the Mendez shale represent the stratigraphically highest lithology involved in the deformation within the field area (Imlay, 1937; Padilla y Sanchez, 1982). The marine strata are in depositional contact with the undifferentiated carbonate below. Bedding is well defined within the unit but can be highly deformed when faulted (Padilla y Sanchez, 1982; Marrett, 2002; Zhou et al., 2005; Hamade, 2006). The equivalent to the Parras shale of the Parras basin to the north of the SMO structural front, the Mendez shale signifies a syn-tectonic, off-shore depositional event. Interpretation of the deep-water environment was determined in past works by (Muir, 1936; Padilla y Sanchez, 1982). The unit is distributed as a laterally extensive unit along the eastern edge of the SMO (Figure 1A, 6, 14A-B).

Structural Geology, Effects of Unit Distribution, and Approximate Depth of Basement

Regional cross-sections, well data, and compiled geologic maps were used to investigate the structure of the Potosi Recess. Well data consisted of published well bore and measured section information by Basanez-Loyola et al., 1993; use of these data helped guide the thicknesses in the initial construction of cross-sections for the study area. Regionally, there are four separate structural domains, 1) the Monterrey Salient, 2) Linares Salient, 3) Potosi recess, and 4) a linear structural system near Ciudad Mante towards the eastern foreland of the SMO (Figure 1). Geological map information was compiled from Zhou 2006 (PhD dissertation); Padilla y Sanchez, 1994; Basanez-Loyola et al., 1993; Salvador, 1987; and INEGI, 1982 (Figures 5 and 6). Research was also supplemented with the use of magnetic data procured through the GeoSoft ArcGIS plug-in. The magnetic data was used to define the western margin of the rift boundary. The margin of the rift was chosen based on the inflection from positive to negative magnetic susceptibility.

The structural elements of the Potosi Recess are shown in figure 5. A rift, first identified by Salvador (1987), herein named the East Mexican Rift, borders the eastern region of the study area and trends approximately north-northwest, Also present is the large carbonate build-up of the Valles San Luis Potosi platform (VSLP). The northern section of the study area contains a number of Precambrian crystalline basement outcrops. They are: 1) Peregrina-Huizachal anticlinorium, 2) Zaragoza, 3) Miquihuana, and 4) Villa de Bustamante, each of which is located within the area defined by the East Mexican Rift.

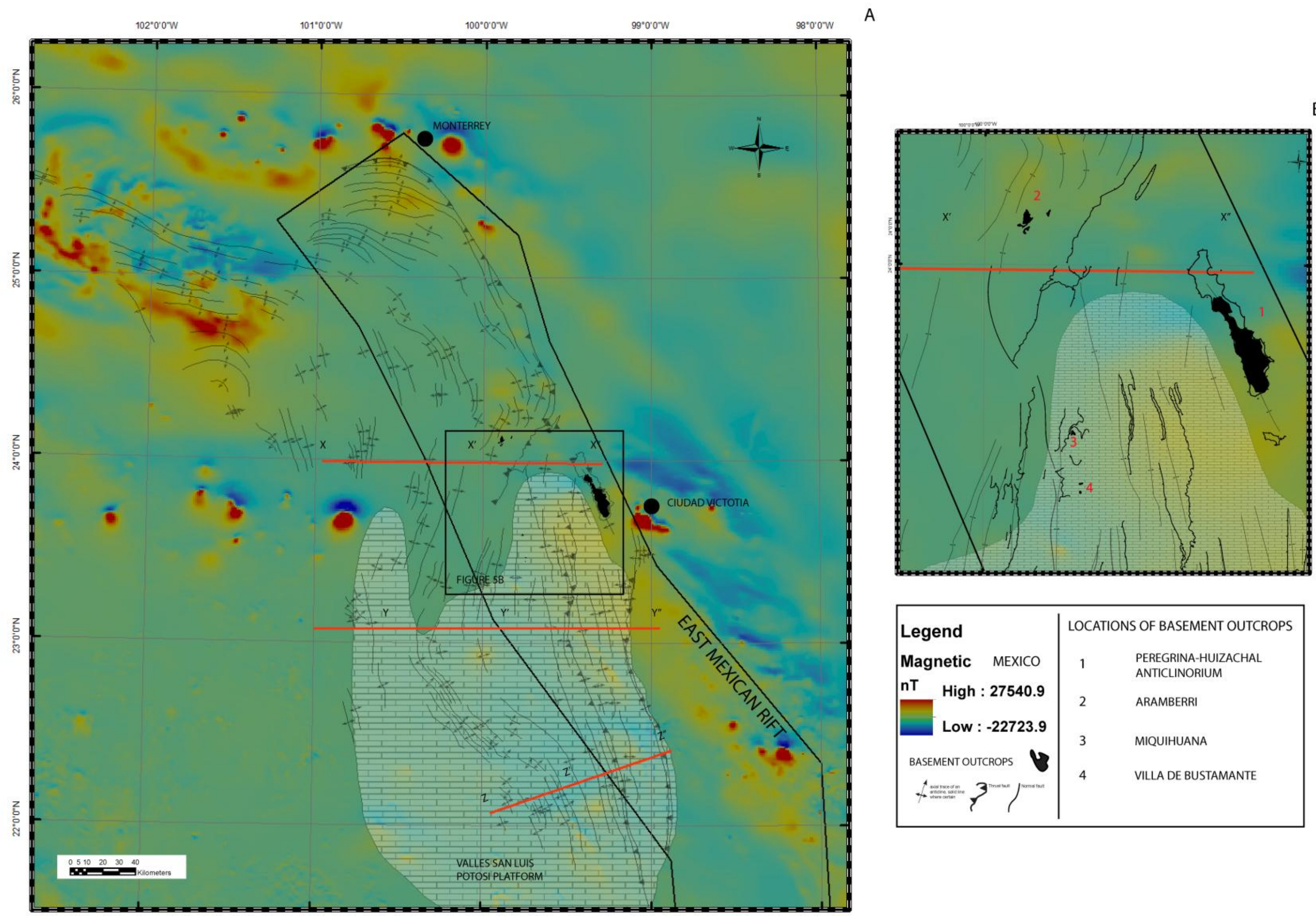


Fig. 5.(A) Structural map of the leading edge of the SMO on aeromagnetic basemap with inferred extent of East Mexican rift shown; (B) Close-up of basement outcrops occurring with the study area.

FIGURE 5A, B

Use of this geological information helped develop a regional geological understanding of the Potosi Recess. The information helped to identify possible depositional influences of the Jurassic rift architecture. The thick evaporitic sequences of the Potosi Recess indicate to us a restricted marine setting occurred for a substantial amount of time. The discontinuous nature of the two evaporite sequences (Minas Viejas and Guaxcama Formations) is interpreted to be the dominant influence on the formation of the Potosi Recess. It is also of note that as the ramp flat geometry increases from west to east, folds are more asymmetric, this can be clearly observed in figure 6. We interpret this to be the combined effects of a more shallow detachment, and of a shallowing basement depth.

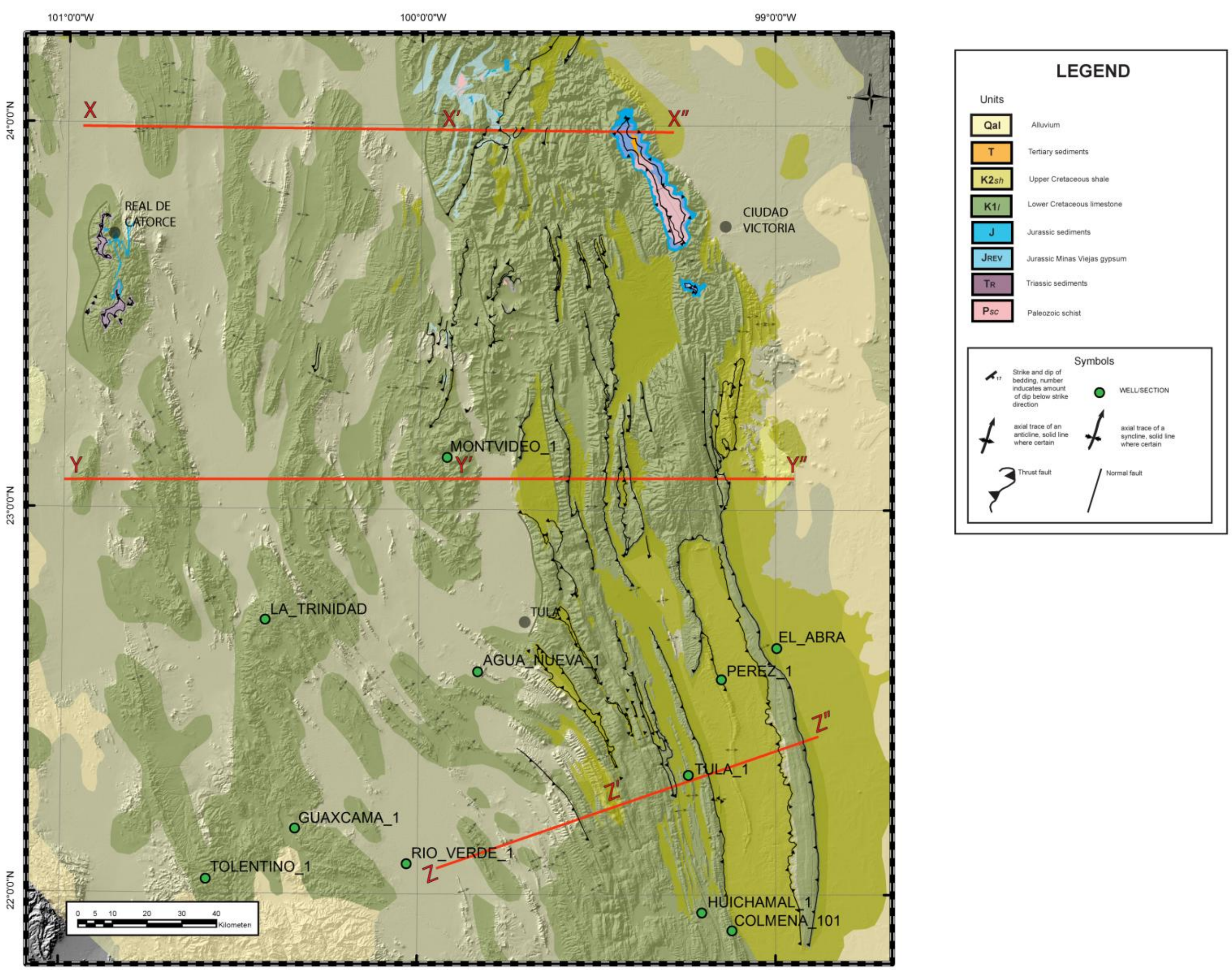


FIGURE 6

Fig. 6. Geologic map of the Potosi Recess modified after Zhou (2006) and Padilla y Sanchez (1994).

