

Geometry and kinematics of the Nuncios detachment fold complex: Implications for lithotectonics in northeastern Mexico

I. Camilo Higuera-Díaz and Mark P. Fischer

Department of Geology and Environmental Geosciences, Northern Illinois University, DeKalb, Illinois, USA

M. Scott Wilkerson

Department of Geosciences, DePauw University, Greencastle, Indiana, USA

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[1] Using recent geologic mapping combined with digital elevation data, aerial photo interpretation, and cross section balancing, we describe the three-dimensional (3-D) geometry and kinematics of the Nuncios Fold Complex in the Monterrey Salient of northeastern Mexico. This map-scale, evaporite-cored detachment fold structure involves Upper Jurassic through Cretaceous rocks deformed during the Laramide orogeny and comprises two westward plunging anticlines and an intervening, eastward plunging syncline. Seven balanced cross sections and a 3-D model of this north vergent structure document substantial along-strike variations in both fold geometry and detachment depth, suggesting that 3-D flow of the detachment layer may have occurred during folding. Comparison of folds in the Monterrey Salient with those in the neighboring Parras Basin suggests that the latter south vergent folds root to a shallower detachment. We suggest that northward transport of the Monterrey Salient folds on the lower evaporite detachment may have been inhibited by a thick sequence of foreland basin rocks in the northeastern Parras and southern La Popa basins and that the smaller, south verging folds formed where the lower detachment was abandoned and slip was transferred to the shallower detachment, forming a triangle zone at the front of the Sierra Madre orogenic wedge. **Citation:** Higuera-Díaz, I. C., M. P. Fischer, and M. S. Wilkerson (2005), Geometry and kinematics of the Nuncios detachment fold complex: Implications for lithotectonics in northeastern Mexico, *Tectonics*, 24, TC4010, doi:10.1029/2003TC001615.

1. Introduction

[2] In numerous locations around the world, detachment folds have formed in response to shortening above very weak evaporites or overpressured shales. Classic examples

of such structures occur in the Mississippi Fan and Perdido fold belts of the Gulf of Mexico [e.g., Rowan, 1997; Trudgill *et al.*, 1999], the Zagros Mountains of Iran [e.g., Farhoudi, 1978; Letouzey *et al.*, 1995], the Spanish Pyrenees [e.g., Sans and Verges, 1995; Poblet *et al.*, 1998], and the Parry Islands Fold Belt of Arctic Canada [e.g., Harrison, 1995]. In these and other locations, it is clear that stratigraphic layering plays an important role in detachment folding. Significant competency contrasts are required for detachment folding, and detachment folds commonly form in stratigraphic sections comprising rigid layers overlying weak detachment layers. Layer-parallel shortening of such a stratigraphic section creates folds whose geometry and kinematic evolution depend on the thickness and ductile flow of the detachment layer.

[3] In the last decade a variety of workers have proposed various two-dimensional geometric and kinematic models to describe detachment folding [e.g., Dahlstrom, 1990; Eppard and Groshong, 1995; Homza and Wallace, 1997; Poblet and McClay, 1996; Mitra, 2003]. Each model uses balancing constraints to derive relationships between variables such as fold interlimb angle, limb length, limb dip, shortening, detachment depth, and fold core area. Like most models of fault-related folds [e.g., Suppe, 1983], the general purpose of detachment fold models is to facilitate interpretations of structural geometries in areas where subsurface constraints are poor, or to infer fold kinematics and associated mesoscopic deformation patterns [e.g., Fischer and Jackson, 1999; Salvini and Storti, 2001].

[4] Despite the abundance of excellent two-dimensional detachment fold models, few studies actually constrain the details of natural detachment fold geometry or kinematics [e.g., Mitchell and Woodward, 1988; Anastasio *et al.*, 1997; Rowan, 1997; Poblet *et al.*, 1998; Atkinson and Wallace, 2003]. Such well-constrained examples of natural structures are necessary to evaluate the quality of simplified structural models, and should serve as the basis for refining existing models, or creating the next generation of new two-dimensional, or fully three-dimensional models. This paper presents such an example by describing the detailed three-dimensional structural geometry of an evaporite-cored, map-scale detachment fold.

[5] The structure that we describe is located in the Monterrey Salient of the Sierra Madre Oriental of north-



Figure 1. Satellite image and regional location map of the Monterrey Salient, eastern Parras Basin and La Popa Basin. Lines labeled A, B, C, D, and E show the approximate locations of cross sections shown in Figures 2 and 10. Heavy line marks the approximate position of the top of the Cretaceous carbonate bank sequence (i.e., the top of the Aurora Formation (Figure 3) and its regional stratigraphic equivalents). Thrust fault locations reproduced from interpretations by *Padilla y Sanchez* [1982]. See *Rowan et al.* [2003] and *Millán-Garrido* [2004] for the detailed geology of the La Popa Basin. See *McBride et al.* [1974] for the detailed geology of the Parras Basin.

eastern Mexico (Figure 1). The Monterrey Salient comprises a series of doubly plunging detachment folds with concave-to-the-south, curvilinear hinges that extend along strike for 40–50 km. These folds are generally symmetric,

upright to slightly north vergent, kink-style box folds with steeply dipping limbs (Figure 2). In this part of Mexico, a 3000–5000 m thick [*Mixon et al.*, 1959; *De Cserna*, 1971; *Dillman*, 1985; *Michalzik*, 1991] section of

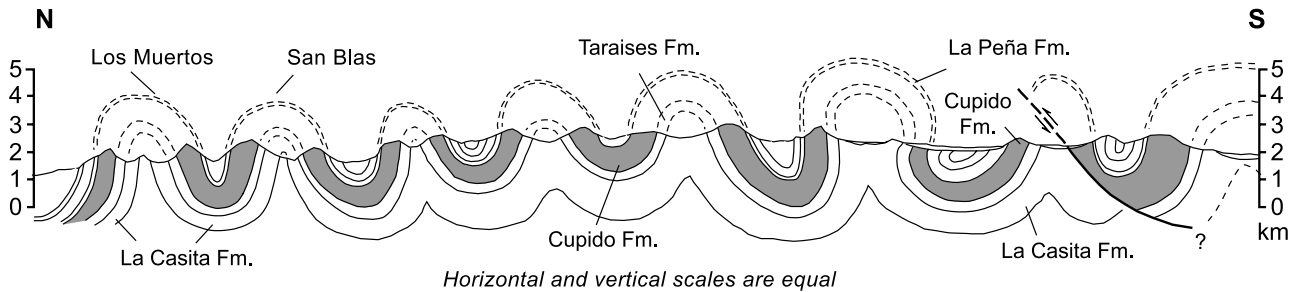


Figure 2. Regional cross section through the Monterrey Salient along line E in Figure 1. Note that the fold system detaches in the Minas Viejas Formation but that *Padilla y Sanchez* [1982] provided no interpretation of the thickness of this formation or the depth to detachment. See Figure 3 for the regional stratigraphic column. Modified after *Padilla y Sanchez* [1982] and *Fischer and Jackson* [1999].

Upper Jurassic and Cretaceous strata (Figure 3) was folded above a nearly 1000 m thick sequence of evaporites [Goldhammer and Wilson, 1999a]. Deformation during the Latest Cretaceous to Eocene Hidalgoan orogeny [Padilla y Sanchez, 1982], an event equivalent to the Laramide orogeny in the western U.S. North and west of the Monterrey Salient are the Parras and La Popa basins, containing an additional 5000 m of clastic rocks that are not exposed in the Monterrey Salient [Weidie and Murray, 1967; Padilla y Sanchez, 1982].

[6] Tectonic basement is not exposed in the Monterrey Salient, but igneous and metamorphic rocks underlying the evaporites have been encountered in oil exploration wells to the north [e.g., McDonnell, 1987]. Precambrian to early Jurassic rocks most likely form the regional basement and are exposed to the south in the Huizachal-Peregrina Anticlinorium [Garrison et al., 1980; Michalzik, 1991; Woods et al., 1991]. During the breakup of Pangaea, these rocks were faulted into a series of rift basins like the Triassic-Cretaceous Monterrey trough. Throughout the subsequent opening of the Gulf of Mexico, these basins significantly influenced regional depositional patterns [Padilla y Sanchez, 1982; Michalzik, 1991; Pindell, 1985; Goldhammer and Wilson, 1999a]. For example, hinterland deepening of a north-south elongated trough is known to have produced a depocenter beneath the present Monterrey Salient, the existence and geometry of which has been interpreted from magnetic and gravity data, as well as oil exploration wells drilled in the Parras Basin [e.g., McDonnell, 1987; Mickus and Montana, 1999].

[7] This paper presents a detailed description and analysis of the three-dimensional (3-D) structural geometry of the Nuncios Fold Complex, the northwesternmost fold in the Monterrey Salient. Arid climate and high topographic relief in the area have led to excellent exposure and have allowed us to create a detailed geologic map and several closely spaced, serial cross sections through this structure. These cross sections, combined with the geologic map and a high-resolution digital elevation model, were used to create a 3-D model of the structure. In section 2 we first describe the creation and interpretation of the geologic map, which we consider to be the primary “data set” in the area. In section 3 we describe the construction and restoration of the geologic

cross sections, including depth-to-detachment and shortening calculations. In section 4 we present our 3-D model of the structure and highlight some of its implications for the behavior of various regional lithotectonic units during folding. Our discussion in section 5 develops a general kinematic model for the formation of the Nuncios Fold Complex and hypothesizes how the distribution and behavior of these same lithotectonic units may have controlled the regional Cretaceous-Tertiary structural evolution of this part of northeastern Mexico.