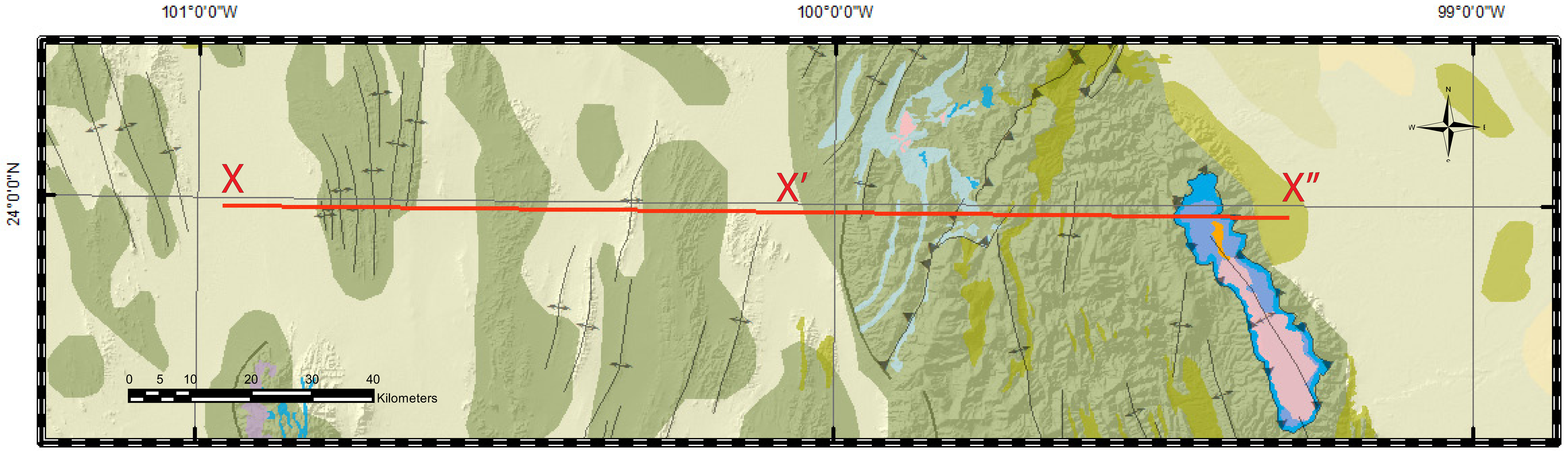
Cross-sections and Analysis

Thicknesses were guided by outcrop data as well as inferences made on sparse well control. Geologic maps, well correlations, and outcrop data from previous workers allowed us to produce models which are in accordance with the available data.

Cross section 1 through northern Potosi recess

Cross section X – X''(Figure 7) highlights broad gentle folds located within the hinterland of the structural belt, while showing well the intense structural styles which developed above, evaporitic (Minas Viejas), shale (Mendez), and continental-derived (Huizachal Group) basement detachment lithologies. In the area of Zaragoza a transition is located between an evaporitic detachment to a shale detachment .This transition correlates to a structural transition between folding and thrusting. As the section continues east to the Peregrina-Huizachal Anticlinorium, thrusting continues to accompany folding until the termination of the thrust front at the foreland basin. Within the Peregrina-Huizachal anticlinorium a basement inversion is shown to have uplifted the area, exposing the Precambrian basement rocks. Within this portion of the Peregrina-Huizachal anticlinorium, Zhou et al. (2006), estimated the inversion to have provide ~3500m of displacement.

A



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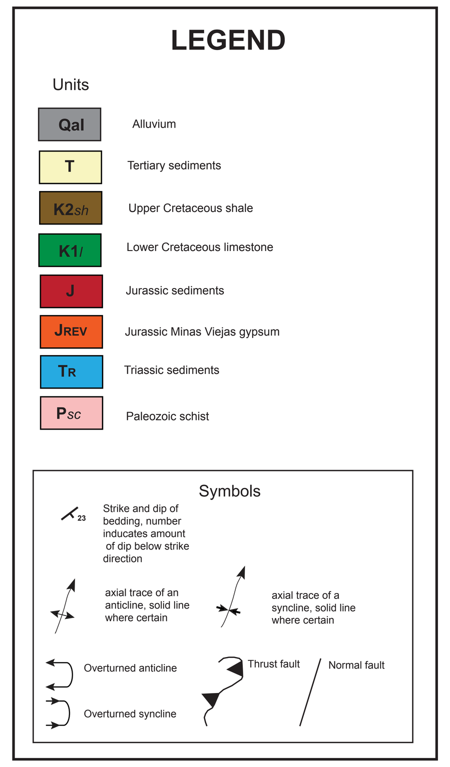


C

EXPLANATION

Cross section X-X'' highlights the thin-skinned deformation experienced in area of the northern portion of the Potosi Recess. As the evaporitic detachment thins and ends abruptly near Zaragoza, the detachment quickly rises to the Upper Cretaceous shale. An inversion of rift related basement blocks occurs in the area denoted as the Peregrina-Huizachal Anticlinorium. The inversion exhumed basement and basement complex lithologies such as the Huizachal Group red beds, as well as older Triassic aged clastics.

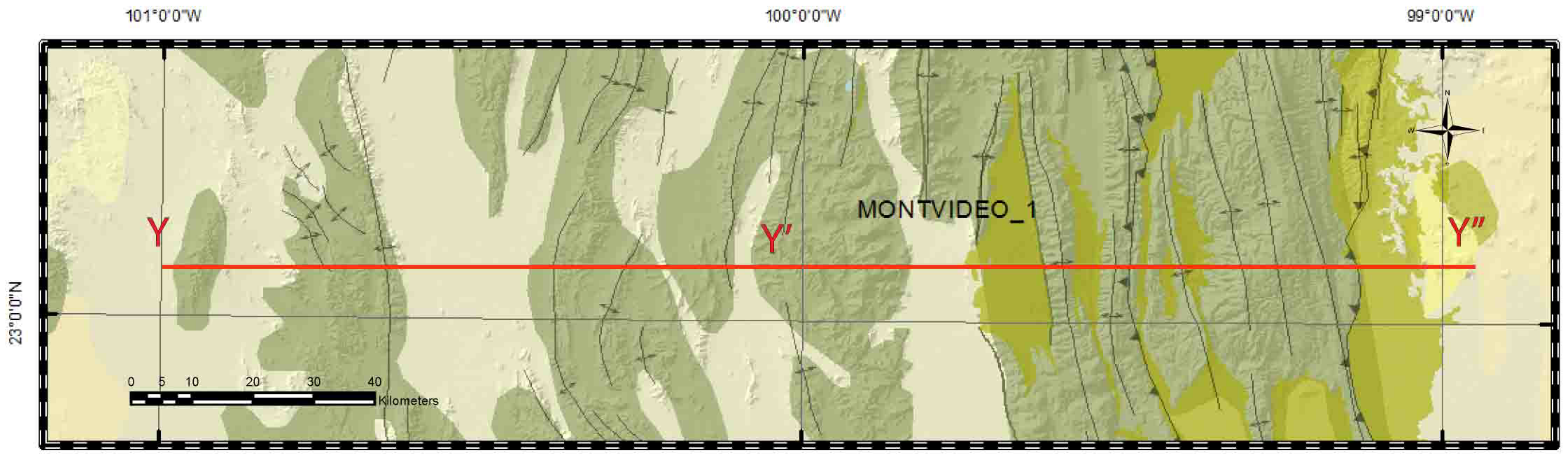
Fig. 7. (A) Cross section X-X'' highlights the thin-skinned deformation experienced in area of the northern area of the Potosi recess. As the evaporitic detachment thins near Zaragoza, the thrust detachment ramps up into Upper Cretaceous shale. Inversion of rift-related basement blocks occurs in the area denoted as the Peregrina-Huizachal Anticlinorium. Inversion exhumed basement and basement complex lithologies such as the Huizachal Group red beds, as well as older Triassic aged clastic rocks. (B) Geologic map for section area; (C) Legend for both map and cross section.

FIGURES 7A, B, AND C

Cross section 2 through central Potosi recess

Cross section Y-Y'' (Figure 8) passes through the apex of the Potosi Recess and shows a slightly greater amount of shortening within the hinterland region. Passing through to the thicker carbonate buildups of the VSLP interior, the Lower Cretaceous unit was modified and thickened by maximum growth stages. This is shown in the well data presented by Basanez-Loyola et al. (1991). Concomitant with the thickening of the Lower Cretaceous platform is a thinning Guaxcama evaporitic detachment. This correspondence also coincides with the initial and dramatic occurrence of thrusting. A jump in the detachment depth from >2km to <1km occurs where the evaporite completely disappears. This jump in detachment depth occurs within the Upper Cretaceous basinal deposits. The Upper Cretaceous units are found laterally throughout the SMO frontal zone, offering a detachment surface for foreland propagation.