2. Analysis of Surface Geology

[8] Although there are several regional geologic maps of the Monterrey Salient area [e.g., Humphrey, 1949; De Cserna, 1956; Vokes, 1963; Padilla y Sanchez, 1982], most of these maps are at scales of 1:50,000 or smaller, lack substantial structural data and use coarse stratigraphic subdivisions that are easily recognized in aerial photos or satellite imagery. Consequently, structures are only broadly delineated, and stratigraphic variability can be confused with structural complexity. Mapping for this project used published, formal stratigraphic formations and informal, finer-scale stratigraphic subdivisions to provide better constraints and higher structural resolution of map patterns. Criteria to define the informal stratigraphic subdivisions used in this project were topographic expression, lateral continuity, bedding thickness and character, lithological homogeneity, and the scale of the base map (1:25,000).

[9] Our geologic map of the Nuncios Fold Complex covers approximately 200 km² of the Ramos Arizpe 1:50,000 map in Mexico (Figure 4). The majority of structural data were collected along a series of subparallel cross-strike transects that followed local dry valleys. Where possible, additional transects along the strike of the structure followed geologic contacts or plunging structures. For high cliffs and some inaccessible areas between major drainage ways, geologic contacts were interpreted from 1:20,000 and 1:75,000 scale aerial photos. To further constrain the structural model, we also conducted an aerial photo interpretation of a part of the Parras Basin and field checked our interpretation by reconnaissance mapping in the areas surrounding the northern parts of sections C-C' and D-D'.

In the last stages of map preparation we used a 20 m cell resolution digital elevation model to refine the final placement of some photo-interpreted, poorly exposed or inaccessible geologic contacts (Figure 4).

2.1. Lithostratigraphy and Mechanical Stratigraphy

[10] Lithostratigraphic units from Jurassic to Late Cretaceous are exposed in the map area and are shown with their respective thicknesses in Figure 3. Because we are particularly interested in the contrasting behavior of strong and weak units during the folding process, we grouped formations with generally similar competency into four kilometer-scale, regional lithotectonic units [Wood and Bergin, 1970]. Our geometric and kinematic analyses focus on these units.

[11] The Minas Viejas Formation is the oldest unit exposed in the map area, and crops out as anhydrite lithofacies in a breached anticline in La Paloma Canyon, where the discordant contacts with other formations are poorly exposed, complex, and are interpreted to be a combination of intrusive and faulted contacts. Aside from this exposure, there are no other direct indications within the Monterrey Salient that significant thicknesses of evaporites underlie the map area. Evidence supporting the regional presence of the Minas Viejas comes from exposures of evaporites in the cores of some anticlines and diapiric bodies in the foreland basins immediately north of the Monterrey Salient [Weidie and Martinez, 1970; Giles and Lawton, 1999]. Records from wells drilled in these areas show that the Minas Viejas Formation is more than 1000 m thick and that it consists of intercalated gypsum, anhydrite and halite [Weidie and Martinez, 1970; Laudon, 1984; McDonnell, 1987]. The Minas Viejas Formation comprises our weak lithotectonic unit 1, and is interpreted to serve as the regional basal detachment layer (Figure 3).

[12] Lithotectonic unit 2 is interpreted to display intermediate competency compared to other units in the map area, and is composed of three formations (Figure 3). The Zuloaga Formation unconformably overlies the Minas Viejas Formation, and consists of thick-bedded gray mudstones and wackestones whose upper parts contain abundant black chert nodules. Laterally discontinuous, irregular breccia bodies occur in tightly folded parts of this unit, whereas these breccias are absent in open-folded areas, suggesting a tectonic origin for the brecciation. The La Casita Formation conformably overlies the Zuloaga Formation and in the area is divided into two informal map units. The lower unit consists of 340–380 m of black, carbonaceous siltstone and shale that we informally named La Casita 1. The upper unit is informally named La Casita 2 and comprises 320–340 m of coarsening upward sequences that grade from black shale to arkosic sandstone and conglomerates. The Taraises Formation overlies the La Casita 2 and consists of two informal map units. The San Juan Lentil comprises a 40 m thick section of well-cemented fossiliferous packstone and wackestone at the base of the Taraises Forma-

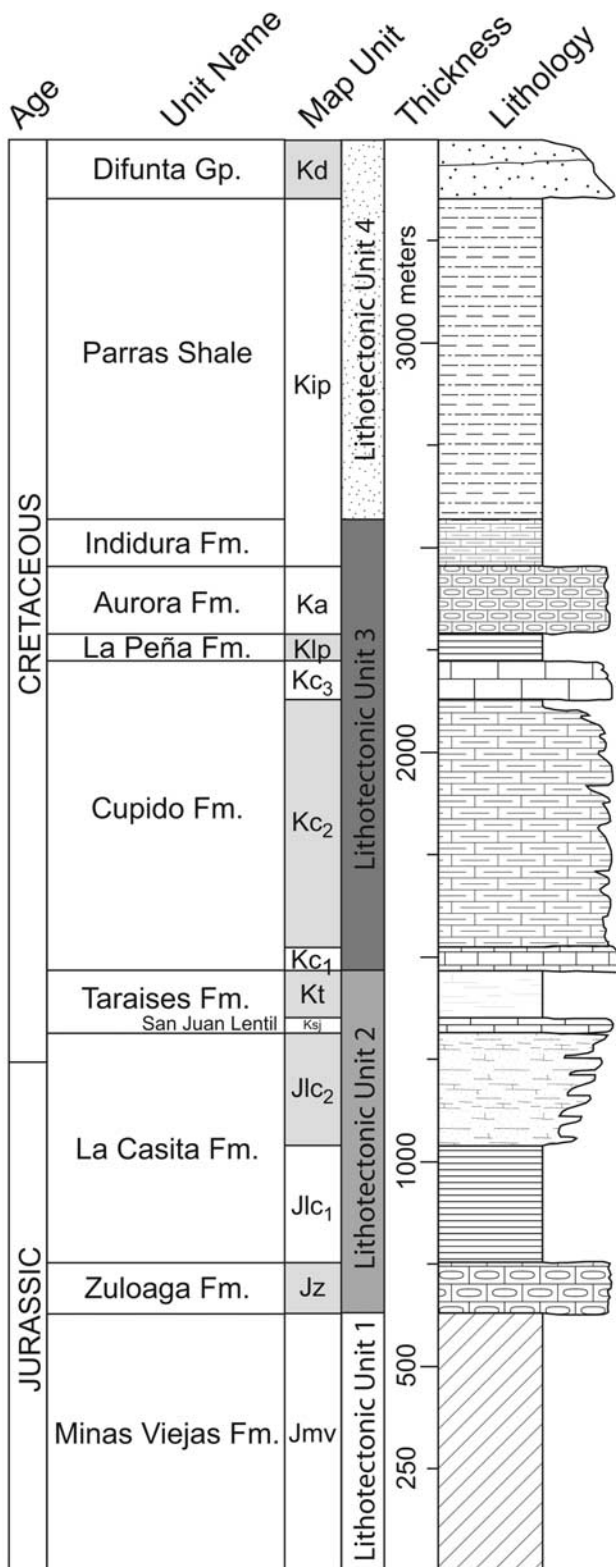


Figure 3. Stratigraphic column of rocks exposed in the map area and in general throughout the Monterrey Salient. We show only a representative thickness of the Minas Viejas Formation and Difunta Group, not the complete thickness. Modified after Padilla y Sanchez [1982], Fischer and Jackson [1999], and Goldhammer and Wilson [1999a].