B



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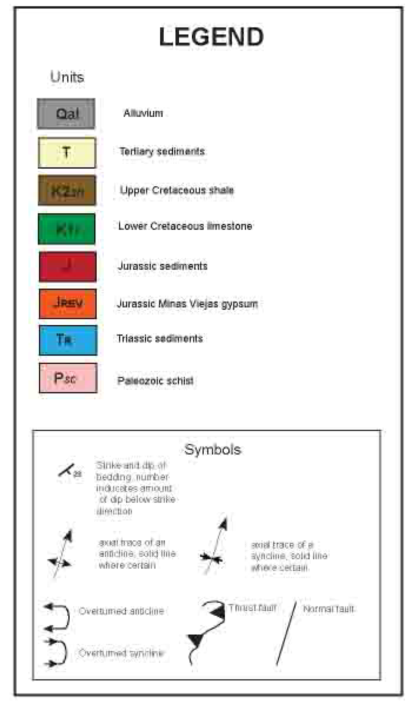


EXPLANATION

Cross section Y-Y" shows folding within the zone of thick evaporitic deposits. Thrusting begins when the thickness of the overlying Lower Cretaceous carbonates reaches that of the evaporitic sequence. As the evaporite sequence thins completely, the detachment is forced to find another weak horizon to accomodate the compressive forces. At this point the Upper Cretaceous shales and marls act as a glide plain. Notice also a shallowing of basement from West to East towards the rift margin.

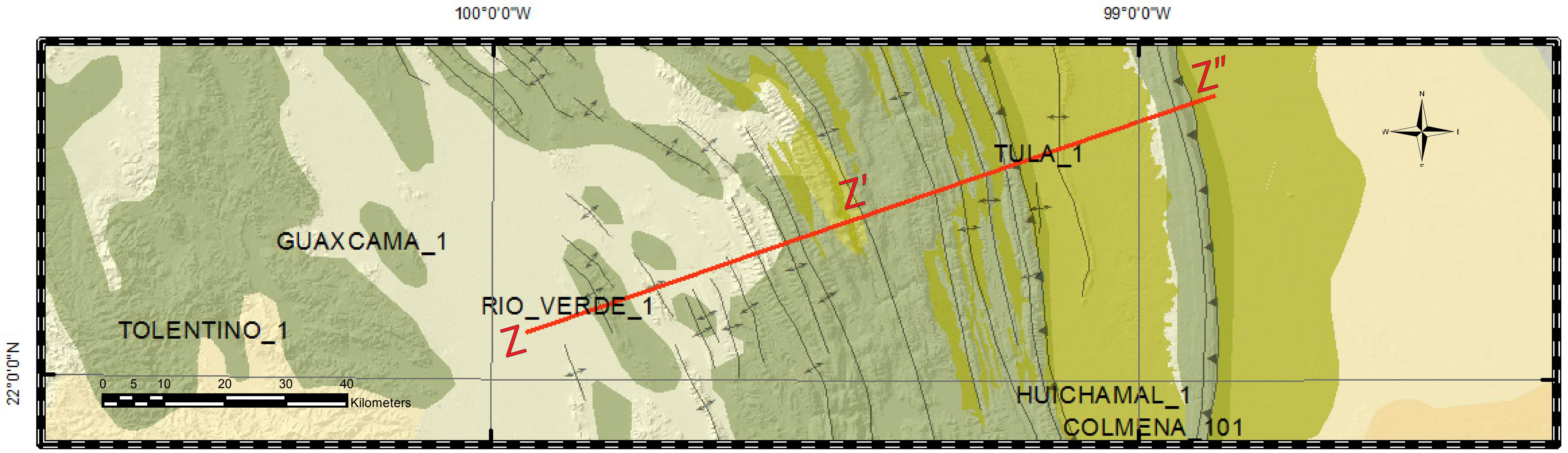
Fig. 8. (A) Cross-section Y-Y' passes through the apex of the Potosi Recess. Cross section Y-Y'' shows folding above the zone of thick evaporitic deposits. In this area, evaporates pinch out the east above a westward-rising basement surface and the basal thrust detachment ramps up from the edge of the evaporites into Upper Cretaceous shale and marl. (B) Geologic map for section area; (C) Legend for both map and cross section.

FIGURES 8A, B, AND C

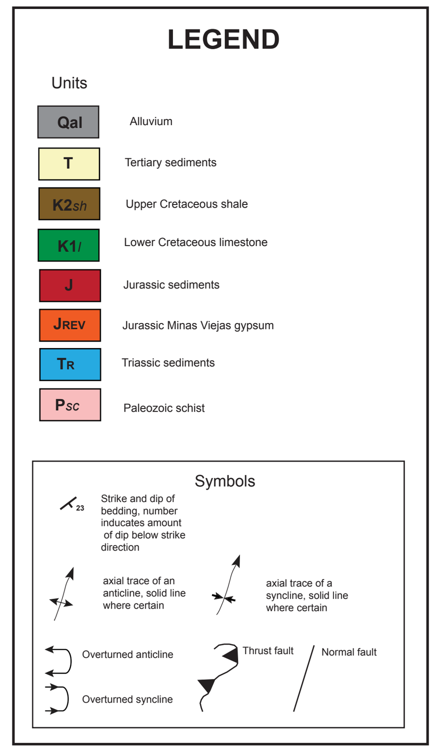
Cross section 3 through southern Potosi recess

Cross section Z-Z'' (Figure 9) is the southern-most section developed for this study. It is of importance because it crosses a zone where thrusting and fenster features are present in higher amounts than anywhere else in the Potosi Recess (Figure 6). The hinterland deformation is similar to the other sections, in that deformation is weak and gentle, but this quickly passes into tight box folds (not represented well in regional scaled sections), and simultaneously passing into many thrusts which continue until the end of the deformation front. As with sections X-X'', and Y-Y'', the section shows a decrease in the depth of detachment which coincides with the rise of detachment to the Upper Cretaceous lithology.

B



C



EXPLANATION

Cross section Z-Z" contains very gentle folds within the hinterland, showing very little shortening. As the deformation propagated east however, the evaporitic detachment quickly ended, causing the detachment to move up section and into the Upper Cretaceous shales. Thrusts developed along the shale detachment, allowing for a greater rate shortening in the frontal thrust system.

Fig. 9. (A) Cross-section Z-Z' begins near the town of Rio Verde in the hinterland and passes through Alaquines, and Tula. Cross section Z-Z'' contains very gentle folds within the hinterland, showing very little shortening. As the deformation propagated east however, the detachment ramped upward into the Upper Cretaceous units. Thrusts developed along the shale detachment, allowing for a greater rate shortening in the frontal thrust system. (B) Geologic map for section area; (C) Legend for both map and cross section.

FIGURES 9A, B, AND C

Depth to Detachment and Fold Spacing Implications

Efforts were made throughout the research to validate measurements being used for model generation. Data compiled from the creation of cross sections, available well data and both ground- and satellite-based strike and dip data were of use in this structural analysis.

Depth to detachment calculation

Using the depth to detachment guidelines, the conserved area beneath a prominent fold located west of the town of Zaragoza was used. The fold occurs above an evaporitic detachment which outcrops at the contact with the (Kl1) carbonates seen in the section. Line length differences between the folded unit and the length of its X axis were used in conjunction with the area of displaced rock to yield and detachment depth amount. Depth to detachment calculation provided an amount of 2125 meters, which is very close to the estimate average inferred from well log information. This information can be seen in below in figure 10.

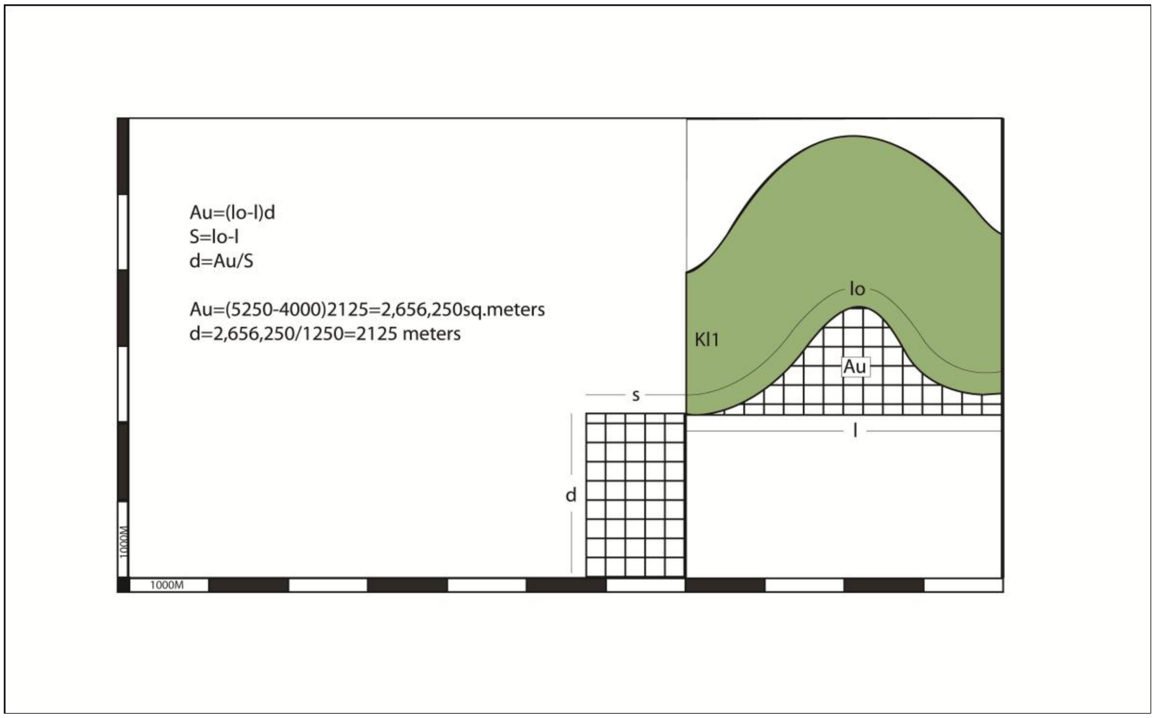


Fig. 10. Detachment depth calculation performed on an area with outcrops of carbonate platform along known evaporitic detachments. See figure 7 for location.