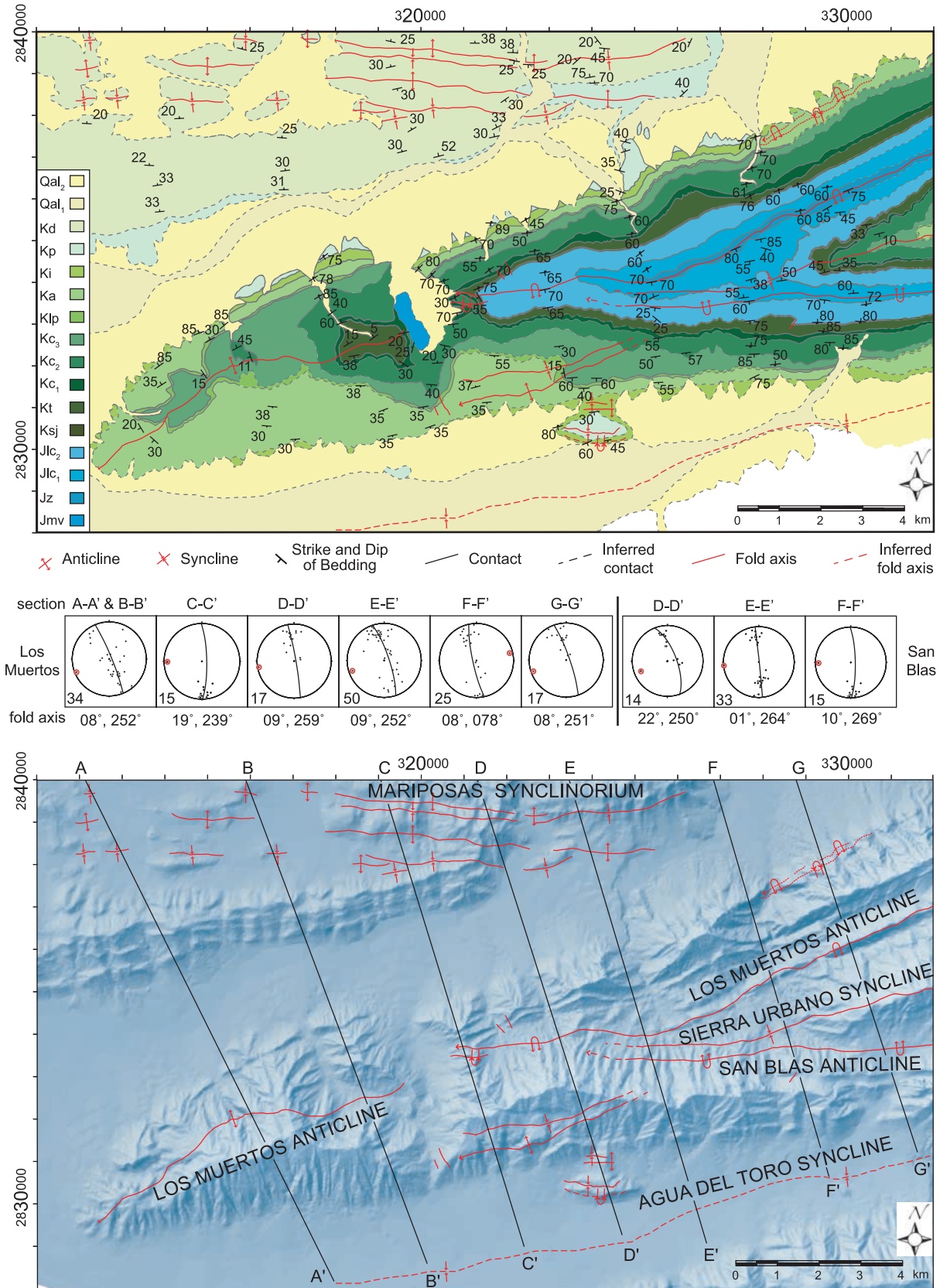


Figure 4

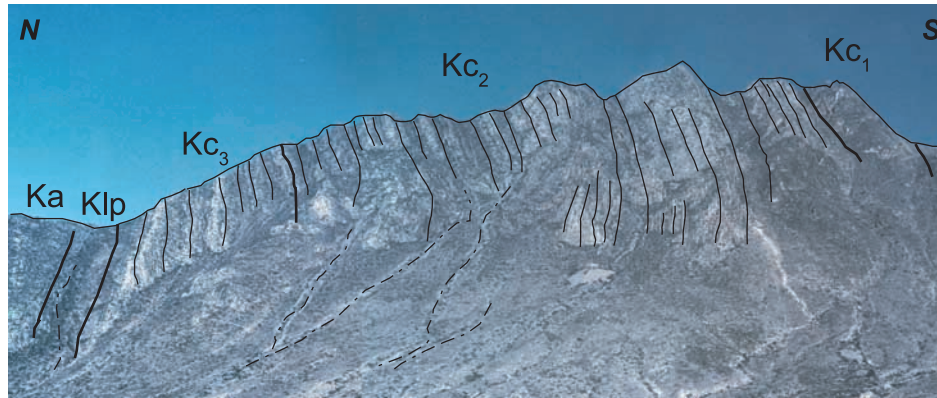


Figure 5. Erosion profile and bedding characteristics of the Cupido Formation exposed along a transect through the southern limb of Los Muertos anticline along cross section C-C' (Figure 4). Massive bedding and high cliffs are characteristic of the Cupido 1 (Kc₁), whereas the Cupido 2 (Kc₂) appears as a well-bedded sequence of thick beds, and the Cupido 3 (Kc₃) as a well-bedded succession of medium to thin beds. See Figure 3 for stratigraphic abbreviations. N-S distance along the picture is approximately 1.5 km.

tion, whereas the upper 120 m is composed of mudstone intercalated with shale.

[13] Lithotectonic unit 3 is interpreted as the most competent unit in the area and comprises a thick carbonate interval formed by four formations that conformably overlie the Taraises Formation (Figure 3) [Humphrey, 1949; Wilson, 1981; Goldhammer and Wilson, 1999b]. The Cupido Formation is the oldest and is divided into three informal map units that have characteristic stratigraphic and topographic expression (Figure 5). We named the lower unit Cupido 1 and defined it as a 60 m thick sequence of massive dolostones and dolomitic limestones. This unit forms the most significant cliffs in the map area. The middle unit is informally named Cupido 2, and comprises a 400 m thick package of three well-bedded sequences of packstones, wackestones, and mudstones. Bedding becomes progressively thinner upward in these sequences. The upper unit is the Cupido 3, a 120 m thick section composed of three thin-bedded sequences of packstone and wackestone. Overlying the Cupido Formation is the La Peña Formation, a 60 m thick, fossiliferous, black, calcareous shale with local black chert lenses. Near the top of lithotectonic unit 3 is the Aurora Formation, a roughly 220 m thick sequence of well-bedded wackestone interbedded with shale and black chert nodules in the lower part of the formation. The Aurora Formation is overlain by the poorly exposed

Indidura Formation, a 60 m thick package of dark to medium gray, medium-bedded to laminated wackestone and packstone that alternates with brown wackestone, calcareous shale, and thin gypsum laminae.

[14] Lithotectonic unit 4 is the uppermost unit in the area, is interpreted as a weak mechanical unit, and consists of two formations. The Parras Shale overlies the Indidura Formation and is a 1200–1500 m thick succession of black to gray shale interbedded with minor limestone and gypsum. The overlying Difunta Group comprises over 3000 m of fine-grained sandstone with thick successions of red beds and limestone. Regionally the Difunta Group is nearly 5000 m thick [McBride *et al.*, 1974; Lawton *et al.*, 2001], but only the lower half crops out in the mapped area.

2.2. Structural Geometry

[15] The Nuncios Fold Complex comprises three interfering folds: the westward plunging Los Muertos and San Blas anticlines, and the eastward plunging, intervening Sierra Urbano syncline (Figure 4). Los Muertos anticline is a box-shaped structure that changes from upright in the east to north verging in the west, with an average axis orientation of 09°, 246°. Locally, in areas to the east of cross section F-F', the axis of Los Muertos anticline plunges in the opposite direction at 08°, 078°, suggesting a structural high exists near cross section F-F'. Other significant changes in

Figure 4. Geologic map and digital elevation model of the study area outlined in Figure 1. Stereoplots show pi diagrams and the best fit cylindrical fold axis to bedding collected along each cross section line. The small number of data along section lines A-A' and B-B' could not be used to create separate plots along each line, so these data are combined into a single stereoplot and fold axis calculation. The plunge and bearing of each best fit fold axis are written below each plot, with the six plots on the left for Los Muertos anticline and the three plots on the right for the San Blas anticline. The number of data used along each section line is written in the lower left corner of each stereoplot. Note that in most places the folds generally exhibit cylindrical geometries. See Figure 3 for the map unit abbreviations for the local stratigraphy. Structural data on the map are only a representative set of the complete data set.

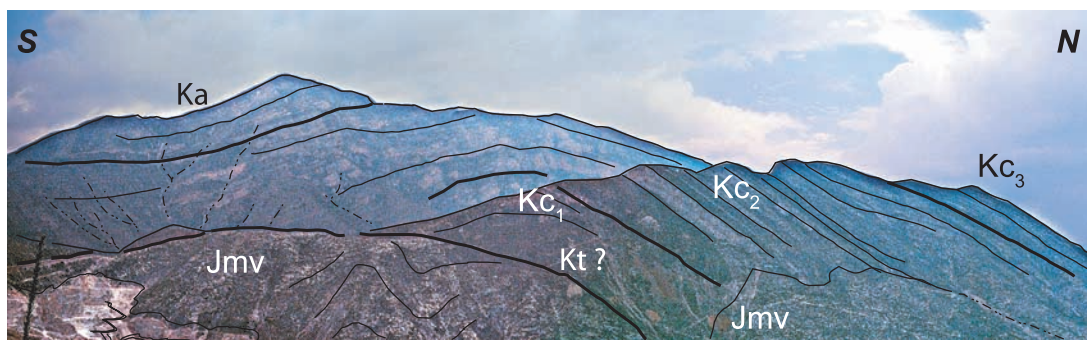


Figure 6. West facing view of a profile through Los Muertos anticline along section B-B' (Figure 4). Photo shows the discordant contact of the evaporites of the Minas Viejas Formation (Jmv) with different levels of the Taraises (Kt) and Cupido (Kc₁, Kc₂) formations at the core of the anticline. See Figure 3 for stratigraphic abbreviations. N-S distance along the picture is approximately 2 km.

fold axis orientation occur near cross section C-C', where the plunge of Los Muertos anticline locally doubles to 19°, the San Blas anticline appears to terminate, and the Minas Viejas Formation is in discordant contact with the Cupido and Taraises formations (Figure 4). These relationships, when combined with the presence of several low-amplitude, small-wavelength, disharmonic folds in the Cupido 1 and 2 in the core of Los Muertos anticline near cross section C-C' (Figure 6), suggest the evaporite body in Las Palomas Canyon was extruded during folding, perhaps by injection along small crestal faults during fold tightening. In addition to this main extrusion, several decameter-scale outcrops of the Minas Viejas Formation are scattered along the crest of Los Muertos anticline, but are too small to appear on our map. If these outcrops represent additional small evaporite bodies that pierced through the Zuloaga Formation, then their narrow, strip-like distribution suggests they were sourced from a "wall" of Minas Viejas rocks in the core of the fold.

[16] Similar to Los Muertos anticline, San Blas anticline is a box-shaped structure with an average axis orientation of 06°, 265° (Figure 4). This fold verges southward and gradually terminates between cross sections E-E' and C-C', where there is a substantial, coincident map view distortion and northward deflection of Los Muertos anticline. The Sierra Urbano syncline lies between Los Muertos and San Blas anticlines in areas east of cross section F-F', and has an average axis orientation of 02°, 081° (Figure 4). Like the reversal in plunge of Los Muertos anticline, the westward termination and eastward plunge of the Sierra Urbano syncline suggest the presence of a structural high near cross section F-F'.

[17] Further analysis of our geologic map reveals that there is a stark geometric contrast between major structures in the Monterrey Salient (e.g., the Nuncios Fold Complex) and major structures in the northeast corner of the adjacent Parras Basin (Figures 1 and 4). In general, first-order folds in the salient are WSW plunging, upright to north verging structures that trend ENE-WSW. In our map area, folds in the adjacent Parras Basin, such as those in the Mariposas synclinorium, trend E-W, plunge to the west and are

strongly south vergent (Figure 7). In addition, folds in the synclinorium are approximately 1.5 km in amplitude and less than 1 km in wavelength, significantly smaller than folds in the salient, which typically exhibit amplitudes and wavelengths on the order of 3.5 km and 6–8 km. These contrasting structural styles suggest different levels of detachment for the folds in the Nuncios Fold Complex and the Mariposas synclinorium. The geometry of folds in the Nuncios Fold Complex suggests these structures root to a deep detachment, most likely located in the evaporites of the Minas Viejas Formation [Padilla y Sanchez, 1982; Marrett and Aranda-Garcia, 1999; Gray et al., 2001]. By comparison, the smaller size and divergent trends of the structures in the Mariposas synclinorium suggest that those folds root to a shallower detachment, mostly likely within the thick shales of the Parras Formation [e.g., Weidie and Murray, 1967; Dillman, 1985], and do not significantly involve the underlying carbonate section or Jurassic rocks. The presence of such an upper detachment suggests that

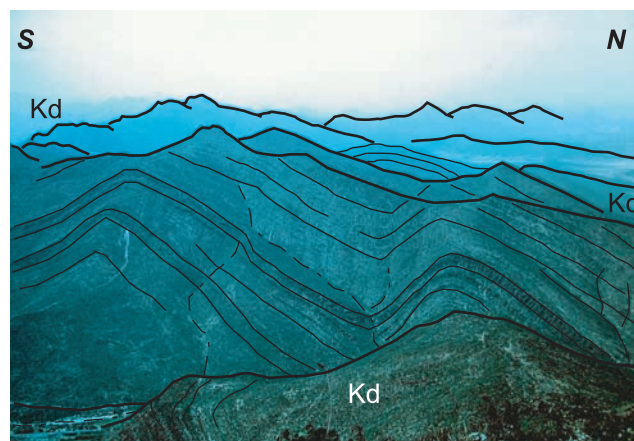


Figure 7. West facing view of south verging folds in Difunta Group (Kd) rocks exposed in the southern limb of the Mariposas synclinorium near cross section D-D' (Figure 4). N-S distance across the photo is approximately 1 km.

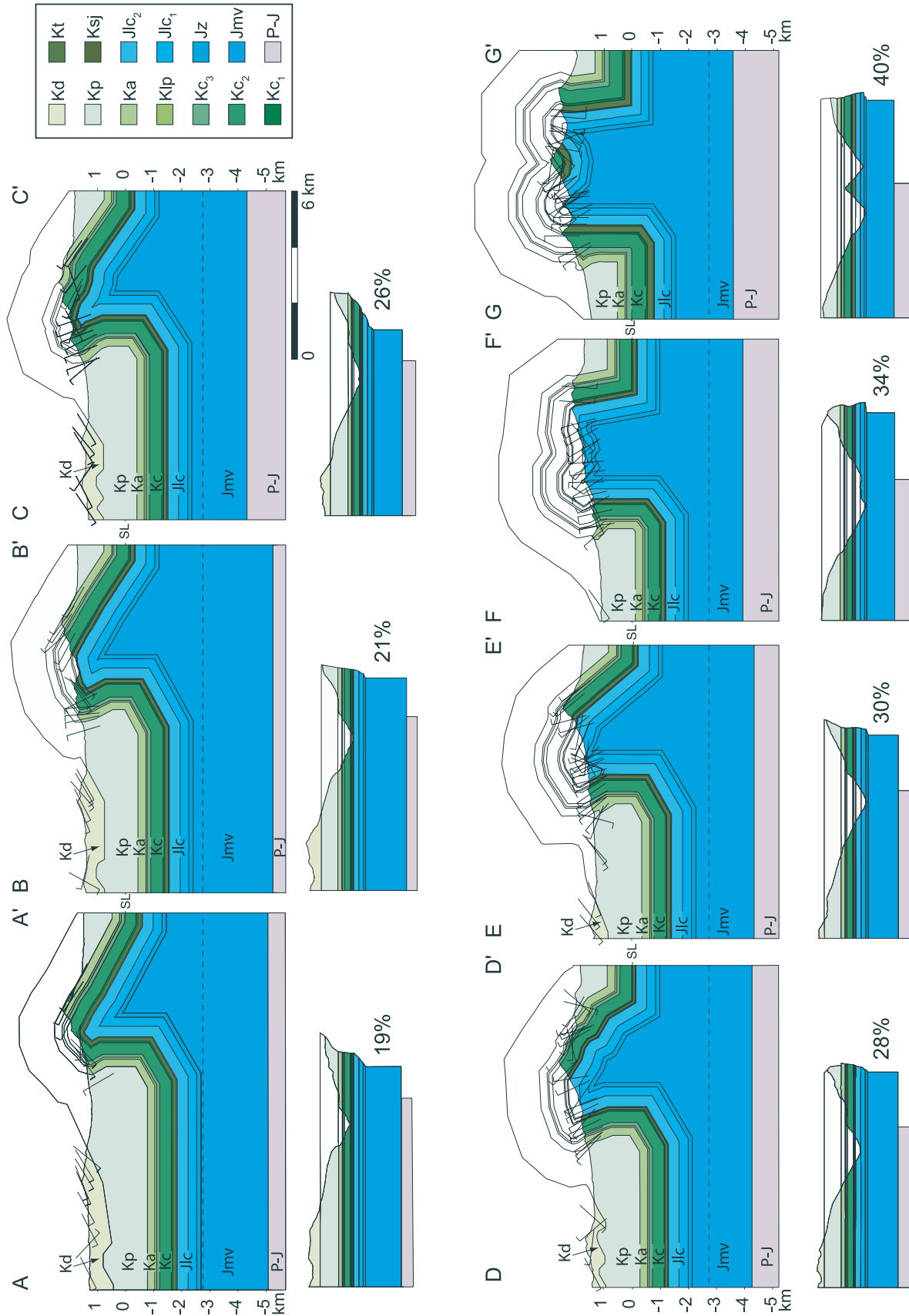


Figure 8

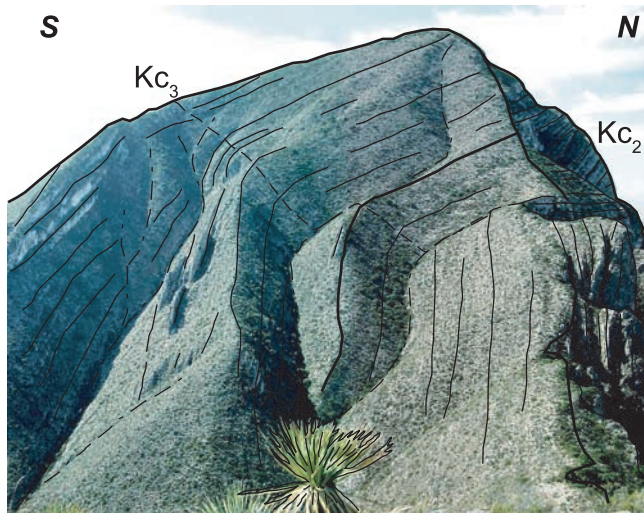


Figure 9. West facing view of a kink-style bend in the Cupido Formation exposed in the southern limb of San Blas anticline along section F-F' (Figure 4). Distance across the picture is approximately 0.5 km.

the Parras Formation and Difunta Group form a regional cover sequence [Ferrill and Dunne, 1989], an uppermost lithotectonic unit whose deformation is decoupled from the folds exposed in the Monterrey Salient.

3. Geologic Cross Sections

[18] Seven balanced geologic cross sections were drawn through the Nuncios Fold Complex to obtain insights into the local subsurface geometry and to examine the nature and cause of along-strike variations in the fold geometry, kinematics and shortening (Figure 8). The cross sections are spaced roughly 2 km apart, and are oriented perpendicular to local fold axes, which are assumed to be normal to the local maximum displacement direction [e.g., Macedo and Marshak, 1999]. This approach minimizes any out-of-plane motion of material, and the resulting sections have a slightly fanning geometry in map view (Figure 4).

[19] The sections are constrained by mapped geologic contacts as well as by field-measured, three-point method-calculated and photo-interpreted strikes and dips that are projected into the plane of each cross section. The structural data were divided into planar dip domains, giving the constructed structures kink-style geometries similar to those observed in the field (Figure 9). In each cross section layers were drawn using constant thickness projections, creating parallel-style fold geometries in all units except the Minas

Viejas Formation and the Parras Shale. Field observations suggest that this constant thickness assumption is reasonable in the cross-strike direction for a given fold, but that all units experience along-strike variations in thickness. Therefore each cross section was drawn using constant thickness projections within the section plane, but individual unit thicknesses were allowed to vary from section to section.

[20] Units above the Minas Viejas and below the Parras were restored using a Geosec2D™ flexural slip algorithm that maintained layer length. Restoration for the Minas Viejas Fm., the Parras Shale and the Difunta Group was done using area balance methods. Shortening of each cross section was calculated from the length of the top of the Cupido 1 because this unit is the most competent in the sequence. We infer, therefore that it has experienced the smallest amount of penetrative ductile strain, thus preserving the layer length throughout the folding process. In the following sections we describe the geometries of the detachments, major folds and along-strike changes in shortening magnitude.