Shortening estimates

Shortening estimates were calculated across each cross-section (X-X", Y-Y', Z-Z"). Shortening estimates were calculated using line-length balancing of the base of the Cretaceous section (Kl1). Zones of shortening can be seen in figure 11; these were partitioned on the basis of structural similarities (i.e. faulting, fold magnitude, etc.). These estimates show: 1) an increase in shorten towards the foreland of the SMO, averaging ~25%; 2) that the greatest amounts of shortening occur within the Mante structural-belt; and 3) the hinterland experienced very little deformation with respect to the SMO as a whole. My estimates are considered minimums due to the lack of hanging wall cutoffs. Moreover, intraformational deformation was not considered or included in the model creation.

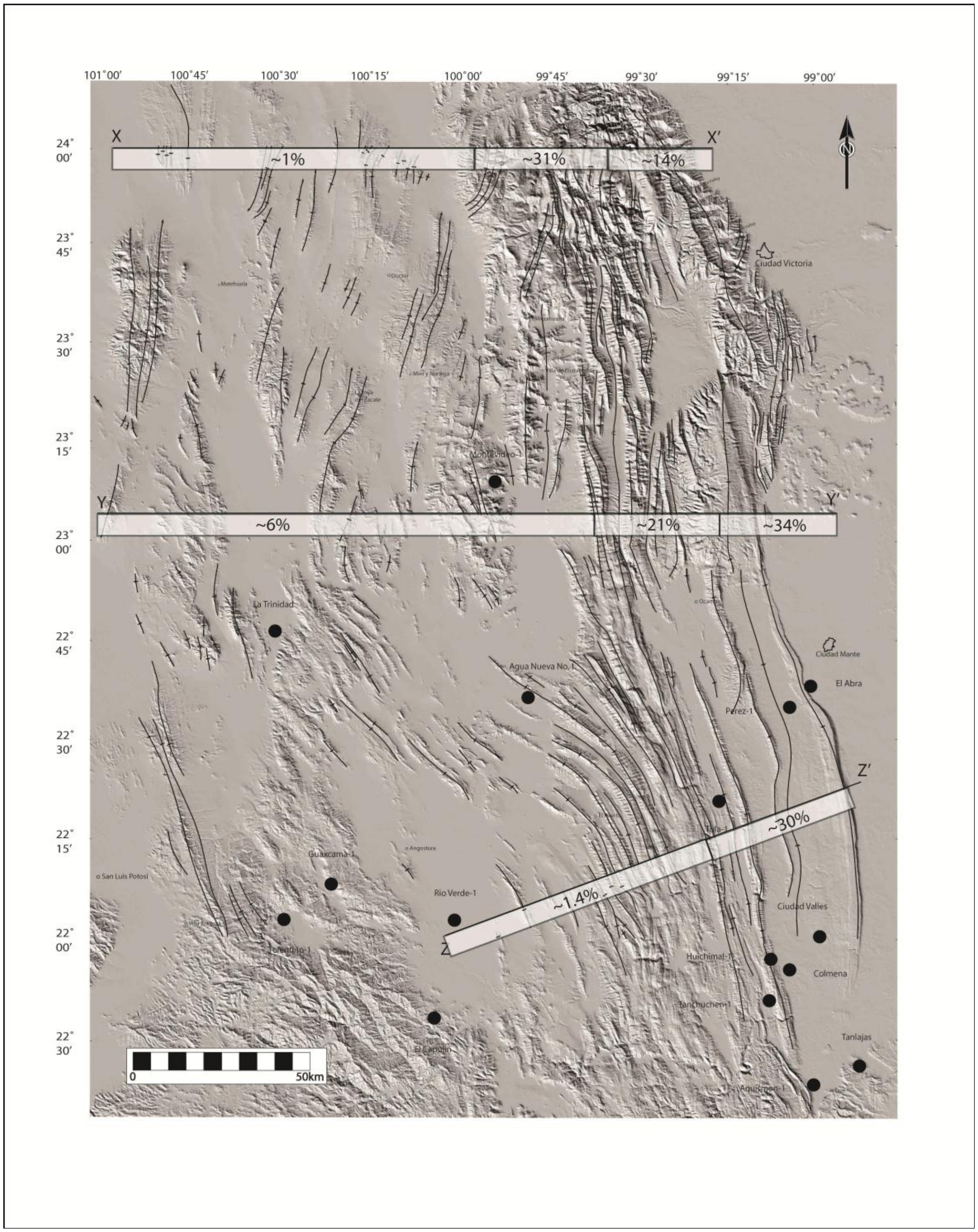


Fig. 11. SRTM overlaid with shortening estimates taken from line length balancing of cross sections constructed for the field area.

Stratigraphic fold analysis

The fold styles of the Potosi Recess show a dominant vergence to the east, and can be seen in the area indicating movement was to the east. Plotting the structural information for the recess on Beta-Pi plots highlights the fold trends for the Potosi Recess (Figure 12). The data typically shows that the folds have a minimum amount of plunge throughout the study area.

Strike and dip data for the field area was not robust and at times gathered by trigonometric methods using SPOT satellite imagery draped over SRTM DEM's. The extraction of greater amounts of dip (>25 degrees) is not possible within heavily complicated regions such as the study area using this remote sensing method.

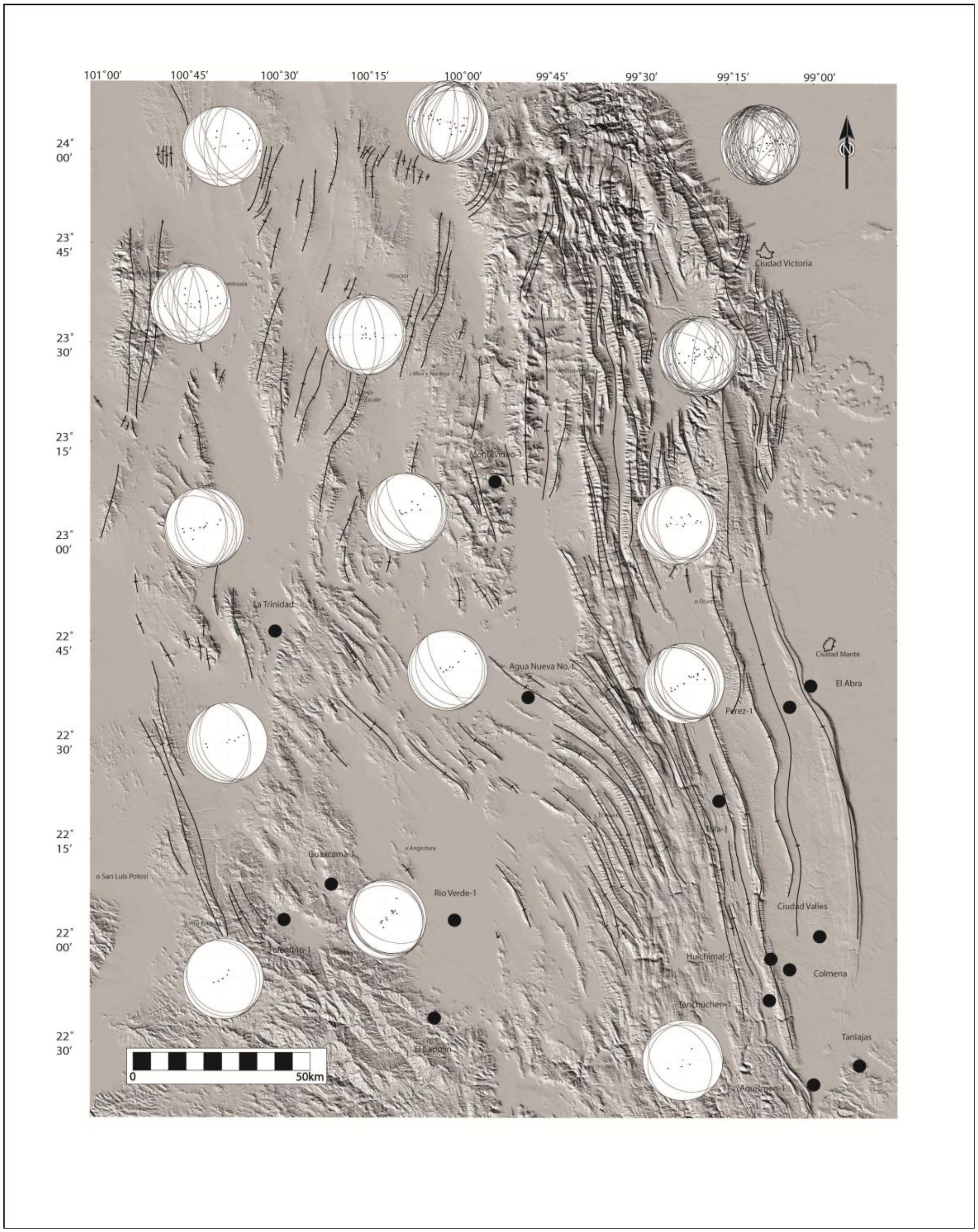


Fig. 12. SRTM overlaid with Beta – Pi plots of bedding data taken from satellite data.

Fold style comparison

The images in figure 13, show very clearly two styles which occur above weak shale detachments and weak evaporitic detachment (13A, and B) respectively. The parallel ramping of thrusts along shale detachments can be seen in 13A, where here, the Lower Cretaceous carbonates are thrust along a weak shale detachment (Mendez) in the area of Zaragoza. Image 13B shows an upright box fold which suggests formation above weak evaporitic deposits. Well data indeed shows this area is most likely underlain by evaporites. Many locations exist within the Potosi Recess which offers variations of these two styles of deformation, but these are exemplary for their definitive form.