3.1. Detachments and Detachment Layers

[21] For the purposes of this paper it is useful to discriminate between detachment surfaces and detachment layers. A detachment surface (hereafter simply called a detachment) theoretically is a zero thickness interface separating rocks that have undergone significant deformation from those that have not. In contrast, a detachment layer is a section of rock with finite thickness that both contains the detachment and that accommodates this deformation. Depth-to-detachment calculations [e.g., Epard and Groshong, 1993] determine the position of a surface above which rocks may have been shortened, but it is the flow and deformation of the detachment layer that are important in fold kinematics and mechanics.

[22] Although it is generally agreed that the regional detachment beneath the Monterrey Salient is somewhere in the evaporites of the Minas Viejas Formation, there are few published reports of specific depth-to-detachment measurements or calculations in the area [e.g., Gray and Johnson, 1995]. There are similarly no published records of the thickness of evaporites beneath the Monterrey Salient, although Goldhammer *et al.* [1991] estimated 1000 m of pre-tectonic thickness, and some published cross sections (Figure 10) show deformed thicknesses of 1–2 km beneath synclines in the interior of the fold belt [e.g., Marrett and Bentham, 1997; Marrett and Aranda-Garcia, 1999], or locally up to 6 km of evaporites beneath portions of the adjacent Parras and La Popa basins [e.g., Gray *et al.*, 2001; Millán-Garrido, 2004].

Figure 8. Geologic cross sections through the Nuncios Fold Complex. Horizontal and vertical scales are equivalent in each section. Restored cross sections are shown at one-half scale beneath each corresponding deformed section and were constructed with a pin line along the northern edge of each deformed section. Percent shortening for each section is listed adjacent to the corresponding restored section. As explained in section 3.1, the dashed line in each cross section is the reference level used in depth-to-detachment calculations and is a horizontal plane at approximately –2.8 km elevation. Symbol P-J in the explanation refers to Paleozoic through Lower Jurassic rocks comprising the regional basement. See Figure 3 for the stratigraphic abbreviations and Figure 4 for the location of each section line.

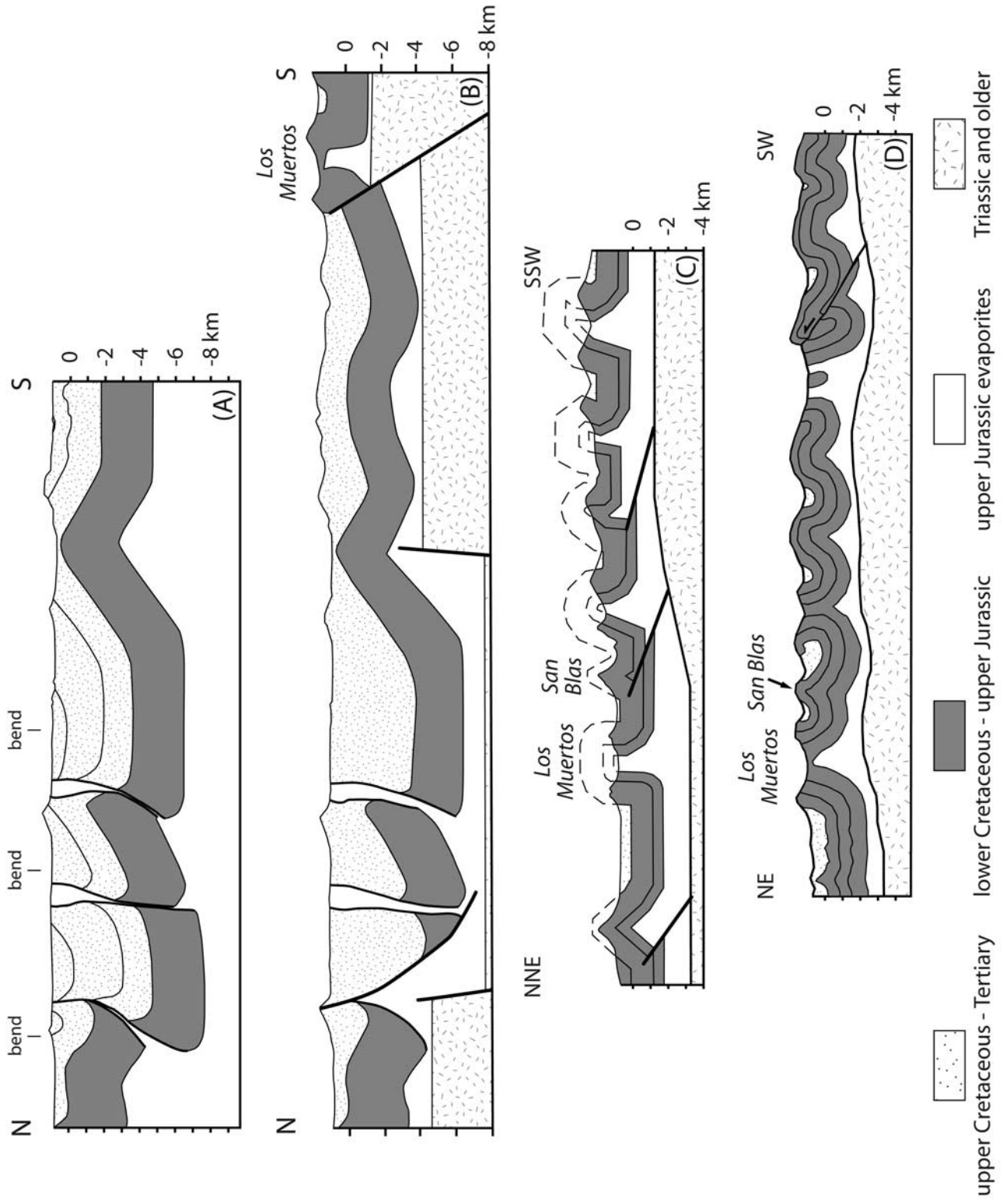


Figure 10

[23] We calculated the detachment depth for each cross section using the method of *Epard and Groshong* [1993]. This method determines the depth to a 2-D, horizontal detachment surface by plotting the excess cross-sectional area above a reference level for several stratigraphic horizons versus each horizon's undeformed, or "regional" elevation above that reference level. Ideal application of the method requires that the original regional elevation of each horizon is known, that the reference level is drawn parallel to the presumed detachment surface, and that no material is transported into or out of the cross-section plane. Although some of these assumptions and requirements may not be strictly adhered to in our particular study area, the approach provides a consistent methodology for estimating detachment depth beneath the Nuncios Fold Complex. These estimates can then be compared with solutions obtained from other methods or implied by field observations.

[24] Although the calculated detachment depth does not depend on the choice of reference level, we placed our reference level at the shallowest possible position for a horizontal, regional detachment. The minimum elevation for such a surface is roughly 2.8 km below sea level, and is obtained by assuming there are no Minas Viejas evaporites and a normal thickness of Zuloaga and younger rocks beneath the deepest part of the Mariposas synclinorium in the northwestern part of the map area. Figure 11 shows graphs of the excess area versus depth to the reference level for the seven cross sections in the Nuncios Fold Complex. Although we assumed that the calculated detachment is a horizontal line in the plane of each cross section, the calculated depth-to-detachment varies in each cross section. Connecting the 2-D detachments in each cross section creates a planar 3-D detachment surface that dips 7° toward an azimuth of 252°.

[25] When evaluating our depth-to-detachment calculations, it is important to note that our assumption of parallel folding will, by necessity, create excess area-versus-reference level data that show a strong linear trend. Moreover, because there is no constraint on the original, regional elevation for any of the units, we had to assume one. Here the presently large difference in elevation between horizontal units on the northern and southern sides of the folds creates some complications. We chose the elevation of horizontal units on the north side of the structure as the regional for the calculation of detachment depths (Figure 8). This assumption, coupled with the requirement that no material has moved into or out of the cross section, automatically results in a deeper detachment. Shallower calculated detachments, and therefore thinner detachment layers, would result if we chose a higher regional level or assumed that some of the

evaporites in the deformed section did not originate there. Given the existing constraints, our calculations likely predict the deepest possible position for the detachment. Greater constraint on the depth-to-detachment can only be obtained by examining the detailed kinematics of fold growth. Recent work in this area suggests a deep detachment is compatible with the best fit, realistic fold kinematics [e.g., *Bowman et al.*, 2003; *Smaltz and Wilkerson*, 2004; *Wilkerson et al.*, 2005].

3.2. Along-Strike Changes in Fold Geometry and Shortening

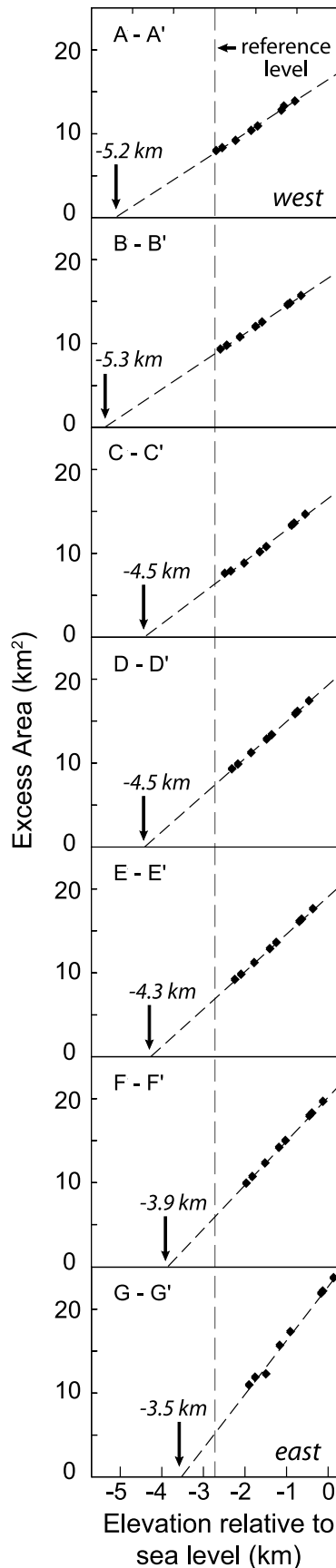
[26] As shown in the geologic map and in the cross sections, the Nuncios Fold Complex exhibits a dramatic along-strike change in geometry from its more eastern portions to its western plunging nose (Figures 4 and 8). East of cross section E-E', the structure can be clearly divided into two tight-to-isoclinal, upright anticlines with subvertical limbs. The northern Los Muertos anticline is continuous along strike throughout the entire map area, whereas the southern San Blas anticline terminates near cross section C-C'. West of this cross section Los Muertos anticline is a NNW verging fold with a short, subvertical forelimb, narrow crest, and longer, homoclinal back limb.

[27] Coincident with the along-strike changes in the geometry of the Nuncios Fold Complex are substantial changes in the calculated depth of the detachment and fold-related shortening. Assuming flexural slip kinematics, restoration of each cross section indicates that shortening systematically decreases from east to west along the Nuncios Fold Complex (Figure 8). As shown in Figure 12, shortening changes gradually from 6.3 km (40%) in the east to 3.2 km (19%) in the westernmost cross section. Extrapolating this shortening gradient westward suggests that major folds in lithotectonic unit 3 should die out no more than 14 km west of cross section A-A'.

4. Three-Dimensional Geometry of Lithotectonic Units

[28] We created a multilayered, three-dimensional structural model of the Nuncios Fold Complex by importing our Geosec2D™ cross sections into GOCAD™, and then linking the traces of each corresponding horizon in all cross sections (Figure 13). We applied constraints to each set of horizon lines so that fold axial surfaces, dip panels, and dip domain boundaries would be honored and retained during the surface generation process. Because of its small size and poorly constrained 3-D geometry, we decided not to include the surface-exposed evaporite body in our final

Figure 10. Four examples of regional cross sections that pass through or near the study area, and which also show depth to detachment or detachment layer thickness. See Figure 2 for a fifth example. Section (a) from *Millán-Garrido* [2004], (b) from *Gray et al.* [2001], (c) from *Marrett and Aranda-García* [1999], and (d) from *De Cserna* [1956]. Note the highly variable interpretations of basement geometry, detachment layer thickness and depth to detachment. See lines labeled A, B, C, and D in Figure 1 for the approximate location of each cross section. See Figure 3 for the regional stratigraphic column.



structural model. We tested the accuracy of the completed 3-D model by intersecting the model with our DEM of the area. The model map patterns resulting from this intersection reproduce not only the first-order features of the structure, but also many of the fine details of the geologic map (Figure 14). This implies a high degree of accuracy in areas where the 3-D model surface was projected between cross sections.

[29] We used our 3-D model to examine the thickness and geometry of each regional lithotectonic unit involved in the folding. Our purpose in doing this was to search for relationships or patterns that might further constrain important regional unknowns like detachment depth, thickness and 3-D deformation of the detachment layer and cover sequence. Within each lithotectonic unit, structural domains were defined by their 3-D geometry and thickness variations. Approximate isopachous thicknesses were determined by calculating the perpendicular distance between the opposing top and bottom surfaces of each lithotectonic unit. These distances were measured along lines that are perpendicular to the bottom surface, and extend from each of the nodes that define it. Consequently, the lines are not necessarily perpendicular to the top surface. Because lithotectonic unit 1 does not everywhere contain subparallel, opposing top and bottom surfaces, the thickness of this unit is simply the vertical distance between the unit's top and bottom. Three-dimensional variations in lithotectonic unit thicknesses for units 1 and 4 were visualized and examined by painting the top of each lithotectonic unit with colors characterizing that unit's corresponding thickness (Figure 15).

[30] Analysis of the models indicates that the map area can be divided into northern, central and southern structural domains (Figure 15). The northern domain, which exists beneath the Mariposas synclinorium, is a westward tapering wedge in which the thicknesses are relatively constant for lithotectonic units 1, 2, and 3. In contrast, rocks in lithotectonic unit 4 thicken to the west and thin to the east. This thinning coincides with a N-S oriented tectonic high along the maximum northern protrusion of the Monterrey Salient.

[31] The central domain, which corresponds to the Nuncios Fold Complex, shows a much greater thickness for lithotectonic unit 1 as compared to the northern and southern domains (Figure 15). If this thickening is not entirely stratigraphic, then it suggests tectonic injection of the weak evaporites to fill space created during the folding of

Figure 11. Depth-to-detachment calculations for each cross section through the mapped area. Note that there is a gradual increase in the depth to detachment from the east (cross section G-G') to the west (cross section A-A'). The horizons used for the calculations were the tops of the Minas Viejas, Zuloaga, La Casita 1 and 2, Taraises, Cupido 1 and Aurora formations. The Parras Formation and the Difunta Group were not included in the calculations because we interpret that they overlie a second, upper detachment system. Arrows show the calculated depth to detachment for each cross section.

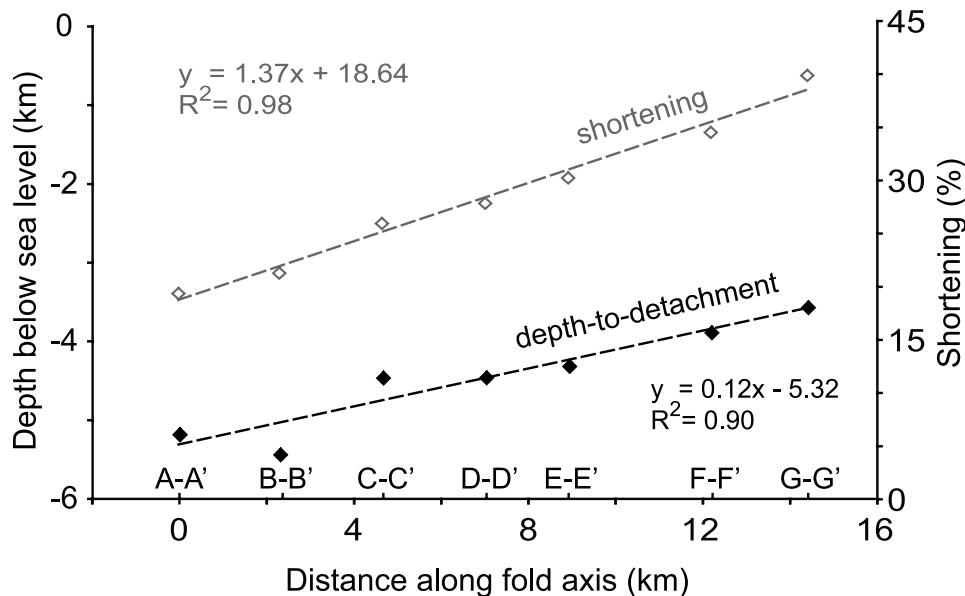


Figure 12. Along-strike changes in calculated shortening and depth to detachment for the Nuncios Fold Complex. The black dashed line and solid symbols represent depths to detachment, whereas the gray dashed line and open symbols represent shortening. Distance along the fold axis is arbitrarily calculated to increase eastward from cross section A-A'. Note the gradual, linear decrease in shortening and corresponding increase in detachment depth toward the west.

lithotectonic units 2 and 3. No major thickness changes exist in lithotectonic units 2, 3, and 4 that can be documented based on field mapping, however data are limited because the crest of the Nuncios Fold Complex is eroded down to the Zuloaga Formation, nearly the bottom of lithotectonic unit 2 (Figure 4).

[32] The southern domain, which is located beneath the Agua del Toro syncline, is a westward tapering wedge that is bounded to the east by the N-S oriented tectonic high along the Monterrey Salient axis (Figure 15). There are no substantial thickness variations in any of the lithotectonic units in this domain. However, the thickness of lithotectonic unit 1 is an average of 500 m thicker in the southern domain than it is in the northern domain, an amount too great to attribute entirely to stratigraphic variability. We refer to this structural thickening as hinterland inflation, and note that when coupled with a lack of constraint on pre-tectonic regional levels, the excess thickness of evaporites in this region will dramatically influence depth-to-detachment calculations, particularly those conducted on only a single structure.

5. Discussion

[33] Bounded on the north and west by sedimentary basins, the Nuncios Fold Complex is the frontal structure in a system of detachment folds comprising the Monterrey Salient of the Sierra Madre Oriental. As such, the structure occupies a unique tectonostratigraphic position in north-eastern Mexico; it likely is in close proximity to basin boundaries, across which the pre-tectonic thickness and character of the basal detachment layer and cover sequence

may have been dramatically different over distances of only a few tens of kilometers. Changes in the thickness or strength of either of these units are important because these two characteristics are known to affect detachment fold kinematics, the efficiency of transport of orogenic wedges, and the creation of triangle zones at orogenic wedge fronts [e.g., *Wiltschko and Chapple, 1977; Davis and Engelder, 1985; Erickson, 1995; Couzens-Schultz and Wiltschko, 1996; Jamison, 1996; Cotton and Koyi, 2000; Couzens-Schultz et al., 2003*].

[34] In this area the pre-tectonic thickness and distribution of the basal detachment layer, lithotectonic unit 1, was almost certainly influenced by the geometry of basement rocks and rift systems that developed during the Triassic-Jurassic breakup of Pangaea and the formation of the Gulf of Mexico. In the absence of strong subsurface constraints, several authors have speculated about the geometry of these rift systems and their subsequent influence on the pre-tectonic thickness patterns of lithotectonic unit 1 [e.g., *Padilla y Sanchez, 1982; Gray et al., 1997*]. Although subsurface data are still lacking in the area, our geometric analysis supports and further constrains some of these earlier speculations; in particular, the idea that lithotectonic unit 1 thins rapidly westward into the Parras Basin.