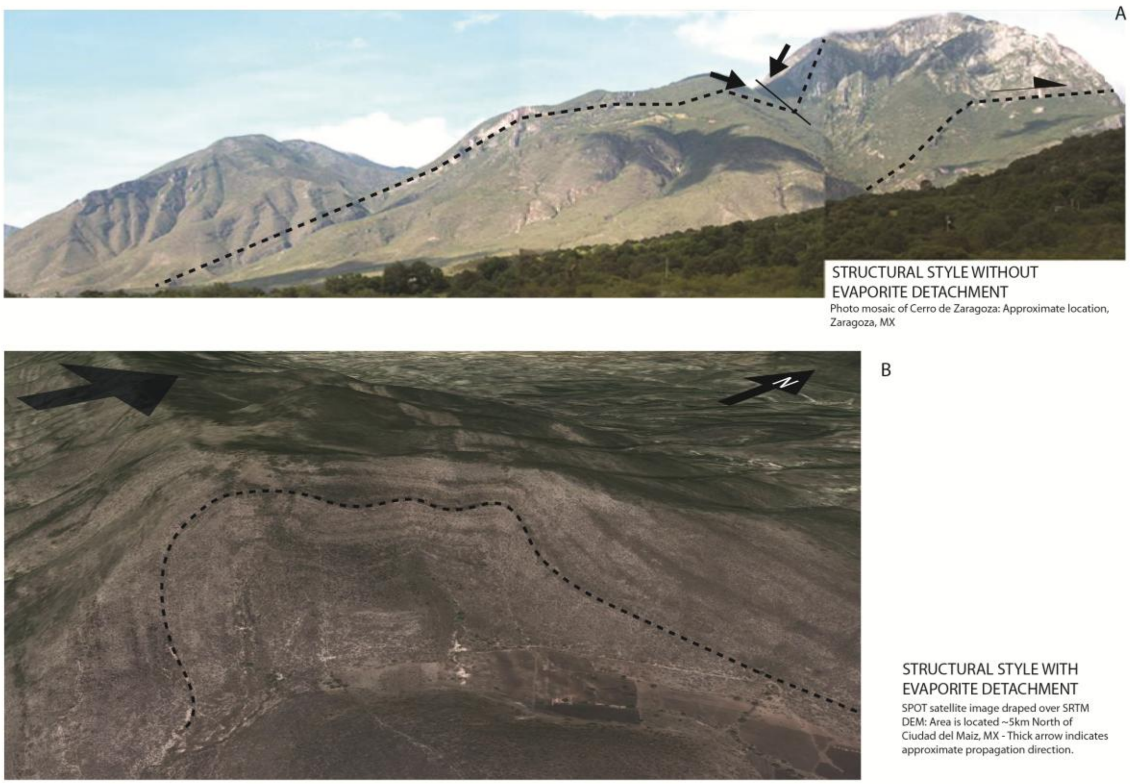


Fig. 13. (A) Image showing structural style above Upper Cretaceous unit, interpretation provides sense of slip and glide planes; (B) box folds over detachment along evaporate horizon.

FIGURE 13A, B

Structural domain changes with underlying lithologies

The SMO can be divided along boundaries separating structural distinct domains (Eguiluz de Antuñano et al., 2000; Gray et al., 2001). The northern portion is dominated by a buckle-fold province, the southern exemplified by fold and thrusts, and in the east contains basement-involved deformation; these are highlighted in figure 1A (denoted by structural domains), near the cities of Monterrey, Linares, San Luis Potosi, and Ciudad Mante, respectively.

The buckle-fold provinces (dominantly found in the Monterrey and Linares sectors of figure 1A) contain high amplitude box folds. Structures presented by (de Cserna, 1956; Padilla y Sanchez, 1982; Fischer and Jackson, 1999; Marrett and Aranda-Garcia, 1999; Eguiluz de Antuñano et al., 2000) represent this type of structural domain. Fold geometries are consistent with a depth to detachment of >2 km, rooting in the Jurassic evaporite sequence (de Cserna, 1956; Marrett and Aranda-García, 1999) and Cretaceous Guaxcama Formation within the VSLP zone.

What appears to be the most influential component in the formation of the Potosi Recess is the presence of thick evaporites between the basement complex and platform carbonates. This does not occur in all locations and is a focus in this research. Well data and outcrop studies performed by (Basanez-Loyola et al., 1993; Zhou et al., 2006) show that there is a gap in time and locus of evaporitic deposits. To the north, the trailing edge of the Minas Viejas gypsum/anhydrite, lies within the northern portion of the study area as outcrops. Moving south, this Minas Viejas unit thins completely and after a lull, is replaced by younger (Albian-Aptian) evaporite named the Guaxcama Formation (Figure 14).

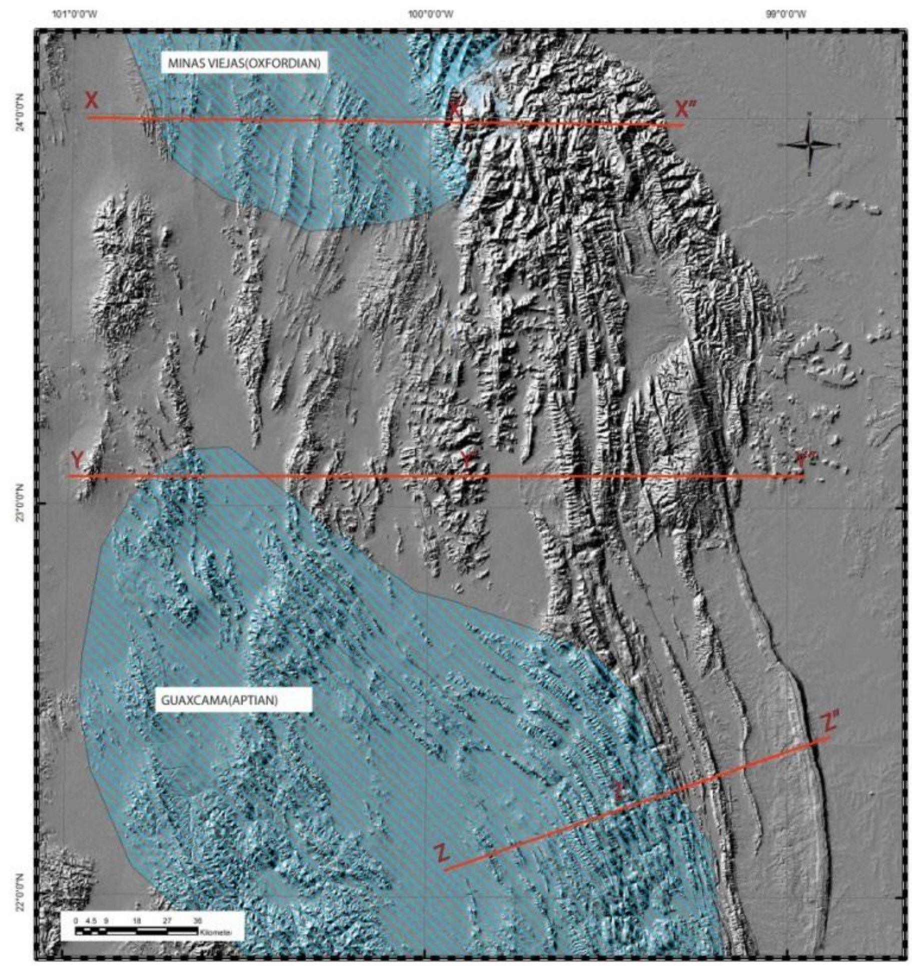


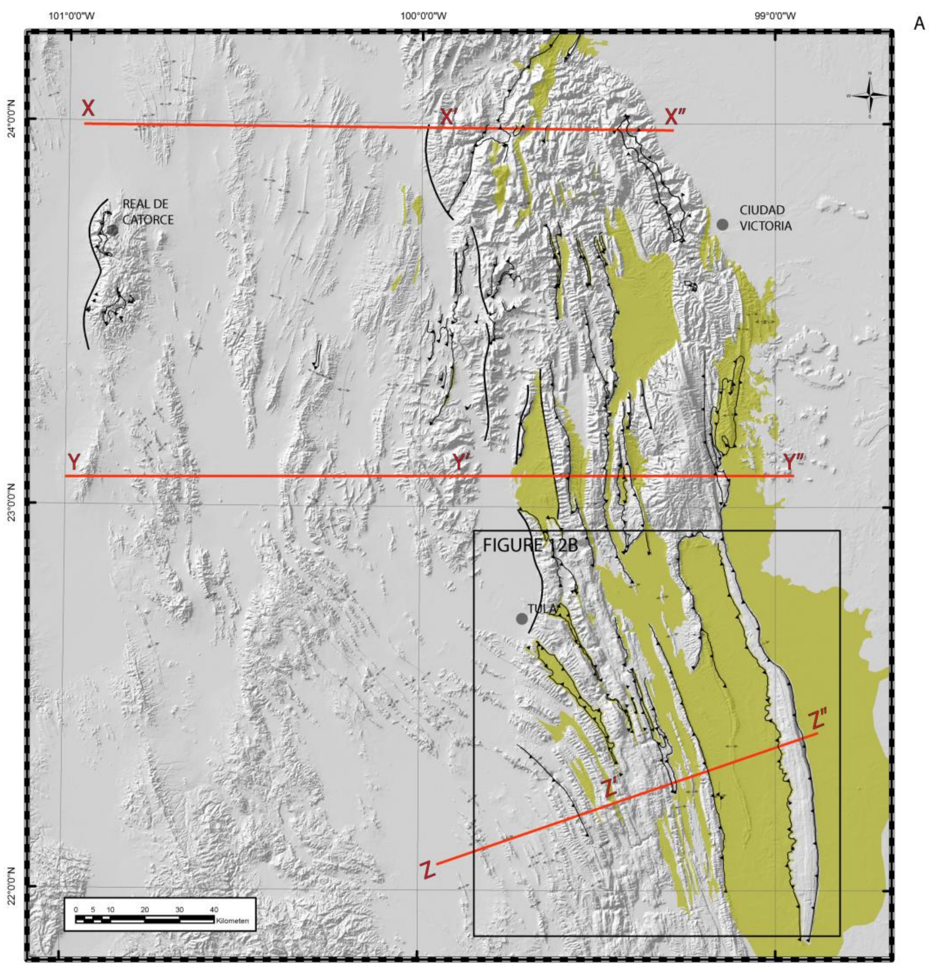
Fig. 14. Distribution of evaporites within the study area. Data gathered from subsurface well control and outcrop information. This should go when you describe the wells.