[35] The Nuncios Fold Complex plunges westward into the Parras Basin, while beneath it, the depth to detachment and thickness of the detachment layer increase toward the west (Figures 8 and 12). Coincident with these changes is a westward decrease in fold shortening as measured in carbonates comprising lithotectonic unit 3 (Figure 12). When considered in the context of possible detachment fold kinematics and acceptable lateral shortening gradients

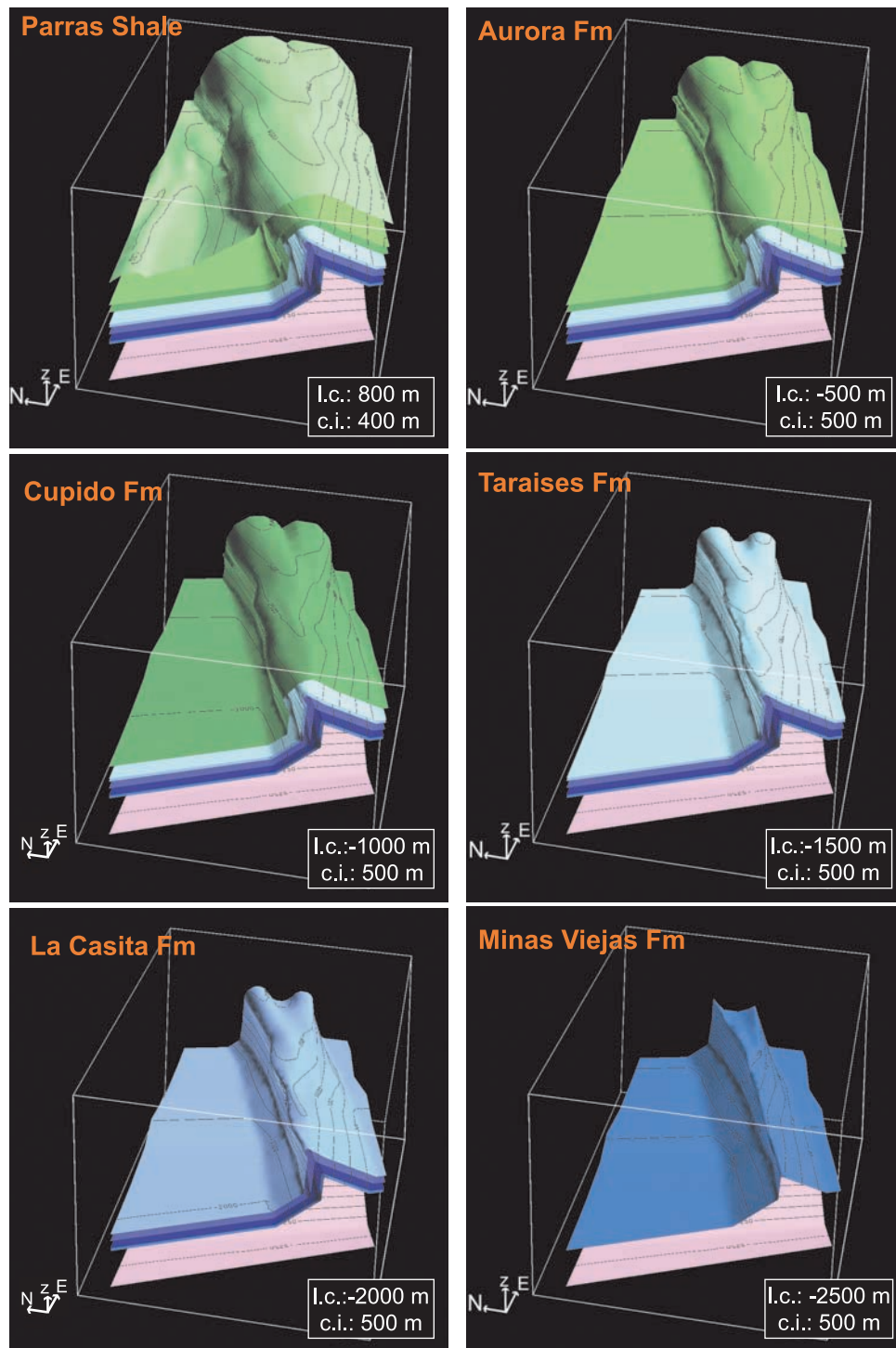


Figure 13. Three-dimensional geometry of the tops of six representative units in the Nuncios Fold Complex. The structure is viewed up plunge from the west, and the lowest surface in each visualization is the calculated top of basement. Note that although each surface is contoured, the contour interval is different for each diagram; for each box we list the value of the lowest contour (l.c.) and the contour interval (c.i.). Dimensions of the bounding box are 12 km along the N axis, 20 km along the E axis and 9 km along z axis. See Figure 3 for the relative position of each surface in the stratigraphic column. Surfaces are colored to match their corresponding formations in Figures 4 and 8.

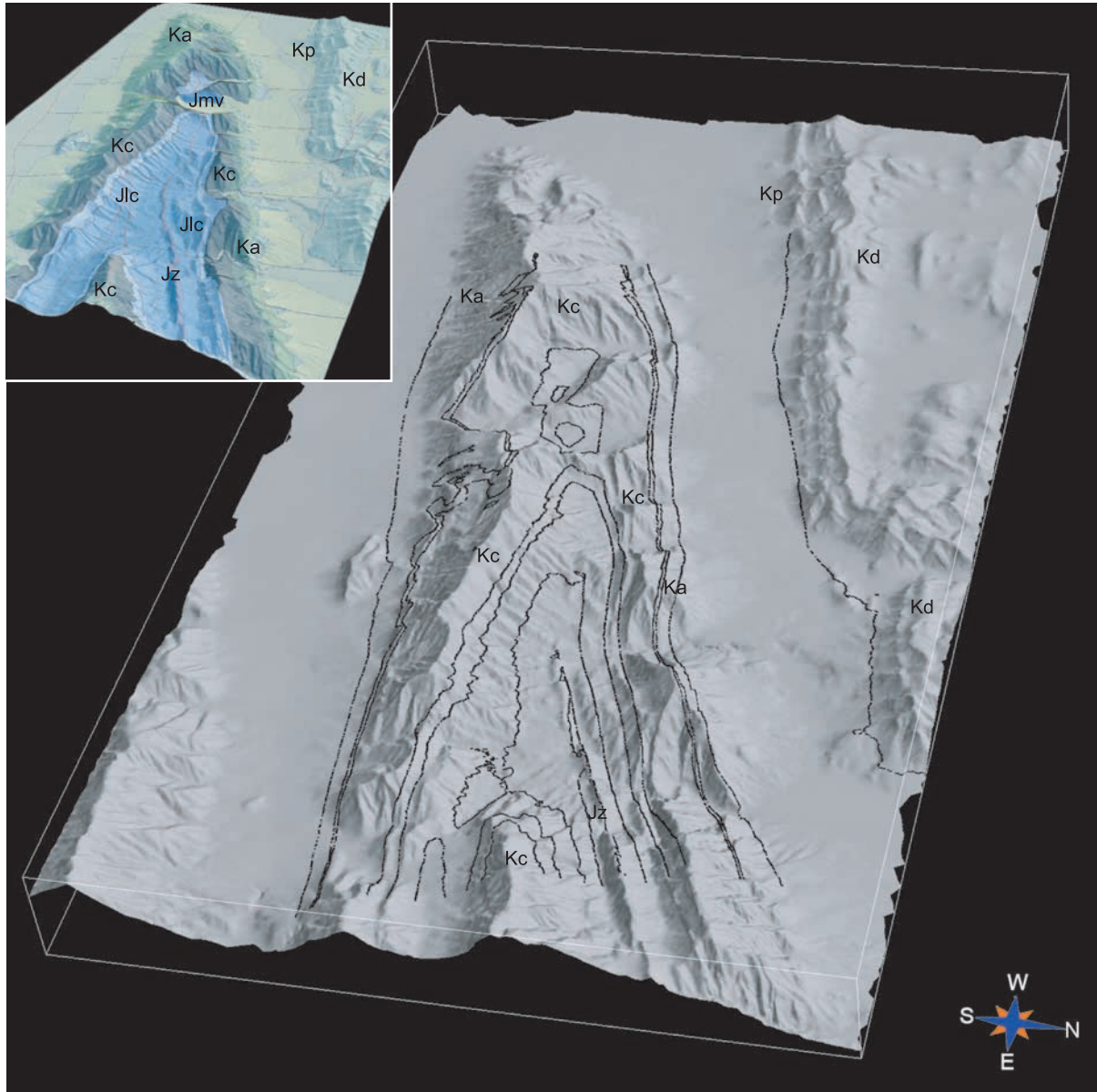


Figure 14. Down plunge view of the synthetic map pattern created by intersecting the 3-D model with the DEM shown in Figure 4. Inset shows the actual geologic map draped over the DEM and viewed in the same down plunge perspective.

[e.g., *Wilkerson, 1992*], these changes suggest that despite local thickening from cross section G-G' to A-A', lithotectonic unit 1 must abruptly thin to the west of our cross section A-A'. As noted by *Wiltchko and Chapple [1977]*, large-amplitude and large-wavelength detachment folds cannot develop without thick detachment layers, and the absence of such folds in the Parras Basin therefore implies a thin or absent lithotectonic unit 1. In addition, although shortening of lithotectonic unit 3 likely decreases to zero within 15 km west of section A-A' (Figure 12), abundant smaller folds and thrust faults in the Parras Basin [e.g.,

Weidie and Murray, 1967; McBride et al., 1974; Dillman, 1985] suggest that total orogenic shortening remains relatively constant along strike. This requires that as folds in the Monterrey Salient die out westward, regional horizontal displacement is progressively partitioned upward, most likely into the upper detachment layer, lithotectonic unit 4. Westward pinch out or thinning of Minas Viejas evaporites would decrease the efficiency for slip and flow of the basal detachment layer beneath the Parras Basin, and would be expected to create exactly this kind of upward transfer of regional shortening.