Both the Minas Viejas and Guaxcama units lie beneath the carbonate buildups which dominated the Cretaceous. The fact that these two lithologically weak units do not communicate and coincide with each limb of the Potosi recess indicate that they are in-part, responsible for the geomorphology which occurred as a result of the Laramide events.

The three structural sections (X-X”, Y-Y”, Z-Z”) were used in conjunction with outcrop information to provide the key indicators in the structural development of the Potosi Recess. The depth to detachment lessens when the evaporite thins and dies out, at which point a jump to a shallow detachment depth occurs. The depth to detachment is shown to occur at the base of Lower Cretaceous platform carbonate deposits resting on evaporites throughout the field area. This Lower Cretaceous unit lies unconformably above Triassic and Jurassic deposits within most of the hinterland when the evaporites are missing. Thrust faults grow in presence to the east, this also suggests that the deep detachment against the evaporite jumped up section. As a transition from deep to shallow, it appears to be accompanied by thrusting of carbonates above a thinning evaporitic detachment. The level at which the detachment continues is located within the Upper Cretaceous units, and is comprised of deep-water shales and marls (Figures, 1A, 6, and 15A, B).

The Upper Cretaceous units mark transition from the buckle-fold province to the thrust domain of the foreland. This domain contains a much greater amount of thrusts than anywhere else in the SMO. This is interpreted to be a two stage product of the Laramide orogeny.

If we look at the basement involvement we see that the eastern-most domain is characterized by imbricate thrusts of fault bend fold style (Suter, 1984, 1987; Marrett and Aranda-Garcia, 1999; Eguiluz de Antuñano et al., 2000), although the geometry of basement thrust sheets are poorly understood. Coincident with the emergence of thrust faulting throughout this region is the termination of evaporite outcrops. A strong dependence between evaporite deposition, graben-filling red beds and fold-versus thrust domains is quite apparent throughout the region.



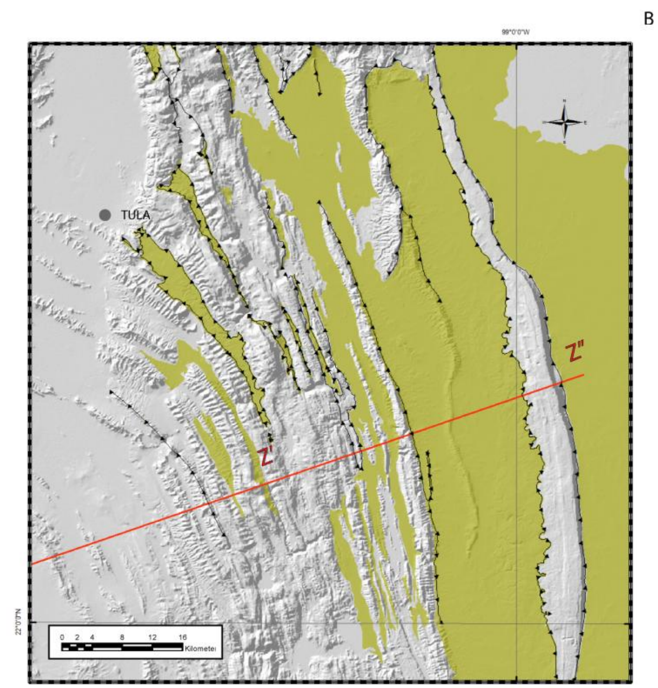


Fig. 15. (A) SRTM map of southern portion of the Potosi recess overlaid by an undifferentiated Upper Cretaceous lithologic unit and mapped thrust faults, (B) Zoom showing details of map.

FIGURES 15A, B

Thrusting is observed at every major Jurassic red bed outcrop known within the SMO, and highlights the role of which basement involvement played within the SMO. Zhou et al. (2006) found the thrusts which reside within the red beds to be a product of basement inversion. The most prominent and largest exposure of basement rock is the Peregrina-Huizachal Anticlinorium (Humphrey, 1956; Zhou et al., 2006) (Figure 5A, B and 6). Located near Ciudad Victoria, the anticlinorium strike north-northwest and exposes stratigraphy from the Lower Cretaceous carbonates to the Precambrian basement at its core. The late stage, thick-skinned event is probably due to low angle reverse faulting along the lithologically weak graben-filling red beds (Zhou et al., 2006). Analysis of fold spacing and fold amplitude shows a decrease in fold spacing from the hinterland to the foreland, while the opposite is true for the amplitude of the folds, which increase greatly in the foreland, with the greatest amplitudes being located within the Peregrina-Huizachal anticlinorium.

The incorporation of correlated well log information seen in figures 16 and 17 were extracted from logs presented by Basanez-Loyola et al. (1993); figure 18 depicts these same wells plus others within a three-dimensional fence diagram. The sections show a great thickness of two main units important in the field area, the El Abra, and the Guaxcama. It was considered for this research that the units could have been tectonically thickened by folding and/or imbricate thrust, but these were not noted by the author, Basanez-Loyola et al. (1993) to have been a confirmed occurrence. Instead, the author (ibid) used correlated sequences within the Yucatan Peninsula which allowed for correct and accurate stratigraphic core and cuttings analysis when developing the stratigraphic correlations seen in figures 16, 17, and 18.

Of note in sections presented in figures 16 and 17, are depths are which the Guaxcama Formation is reached (~2000m). This is well in line to the modeled and calculated depth to detachment for the study area.

Viewing the fence diagram of figure 18, the northern-most well (Montevideo-1) shows a marked increase in El Abra Formation thickness; although this is only one well, it strongly correlates to the large deposits found within the apex of the recess. No evaporite was reported in Montevideo-1.

No original well data was available for use in this study; published data was heavily relied upon for this research.

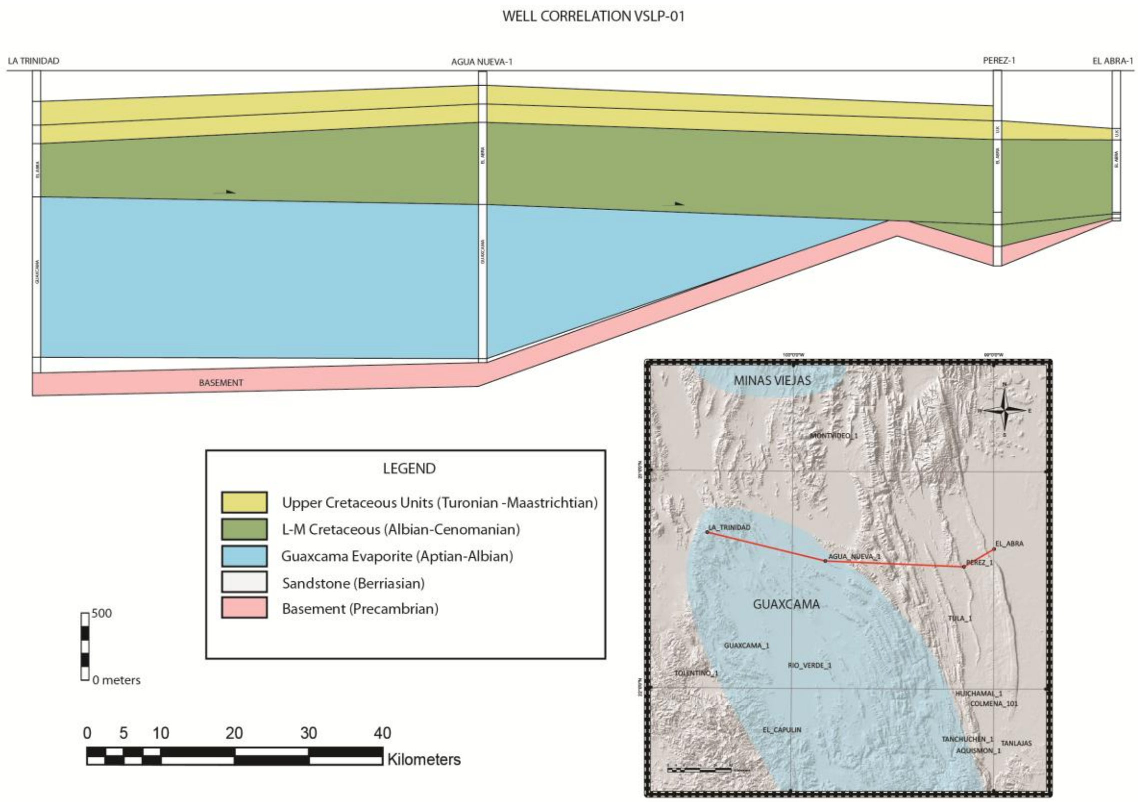


Fig. 16. Stratigraphic correlation of outcrop and well data showing major units within the VSLP platform with inset map showing location of wells and approximate distribution of evaporites.

FIGURE 16

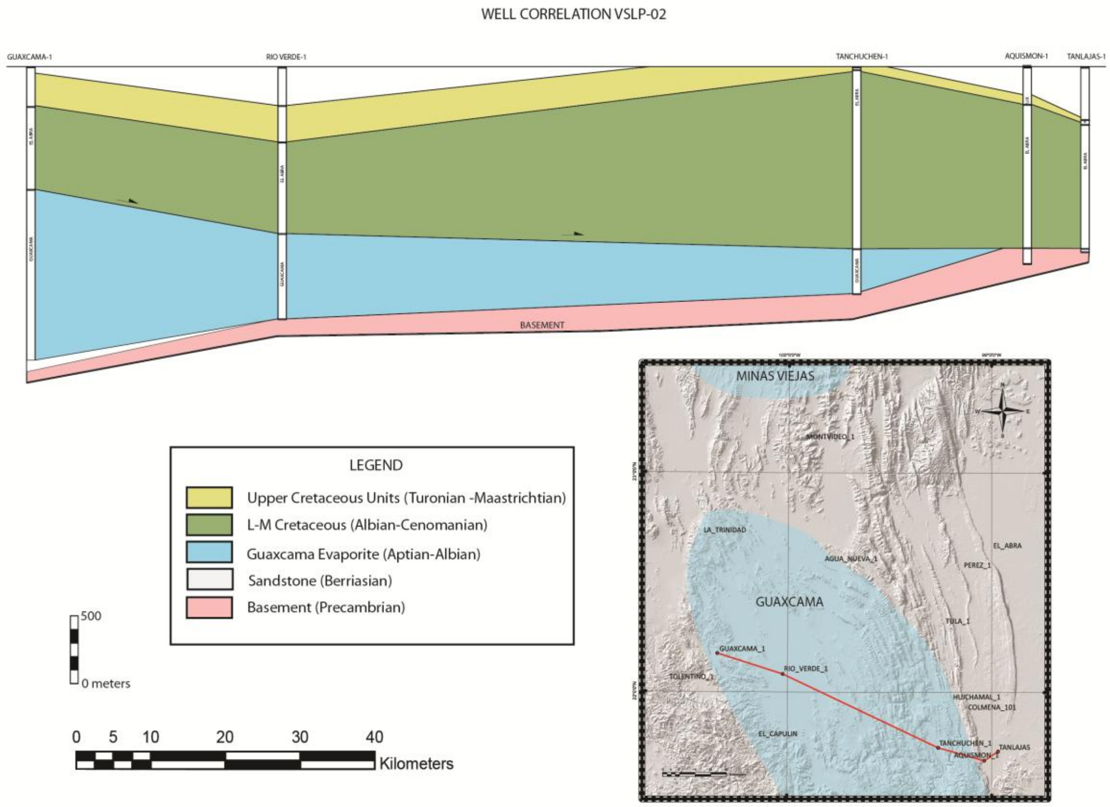


Fig. 17. Stratigraphic correlation of outcrop and well data showing major units within the VSLP platform with inset map showing location of wells and approximate distribution of evaporites.

FIGURE 17

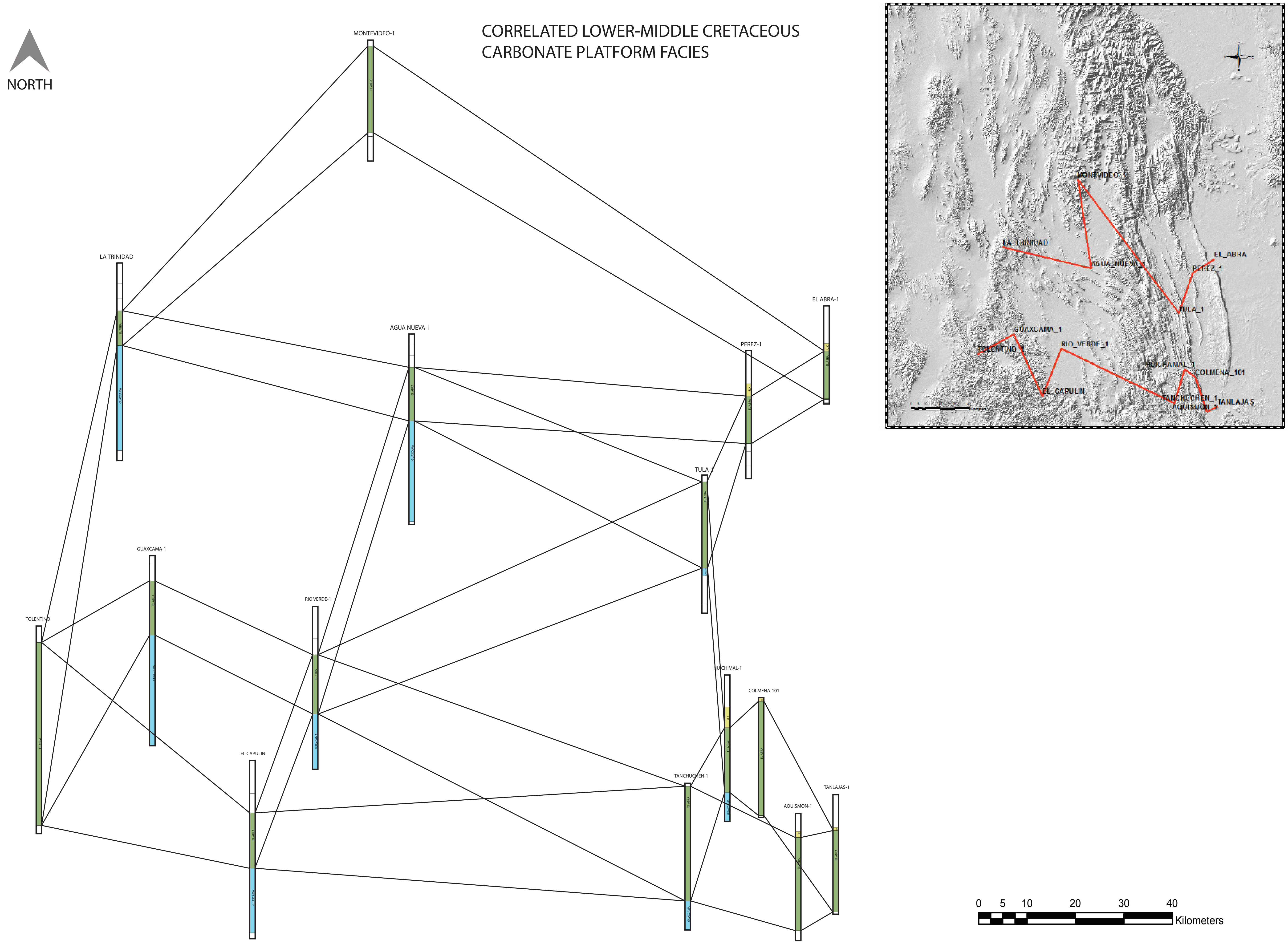


FIGURE 18

Fig. 18. Correlated Lower-Middle Cretaceous carbonate facies for the El Abra limestone based on data from Basanez-Loyola (1993).

Recess influences (Basement structure, detachments)

There are many factors which can influence the formation of a recess structure, as suggested by Macedo and Marshak, 1999 (figures 2A, B, C, and D). Structural components taken into account for its formation where the following: 1. Basement architecture, 2. Detachment depths, 3. Rheological strengths, 4. Continuity of detachment lithologies. These factors will be expanded upon here.

The study of the Potosi Recess offered an opportunity to develop a better understanding of a lesser known component of the SMO. While others works have described components of the SMO in detail, none have fully described the orogenic factors responsible for the creation of the Potosi Recess until now. The structural and sedimentological histories described thus far will provide the framework for understanding the method by which the recess formed.

A dominant controlling factor of the deformation is the hinterland detachment in evaporite. From well data and outcrop studies a map of evaporite distribution has been prepared (Figure 11). The discontinuous nature of these units is interpreted to have had a substantial impact on the formation of the Potosi Recess.

What is important to note, is that the Oxfordian Minas Viejas evaporites do not blanket the region of Mexico evenly as they're equivalents have done to the north. Instead they appear to have been deposited in the deepening depocenters around the basement structures.

Diagenesis of the Guaxcama Formation is interpreted to have facilitated dolomitization within the platform carbonates and as a result inferred to strengthen the overburden (Minero, 1991; Panozzo-Heilbronner, 1993), which could have had substantial impacts on the deformational events.

The discontinuous nature of the evaporite deposits of the Minas Viejas and the Guaxcama is shown in figures 7-9, within the cross sections. The presence of the evaporites within those sections greatly coincides with the type of deformation observed in the surface data.

The evaporite bodies mapped were developed from outcrop data as well as sparse well control. Correlating the subsurface shows of evaporites to the structural sections allows for the inference to be made that the Potosi Recess was at least a partial product of a weak detachment along the evaporite deposits.

Towards the center of the section a sizable carbonate thickness may have provided the addition of a buttress effect to counteract the approaching deformation front of the Laramide events. The effects of the buttress can be seen by increased shortening along the apex, shown in (Figure 8) showing transect (Y-Y'') within the hinterland portion. Padilla y Sanchez (1982) also reported of such a buttress effect. The author noted that the Cupido limestone reef complex of the Monterrey Salient contained greater thicknesses than surrounding areas were shown as zones of thickening as a result of the propagation of compressional forces.

Transition to Linear Thrusts Along Eastern Edge of SMO

A linear frontal thrust belt extends ~250 km from Peregrina to just south of Ciudad Mante. These thrusts are interpreted to be products of an evolving detachment transitioning from a deep, evaporitic detachment in the hinterland to a shallow, detachment within the Upper Cretaceous basinal facies of the frontal thrust zone. While others have cited areas of

Upper Cretaceous rocks developing as detachment surfaces (Suter 1984; Hamade, 2006), none have linked the changes in hinterland features with the frontal features. An interesting feature is the correspondence of the frontal thrust belt with an average elevation loss of ~1000 meters from hinterland to foreland (west to east). This coincides with what is interpreted as the western margin of the East Mexican Rift (Figure 5). The reactivation of normal faults within the basement could show a reorientation such as that presented by (Bump, 2003; Davis and Bump, 2009), in which a “short-cut” occurs between the inverted basement faults and the thin-skinned linear thrust belt. This mechanism provides a geometric link between the two events and can be seen in basement interpretations of figures 8 and 9. Contributions to the linear structural front are related to the initiation of low-angle cutoff ramps within the rift boundary footwalls. The use of these cutoff components is seen throughout the basement interpretation in the works presented here.

Along the eastern portion of the detachment, two aspects of the subsurface are observed: 1) the evaporites thin and die out as seen in both well and out crop data; and 2) the depth to basement decreases. This presents a few important clues to the formation of the recess, in which the structural styles above evaporites and more competent lithologies can be different (Letouzey et al., 1995) and the depth of detachment due to a changing basement depth can have profound effects on the available volume of rock to deform (Macedo and Marshak, 1999).