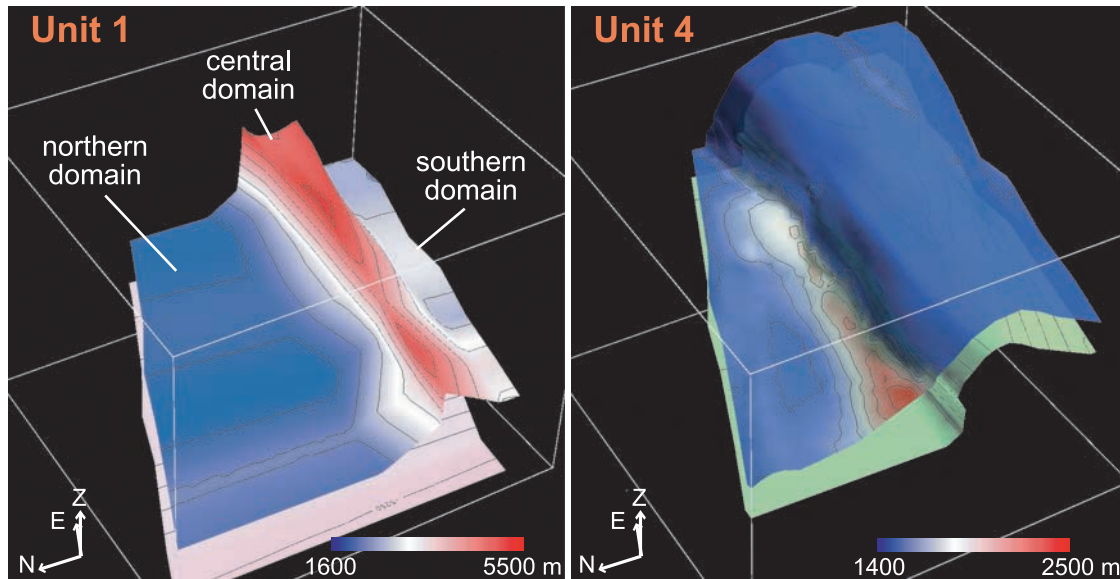


Figure 15. Three-dimensional visualizations of thickness variations in lithotectonic units 1 and 4. Thicknesses were calculated between the two horizons defining the top and bottom of each lithotectonic unit and shown in each visualization. Scale bars show thickness in meters. Dimensions of the bounding box for each model are similar to those of Figure 13. In each diagram the contours on the upper surface show thickness, whereas those on the lower surface indicate elevation.

[36] North of the Nuncios Fold Complex there is an abrupt loss of displacement on the lower detachment and a pronounced reversal of vergence for structures developed in lithotectonic unit 4. These are characteristics of a triangle zone or the leading edge of a passive roof duplex [Jones, 1996], structures that commonly occur where a regional basal detachment layer is abandoned in favor of a weaker upper detachment layer [Couzens-Schultz and Wiltschko, 1996; Couzens-Schultz et al., 2003]. Such abandonment can be associated with facies changes causing strengthening or thinning of the basal detachment layer, or with a buttressing effect caused when an orogenic wedge propagates into an excessively thick or strong cover sequence [Erickson, 1995; Couzens-Schultz and Wiltschko, 1996; Jamison, 1996; Couzens-Schultz et al., 2003]. Although some workers have interpreted a large basement step or fault beneath the leading edge of the Monterrey Salient [e.g., Gray et al., 2001], our depth-to-detachment calculations suggest a roughly 2 km thickness of evaporites persists northward into the southern La Popa Basin. This is compatible with large thicknesses of evaporites interpreted there by Millán-Garrido [2004], and with the presence of evaporite diapirs and withdrawal basins [e.g., Weidie and Martinez, 1970; Laudon, 1984; Giles and Lawton, 1999]. We therefore prefer the interpretation that thick accumulations of Difunta Group strata most likely halted the northward transport of the Sierra Madre orogenic wedge.

[37] Within the Monterrey Salient portion of the Sierra Madre orogenic wedge, lithotectonic units 2 and 3 exerted a strong influence on the geometry and kinematics of detachment folding. The regular system of folds in the salient, all

of which have wavelengths near 5 km [Padilla y Sanchez, 1982], likely formed by buckling of these competent units. Similar to physical and analytical models of 3-D folding [e.g., Dubey and Cobbold, 1977; Fletcher, 1995], the folds most likely initiated as small perturbations at a variety of locations throughout the region, and then progressively amplified while growing laterally along their axes. The mechanism of their amplification, as well as the amplitudes to which they could grow, were influenced by the 3-D deformation and thickness of the basal detachment layer. Recent modeling by Wilkerson et al. [2005] and mesostructural observations by Fischer and Jackson [1999] suggest that amplification of in the Nuncios Fold Complex occurred by fixed-hinge, fixed-limb-length, rotating-limb kinematics. These results are compatible with the uniform wavelengths and geometry of folds throughout the Monterrey Salient.

[38] Where detachment folds form by fixed-hinge, fixed-limb-length, rotating-limb kinematics, their 3-D evolution is closely tied to the volume of the basal detachment layer [e.g., Homza and Wallace, 1997]. As such folds amplify, the detachment layer must first flow into the increasing space beneath anticlines, and out of the space beneath synclines. With continued tightening the detachment layer will be forced out of the collapsing anticline core, either along strike, or toward the hinterland or foreland. In areas where multiple folds are amplifying and growing laterally in three dimensions, fold interference and progressive tightening will result in complex, 3-D flow of the detachment layer. Local increases or decreases in regional must occur in this situation, with the exact, local response being dictated by the available detachment layer volume and local fold

kinematics. We interpret the hinterland inflation south of the Nuncios Fold Complex, as well as the local westward thickening of the detachment layer, as resulting from this type of flow. The extra thickness of evaporites beneath the Agua del Toro syncline may have been extruded along strike from more internal parts of the fold belt, or forced out of an adjacent, tightening fold. Despite what was most likely an original stratigraphic thinning to the west, the detachment layer beneath the Nuncios Fold Complex now slightly thickens westward, also suggesting along-strike flow of evaporites. *Cotton and Koyi* [2000] reported exactly this kind of detachment layer flow near the lateral pinch out of the basal detachment layer in physical models. In their models local tectonic thickening and upward intrusion of the detachment layer also occurred near its lateral edge, results that are strikingly similar to what we observe near the western end of the Nuncios Fold Complex.

[39] In fold belts that form over thick, weak detachment layers, 3-D flow of the detachment material is highly likely. Structural interpretations must be done with caution in these areas because the resulting detachment folds are not easily analyzed with many of the existing 2-D kinematic models. As we have shown for the Nuncios Fold Complex, 3-D changes in detachment layer thickness may contribute to fold plunge, cause significant, nonsystematic changes in regional, and limit the extent to which folds can amplify. Although most models incorporate relations between detachment layer thickness and fold amplification, the lack of a consistent regional elevation across structures poses particular problems when attempting to calculate the depth to a detachment surface. Our modification of *Epard and Groshong's* [1993] method for calculating depth to detachment is an internally consistent, albeit ad hoc attempt to account for this, and most likely only yields a maximum estimate of detachment depth. More accurate depth-to-detachment calculations require models that fully account for the complete history of fold growth, and that rigorously incorporate the existence of differing regional elevations across a fold.

6. Conclusions

[40] We have integrated geological mapping, aerial photo interpretation, digital elevation data, and cross section balancing to describe the three-dimensional geometry and kinematics of the Nuncios Fold Complex, a map-scale, evaporite-cored detachment fold in the Monterrey Salient of northeastern Mexico. The structure involves Upper Jurassic through Cretaceous rocks deformed during the Laramide orogeny, and is formed by three interfering folds:

the westward plunging Los Muertos and San Blas anticlines, and the eastward plunging, intervening Sierra Urbano syncline. Seven balanced cross sections and a 3-D model of the structure document a westward increase in the depth to detachment, and a coincident decrease in shortening. Substantial variations in the thickness of the basal detachment layer occur beneath the fold, both along strike, and across the fold axis. We interpret these thickness variations as evidence for 3-D flow of the basal detachment layer during folding, and note that existing detachment fold models and depth-to-detachment calculations cannot be easily applied in regions where such thickness variations occur.

[41] On the regional scale, our mapped area comprises two structural domains with related tectonic origins and slightly different sedimentary sequences. We propose that the regional geometry and the kinematics of folds in these two areas are dependent on the facies distribution and thickness of two regional detachment layers, as well as the strength of the rigid, fold-forming units. Deformation within the Monterrey Salient is controlled by a weak, basal evaporitic layer and overlying strong carbonates and sandstones. In this structural domain folds have curvilinear hinges that near their western ends trend and plunge west-southwest and terminate beneath the Parras Basin. The westward plunge and termination of the Monterrey Salient folds is due to westward thinning and eventual pinch out of the evaporite facies comprising the basal detachment layer. By contrast, folds in the northeastern Parras Basin define a different structural domain, and are smaller, rectilinear, west trending and plunging anticlines that root to a shallower detachment layer overlain by a thick shale and sandstone succession. We suggest that these folds formed in a triangle zone at the leading edge of the Sierra Madre orogenic wedge, and that this triangle zone most likely formed where thick, syntectonic sediments of the Difunta Group acted as a buttress that inhibited slip on the basal, evaporite detachment.

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- M. P. Fischer and I. C. Higuera-Díaz, Department of Geology and Environmental Geosciences, Northern Illinois University, DeKalb, IL 60115-2854, USA. (higuera@geol.niu.edu)
- M. S. Wilkerson, Department of Geosciences, DePauw University, Greencastle, IN 46135, USA.