As the evaporitic detachment ended throughout the recess, the detachment shifted to a stratigraphically higher unit. The unit was that of the Upper Cretaceous shale, which is lithologically weak, as well as laterally extensive (Figures 15A, and B).

The transition from the recess to the linear frontal thrust belt which evolved as a discontinuous deep to laterally extensive shallow detachment is offered here as a mechanism to create the orogenic features we see today.

Until now, it was thought that the linear features of this domain were the product of late stage Laramide basement involved deformation, but evidence now suggests that detachment depths along the foreland propagation were partially responsible for the features observed today. Had the second episode of Laramide deformation been solely responsible for the deformation of the Mante structural-belt, then we would not see the linear, low-angle structural trends which developed along the deformation front. Instead, this provides evidence that a second Laramide event did occur and was thick-skinned in nature, owing to the high-angle faulting, small lateral displacement, and high-amplitude folds within areas such as the Peregrina-Huizachal Anticlinorium. The fact that the thin-skinned structures present throughout the thrust front and the high-amplitude basement uplifts do not coincide at all times, suggests that the basement was exhumed independent of the location of the thin-skinned deformation. Nowhere is this made more clear than in the Peregrina-Huizachal anticlinorium, in which Jurassic red beds outcrop at more than 2300 meters in elevation, while the same red beds are found at more than 3200 meters deep within the subsurface along the strike of the Mante structural belt some 250 km south within the study area.

Additionally, the limbs of the recess appear to have been translated a considerable amount, the original location was only a fraction of that when compared to traditional views. Structural deformation within this portion of the hinterland is much less than that required to restore the recess to a straight initial structural front. Much of the curvature observed in fold trends is a result of the Laramide deformation front along the leading edge of an irregularly rounded carbonate platform morphology. Hatcher and Geiser (2010), demonstrate the retrodeformation of the Monterrey Salient, showing that in fact there can pre-deformation curvature within salient structures.

Discussion

Expression of Laramide orogeny with thick evaporitic detachment

SMO is the structural expression of the Laramide Orogeny as it occurred in a carbonate passive margin setting overlying an evaporitic detachment surface. This research shows the linear frontal thrust belt to be first, a product of thin-skinned deformation acting on a weak Lower Cretaceous evaporite, transitioning to an Upper Cretaceous detachment and second, a basement inversion caused by the late stage evolution of Laramide deformation retained the structural trends but increased the amplitude of the fold–thrust belt.

Elevation as an inversion indicator

Elevation changes are best observed along strike of the Mante structural belt which comprises the foreland deformation of the Potosi Recess. Within the Peregrina–Huizachal anticlinorium studied by Zhou et al. (2006), elevations greater than 2000 meters occurs within unit traceable to depths >3000meters to the south. Similarities in trend and stratigraphy exists along the frontal thrust-belt, yet elevations along the front are drastically different as described. The presence of Jurassic red beds of the Huizachal Group were shown by Zhou et al. (2006) to have played an important role as a detachment surface for the thick-skinned events within the zone of East Mexican Rift. The presence of these continental deposits along the frontal thrusts of SMO do not demand basement reactivation, at least in the magnitude seen in the Peregrina–Huizachal anticlinorium. Possible geometries within inverted rifts may have contributed to the frontal-thrust system where basement reactivation is interpreted to be greatest (Figures 8, 9, and 19A, B).

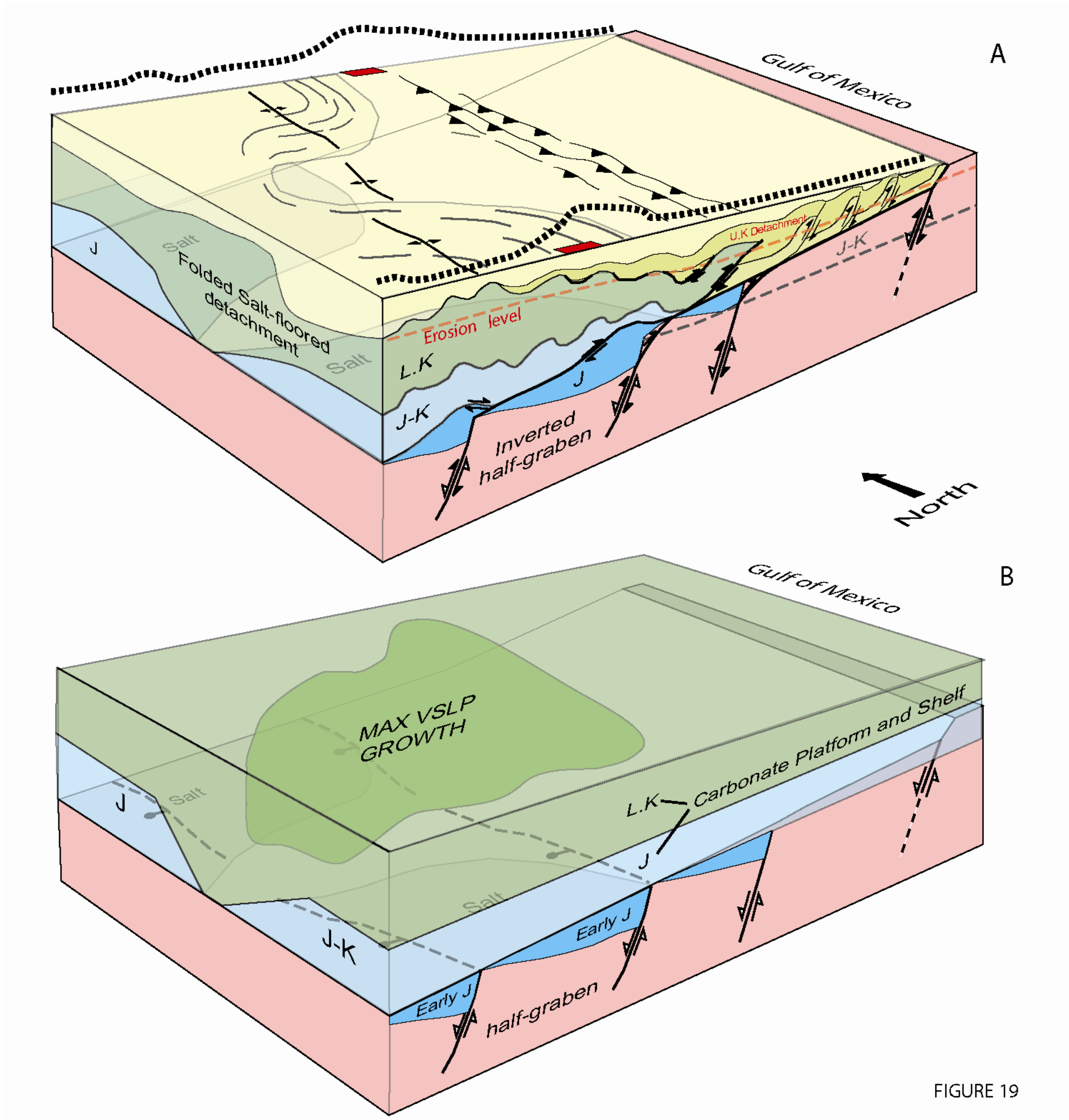


Fig. 19A, B. (B) Initial deposition of evaporites, carbonate platform, and passive margin deposits over rifted basement structures, (A) Effects of thin and thick-skinned deformation episodes in the SMO showing hinterland structures which were dominantly affected by an evaporitic detachments and carbonate growth. Along the frontal thrust of the SMO there are shallower detachment lithologies and basement influences from the presence of a partially inverted Jurassic rift.

Since little is known about the orientation of crustal blocks within SMO it is not unreasonable to suggest that lateral changes on the order of 10's to 100's of kilometers could reflect varying degrees of vergence within the deformed structures. Changes in basement paleo-relief, and/or degree of inversion could have influence the vergence of folded structures. This could explain why the area of Peregrina is so much higher than structures located near Mante, as well as the westward vergence of the Peregrina-Huizachal anticlinorium.

Conclusion

The research presented in the preceding thesis allow for some new ideas to be developed on the formation of these portions of SMO known as the Potosi Recess and Mante frontal thrusts. These are: 1) The transitioning of curvilinear features to a linear belt within the focus area is due to a detachment along a deep, discontinuous evaporite units which thin towards the east, allowing the detachment to jump up in section to the laterally extensive Upper Cretaceous units; 2) Frontal thrusts along the leading edge of SMO do occur along weak Upper Cretaceous shales; and finally 3) Topographic differences along the Mante structural-belt indicate that a late stage, thick-skinned Laramide event occurred in some segments of the East Mexican Rift (Figure 19B). The basement inversion appears to have occurred only within a segment of the linear frontal thrust system, effectively imprinting an elevation change in the structures. The fact that the northern area of Peregrina-Huizachal anticlinorium is ~1500 meters higher on average, than the zone to the south towards Ciudad Mante which exhibits the same structural trends, indicates that the basement inversion as a last pulse of the Laramide orogeny did occur after the thin-skinned event.

Ultimately, the basement structures were responsible for guiding the deformation of the Sierra Madre Oriental Fold-thrust belt, but the stratigraphy present at the time of the Laramide orogeny allowed a preferred propagation of the deformation front from west to east, creating the salient to recess transitions observed (Figure 1A). The prominent curvature of the Sierra Madre Oriental Fold-thrust Belt is in part a product heterogeneities observed in the subsurface lithologies.

Acknowledgements

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Curriculum Vita

Zachary David Wolfe was born to Melvin and Janice Wolfe in Houston, Texas; where from the youngest of age enjoyed the outdoors and inquired into the reasons for nearly everything he saw. Throughout his educational career he developed a broad understanding of the sciences which permitted him to succeed in industry related geophysical roles. Upon completion of the Master of Science in Geology, he hopes to incorporate more geological aspects into his everyday role as a professional.